Title
A Ubiquitous Optical Microsystem Platform with Application to Optical Metrology and Chemical Sensing

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A Ubiquitous Optical Microsystem Platform
with Application to Optical Metrology and Chemical Sensing

by

John David Gerling

A dissertation submitted in partial satisfaction of the requirements for the degree of
Doctor of Philosophy

in

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in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:
Professor Nathan W. Cheung (Chair)
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Professor David B. Graves

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A Ubiquitous Optical Microsystem Platform
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By
John David Gerling
Abstract
A Ubiquitous Optical Microsystem Platform
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Doctor of Philosophy in Applied Science and Technology
University of California, Berkeley

Professor Nathan W. Cheung, Chair

This dissertation is concerned with the development of a novel, versatile optical sensor platform for optical metrology and chemical sensing. We demonstrate the feasibility of embedding optical components between bonded silicon wafers with receptor cavities and optical windows to create a self-contained sensor microsystem that can be used for in-situ measurement of hostile environments. Arrays of these sensors internal to a silicon wafer can enable optical sensing for in-situ, real-time mapping and process development for the semiconductor industry in the form of an instrumented substrate. Single-die versions of these optical sensor platforms can also enable point-of-care diagnostics, high throughput disease screening, bio-warfare agent detection, and environmental monitoring. Our first discussion will focus on a single-wavelength interferometry-based prototype sensor. Several applications are demonstrated using this single wavelength prototype: refractive index monitoring, SiO$_2$ plasma etching, chemical mechanical polishing, photoresist cure and dissolution, copper etch end-point detection, and also nanopore wetting phenomena. Subsequent sections of this dissertation will describe efforts to improve the optical sensor platform to achieve multi-wavelength sensing function. We explore the use of an off-the-shelf commercial RGB sensor for colorimetric monitoring of copper and aluminum thin-film etchings. We then expand upon our prior work and concepts to realize a fully integrated, chip-sized microspectrometer with a photon engine based on a diffraction grating. The design, fabrication, and demonstration of a working prototype with dimensions < 1 mm thick using standard planar microfabrication techniques is described. Proof-of-concept demonstrations indicate the working principle of dispersion, although with a low spectral resolution of 120 nm. With working knowledge of the issues of the first prototype, we present an improved 5-channel microspectrometer with a spectral range 400-900 nm and demonstrate its ability for spectral identification with 3 different phosphor powder samples. Finally, we conclude with suggestions for future areas of research.
To my family,
my one constant.
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All the fabrication work presented in this dissertation was performed in the Marvell Nanofabrication Laboratory.

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In parts of this dissertation, data and/or images were made possible by the following individuals: Patrick Bennett provided AFM data of fabricated mirrors; Kevin Wang provided SEM images of the fabricated photodiode arrays; Evan Stateler provided SEM images of porous aluminum oxide samples; and Erick Avila provided aluminum evaporation for the gratings used.
1 Introduction

1.1 Motivation

An ubiquitous optical microsystem platform which can perform point-of-care diagnostics, high throughput screening for diseases, bio-warfare agent detection, and environmental monitoring is highly desirable if a miniaturizing system usually called micro total analysis systems (u-TAS) is commercialized [1]-[3]. Conventional micro analytical systems typically involve integration of various material systems and device components: III-V photonic emitters, III-V or II-VI optical filters, polymer fluidic channels, silicon-based or III-V photodetectors and Si CMOS data processing units [4], [5]. Miniaturization of these systems not only will reduce the physical size, which greatly improves the portability, but will also gain wide spread acceptance due to the significant reduction of reagent and sample consumption [1]-[5].

There are two key technologies enabling the development of a ubiquitous optical microsystem platform – laser lift-off (LLO) technique and hybrid integration. Recent advances in the laser lift-off (LLO) technique (Fig. 1-1) has resulted in a new genre of optical sources such as ultra-bright light-emitting diodes (LEDs) and laser diodes to be mass produced with a form factor of 1 mm² and 100 um thick [6]-[9]. LLO technique consists of a pulsed KrF excimer laser (248 nm) directed through the backside of a transparent sapphire (Al₂O₃) substrate causing an interfacial dissociation of the GaN layer to Ga + N₂ vapor. Subsequent thermal detachment at 40 °C removes or lifts-off the GaN LED for later pick-and-place integration [10]. Removal of the thermally insulating sapphire substrate results in notable performance improvements such as improved heat sinking and a reduction in the series and spreading resistance from using a backside metal contact [10], [11].

![Figure 1-1: Laser lift-off (LLO) process, from Wong [10]; 1) metal deposition on LED array; 2) low-temperature bonding to temporary receptor substrate; 3) laser lift-off via KrF excimer laser (248 nm) and subsequent thermal detachment.](image-url)
These paper thin photon engines can be placed by cut-and-paste approaches, also known as hybrid integration (Fig. 1-2), on various locations of the microsystem either as a single pixel or as an array of pixels. Hybrid integration allows one to alleviate the limitations of monolithic integration by synthesizing and fabricating each material subsystem independently, and then later assembling them onto a receptor substrate. This technique enables new and novel functionalities by integrating dissimilar semiconductor material systems to assemble a microsystem [11]-[16]. When coupled with substrate thinning technologies, multi-chip modules, grid arrays, and flip chip technology for 3D integration [17], [18], we envision new architectures using heterogeneous integration of III-V photonics with Si CMOS for ubiquitous optical microsystem platforms [19].

![Figure 1-2: Schematic drawing of a cut-and-paste hybrid integration process of disparate functional units having independent thermal, chemical, and mechanical budgets with two levels of integration [11]-[16].](image)

It is the objective of this research project to capitalize on the recent advances afforded by the high-brightness LED and hybrid integration to realize a ubiquitous optical microsystem platform. With a single-wavelength platform (e.g. LED and photodiode), one can obtain time-domain reflectance and interferometry information [11]. With an extension to a multi-wavelength platform (e.g. LED and wavelength-specific detectors), one can gather time-domain spectroscopic data for modeling chemical reactions and molecular identification.
One example is a zero-footprint optical metrology wafer for in situ, real-time process monitoring and process development. Such a wafer would meet dimensional specifications of a regular silicon wafer (e.g. 500 um to 1000 um thickness) so that it can pass through all the processing equipment typically found in a semiconductor fab; it will have all the optical metrology components embedded so that information about the wafer state can be gathered in a real-time and location-specific manner. The uniqueness of this optical platform is that the surface information of the wafer is probed with an optical source and monitored by detectors inside a self-contained, self-powered, and environmentally sealed wafer pair. The encapsulation is designed to allow the metrology wafer to be used in hostile environments such as plasma etching, corrosive etch or clean, and polishing slurries.

Another example is a red, green, and blue (RGB) image sensor with a high-brightness LED that can yield three-channel spectroscopic information. Like the metrology wafer, this too would be in real-time, in-situ fashion. Rather than employing lenses, this platform provides the simplicity of direct LED excitation and monitoring with only two components. Such a system could find wide spread use in consumer and portable field devices.

Yet another example is a fully integrated, chip-sized, grating-based microspectrometer with a photon engine. With greatly expanded sensing capability over an interferometric or RGB-based optical platform, the micro spectrometer can find use as a stand-alone or embedded device. The applications for spectroscopy are far-reaching; anything with an optical characteristic of interest is a potential area to explore, such as dermatology, disease screening, bio-warfare agent detection, and environmental monitoring. We have enumerated some of the potential applications in Table (1-1) with asterisks (*) denoting demonstrated applications.

<table>
<thead>
<tr>
<th>Optical Interference Function</th>
<th>Spectroscopy Function</th>
<th>Future Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index Monitoring*</td>
<td>Fluorescence Spectroscopy*</td>
<td>Thermal/Chemical/Mechanical Induced Optical Changes</td>
</tr>
<tr>
<td>Resist Development/Stripping*</td>
<td>Precursor Identification</td>
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<td>Metal End-point Etch*</td>
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<td>CMP*</td>
<td>Thin Film Deposition and Etch</td>
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<tr>
<td>Lateral Feature Monitoring*</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
1.2 General Design Philosophy

Since we concern ourselves with the manipulation and measurement of electromagnetic waves, in particular to extracting spectral information, let us consider a time-harmonic electromagnetic plane wave of frequency $\omega$ traveling along the $x$-direction in a medium with a complex, frequency dependent refractive index $\tilde{n}(\omega)$ [20]:

$$E = E_o \exp(ik\tilde{n}(\omega)x) \tag{1-1}$$

where $E_o$ is the amplitude of the electric field, and $k$ is the wavenumber ($k = 2\pi/\lambda$). The complex index of refraction $\tilde{n}(\omega)$ is given as:

$$\tilde{n}(\omega) = n(\omega) + i\kappa(\omega) \tag{1-2}$$

where $n(\omega)$ represents the ratio of the wave velocity in the medium to vacuum and $\kappa(\omega)$ represents the energy absorption in the medium; these terms are wavelength/frequency dependent. We expand Eq. (1-1) with the complex index of refraction and get:

$$E = E_o \exp(ikn(\omega)x)\exp(-\alpha(\omega)x) \tag{1-3}$$

where $\alpha(\omega)$ is the attenuation coefficient containing the imaginary part of the refractive index i.e. $\alpha(\omega) = 2\pi\kappa(\omega)/\lambda$. From this result we can deduce several approaches one can take to manipulate an electromagnetic wave. We illustrate some examples of these methods schematically in Fig. (1-3).

\[
\begin{array}{c}
\text{a)} \\
\text{b)} \\
\text{c)}
\end{array}
\]

Figure 1-3: Illustrative examples of three methods to separate photons of different frequencies. One can employ a) dispersive (real index of refraction), b) absorption (complex index of refraction), or c) diffractive (reciprocal space) phenomena to separate photons of different frequencies.

By making use of the real part of the refractive index $n(\omega)$, one can exploit the phase velocity differences of photons to spatially separate wavelengths of interest (Fig. 1-3a). This is the concept behind the classical prism [21], and more recently on the work regarding metamaterials – materials that derive their properties from structure rather than composition, such as the multilayer thin-film stack [22]-[25], and the photonic crystal [26]-[29].
A second approach utilizes the absorption $\alpha(\omega)$ properties of materials, to separate photons based on their energy. This principle is widely used as monolithic RGB pixel arrays in digital cameras to separate color components for digital processing [30]. Other absorption based approaches also include dye-based color filters [31] and ionically colored glass [32]. One can also engineer colloidal nanocrystals with the desired band gaps for tunable absorption properties [33].

A third approach is to engineer the optical path length $\chi$ to obtain a phase shift between two waves (incoming and outgoing) of the same frequency and location in space to satisfy conditions for constructive or destructive interference. In reciprocal space, one seeks a condition that would cause the incoming $\mathbf{k}$ and outgoing $\mathbf{k}'$ wave vectors to satisfy the relation (Fig. 1-4):

$$\mathbf{k} - \mathbf{k}' = G$$  \hspace{1cm} (1-4)

where $G$ is the reciprocal vector.

![Figure 1-4: Definition of the incoming $\mathbf{k}$ and outgoing wave vectors $\mathbf{k}'$ in terms of the reciprocal vector $G$ for the case of a periodic structure with period $d$ in the horizontal direction.](image)

For a periodic structure such as a grating with a period $d$, Eq. (1-4) can be expressed as the well known grating equation:

$$m\lambda = d\left(\sin \theta_{inc} + \sin \theta_m\right)$$  \hspace{1cm} (1-5)

where $\theta_{inc}$ and $\theta_m$ are the incident and diffracted angle, and $m$ is the diffraction order. Examples of wavelength separation using this phenomena include thin-film interference filters [34]-[36], waveguides [37], [38], and gratings [39]-[42].

1.3 Active versus Passive

In the context of designing a robust ubiquitous optical microsystem platform that can be used in hostile environments, we do not consider active or MEMS-based (micro-electrical-mechanical systems) approaches in the present work. MEMS-based optical devices carry several design and fabrication challenges such as:
1. Release and stiction issues of floating structures resulting in zero-life and long-term reliability concerns [43], [44].

2. Avoiding the electrostatic pull-in or snap-down of structures which results in device failure [43].

3. Tuning the movable elements (e.g. mirrors, gratings, or cantilevers) or a sufficiently large enough range with acceptable voltage levels [45].

4. Stress issues originating from material mismatch and different coefficients of thermal expansion [43], [45], [46]. During fabrication, film thickness variations and also stress variations across the wafer further add to the complexity of MEMS-based optical devices.

5. With the above stress issues in mind, another concern is maintaining the flatness of optical surfaces over a temperature range [43], [45], [47]. Additionally, one is also concerned with maintaining parallelism between flexing structures [47].

6. MEMS-based devices carry additional design constraints for mechanical vibration and noise immunity. One needs to consider structural compensation and/or electrical control methods [48].

7. MEMS are in principle dynamic systems and require power consumption. There is effort to develop MEMS devices that exhibit latch on or off states, but this returns us to the stiction and reliability concerns [43].

8. Finally, the packaging of MEMS must be thoroughly considered to avoid particulate and contamination issues that can impair the moving parts [43], [44], [46]. This in turn can affect the manufacturing yield for more complex systems [43].

With all of the above in mind, in order to implement a MEMS-based optical device, one also needs to consider the details of light collimation, focusing, wavelength selection and methods for the precise control of structures. Despite these challenges, MEMS-based optical devices have been successfully fabricated with wavelength resolutions ranging from 1 to 50 nm. Implementations vary from gratings, resonators, or waveguide approaches. Resonator-based Fourier transform devices have demonstrated wavelength resolutions around 40-60 nm [49], while grating-based Fourier transform devices have demonstrated resolutions as low as 2.8 nm over a 400 to 1100 nm operating range [50]. Actuated waveguide-coupled micro-disk resonators have also demonstrated resolution < 1 nm, but over a smaller operating range of 1530-1585 nm [49], [51]. Besides improved resolution, these MEMS-based optical devices only require one optical detector to be effective. This reduces the number of components needed for final system assembly.
1.4 Research Objectives

A passive optical platform with no moving parts allows us to be free of concerns regarding mechanical vibration, electrostatic actuation and stiction concerns associated with MEMS-based devices. Microfabrication technology is uniquely posed to solve the problem of wavelength demultiplexing. One can choose from a wide range of materials that can be deposited, grown, or patterned to obtain a means to control light. Other than the advantageous form factor reduction and reproducibility suitable for mass production, microfabrication also has the potential to enable scalable, flexible optical platforms. The overall research project seeks to provide evidence that:

1) Robust, non-MEMS optical platforms can be fabricated;

2) The relevant optical and photon engine components can be integrated into a chip-size or a wafer form factor;

3) And that optical microsystems can be used in hostile environments;

1.5 Organization of the Thesis

Chapter 2 will start with a discussion of prior and current work on the zero-footprint optical metrology wafer with interferometry capability. The focus will be on the design, fabrication and demonstrations of the sensor cells themselves. The specifics of power, data transmission and isolation are beyond the scope of this dissertation but will be mentioned in passing. We will cover examples of dielectric and metal film etching, slurry monitoring for chemical mechanical polishing, and also lateral feature monitoring.

In Chapter 3, we expand our efforts to develop a multi-wavelength optical sensor platform using a RGB image sensor and a high-brightness blue LED (460 nm). The linearity and spectral response of the RGB image sensor is characterized and a three-channel spectral model is fitted to the extracted spectral response. We use this information to quantify time developments of the RGB image sensor outputs for in situ copper and aluminum etching experiments in terms of three defined spectral bands.

In Chapter 4, we present a fully integrated, chip-sized, grating-based microspectrometer with a photon engine. The microspectrometer is realized using standard planar microfabrication techniques and bulk silicon micromachining. The design and characterization of the various components will be covered in detail. The final device has a form factor of approximately 1 mm thick and operates in the visible spectrum (400-700 nm). For reasons that will be discussed, only a three-channel device is demonstrated.
With Chapter 5 we cover subsequent improvements to the grating-based microspectrometer. With these improvements we were able to successfully realize a five-channel device that operates over the visible to near infrared spectrum (400-900 nm). The form factor for the improved prototype increases modestly from 1 mm to 1.2 mm thick. We conclude Chapter 5 with a demonstration of the “finger-printing” capability of the microspectrometer with three different phosphor powder samples. Finally, we will conclude with a summary of our research efforts and provide a few suggestions for future research directions.

1.6 References


2 Zero-Footprint Optical Metrology Wafer

2.1 Introduction

Prior work by Luo, Loryuenyong, and Cho has established the concept of a self-contained optical metrology wafer based on an interferometric sensor cell [1]-[4]. Fig. 2-1 illustrates the cross section of the metrology wafer concept. Pre-fabricated devices for optical excitation, detection, data transmission, and a power source are embedded inside of a lithographically defined, environmentally sealed wafer pair. The embedded components occupy no additional silicon real estate (hence the term zero-footprint); allowing for in situ gathering of surface information in a real-time and a location specific manner across the wafer surface. The goal is to enable wafer mapping, feedback/feed forward for yield control, chamber qualification, and process development. The metrology wafer relies on transparent optical windows to obtain interference information from the surface conditions to extract film thickness, refractive index, and film density information. It is not intended to replace existing metrology systems, but rather be a complementary tool for process study and yield control [1].

![Anatomy of a self-powered zero-footprint optical metrology wafer](image)

**Figure 2-1**: Anatomy of a self-powered zero-footprint optical metrology wafer. The essential part of the metrology wafer is the self-contained data acquisition cell which contains a powerful photon engine and detector elements for measuring the reflectance changes at the window. Power can be provided using thin-film Lithium Phosphorus Oxynitride (LiPON) batteries < 300 um thick, inductive coil charging, or backside contacts. Acquired data can be transmitted to a host computer using an embedded photo or RF transmitter [3]-[6].

The zero-footprint optical metrology wafer has the following salient features:

1) Self-contained metrology unit with embedded power and wired or wireless I/O.

2) Durable in aqueous and vacuum processing environments such as plasma deposition and etching, wet etch and clean chemical processing, and Chemical Mechanical Polishing (CMP).

3) Can be used for refractive index, film thickness, etch end-point mapping, and spectroscopic probing in a real-time and location specific manner.
It is worth mentioning before continuing that the concept of a fully autonomous metrology wafer is not unique to this work, but originated in the late 1990’s with the development of wafer-mounted sensor arrays. This original work focused on the full integrated, functional wafer as a system, and on temperature and etch-rate transducers [7]-[11]. In fact, temperature-based metrology wafers are already commercially available [12]. The work presented in this chapter represents the effort to extend the realm of the metrology wafer concept to optical sensing with a novel encapsulation scheme for hostile environments.

2.2 Optical Functions of a Plane Wave

Since the optical metrology wafer relies on the reflected intensity from the optical window, we find it useful to cover the background on estimating the optical properties of thin films. Estimating the optical properties of a multilayer film is integral to instrument design and modeling in many fields such as lithography, plasma diagnostics, and advanced process control. The fitting of calculated reflectance data to measured reflectance data forms the basis of many metrology systems. This enables one to determine film thicknesses, densities, and roughness using the reflectance versus incident angle and/or wavelength data [13].

Computations of the optical functions of a thin film or a multilayer film stack are based on application of the Fresnel equations which describe the reflected and transmitted electromagnetic field amplitudes at the abrupt interfaces of optically dissimilar materials. To account for non-ideal interfaces e.g. rough or diffuse interface profiles, the Fresnel equations can be modified. For composite material systems, effective medium theory can be introduced to estimate the effective optical constants used in the Fresnel equations. Here we present the general framework for computing the optical functions of a thin film.

2.2.1 Reflection and Transmission at an Ideal Interface

When an electromagnetic plane wave reaches a boundary between two media with different dielectric constants, part of the wave is reflected back into the first medium and part of the wave is transmitted into the second medium, as shown in Fig. (2-2).

![Diagram of an electromagnetic plane wave incident at the interface between two optically dissimilar materials](image)

**Figure 2-2:** Diagram of an electromagnetic plane wave incident $E_i$ at the interface between two optically dissimilar materials $n_i$ and $n_j$. The incident wave $E_i$ is reflected $E_i'$ back into medium $i$ and transmitted $E_j$ into medium $j$. 

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The expressions for the reflected and transmitted wave amplitudes are obtained by applying the electromagnetic boundary conditions at the interface and then solving. Since electromagnetic waves are transverse, one will obtain separate amplitude coefficients for the wave vectors perpendicular (s-polarization\(^1\)) and parallel (p-polarization\(^2\)) to the plane of incidence. For s-polarization (i.e. \(E\) perpendicular to the plane of incidence) the expressions are given as:

\[
\begin{align*}
    r_{ij}^s & \equiv \frac{E_j}{E_i} = \frac{n_i \cos \theta_i - n_j \cos \theta_j}{n_i \cos \theta_i + n_j \cos \theta_j} \\
    t_{ij}^s & \equiv \frac{E_j}{E_i} = \frac{2n_i \cos \theta_i}{n_i \cos \theta_j + n_j \cos \theta_i}
\end{align*}
\]  

(2-1a) 

(2-1b)

For p-polarization (i.e. \(E\) parallel to the plane of incidence) the expressions are given as:

\[
\begin{align*}
    r_{ij}^p & \equiv \frac{E_j}{E_i} = \frac{n_i \cos \theta_j - n_j \cos \theta_i}{n_i \cos \theta_j + n_j \cos \theta_i} \\
    t_{ij}^p & \equiv \frac{E_j}{E_i} = \frac{2n_i \cos \theta_i}{n_i \cos \theta_j + n_j \cos \theta_i}
\end{align*}
\]  

(2-1c) 

(2-1d)

where \(r_{ij}\) and \(t_{ij}\) are the Fresnel reflection and transmission coefficients, respectively. The index of refraction for medium \(i\) and \(j\) are noted as \(n_i\) and \(n_j\). The angle of refraction \(\theta_j\) is determined from Snell’s Law \((n_i \sin \theta_i = n_j \sin \theta_j)\). The above four expressions constitute the well-known Fresnel equations for reflection and transmission at an ideal interface [14]-[18]. The reflectance \(R\) and transmittance \(T\), which is a measure of the reflected or transmitted energy, respectively, is given as:

\[
R = |r|^2
\]  

(2-2a)

\[
T = \text{Re} \left\{ \frac{n_i \cos \theta_j}{n_i \cos \theta_j} \right\} |r|^2
\]  

(2-2b)

Again, with separate computations for the s- and p-polarization, i.e. \(R^s\), \(R^p\), \(T^s\), and \(T^p\) [14]-[18].

\(^1\)“s” comes from the German word “senkrecht” meaning perpendicular.

\(^2\)“p” comes from the German word “parallel” which also means parallel.
2.2.2 Interface Imperfections

In order to account for the loss in specular reflectance or transmittance due to interface imperfections (e.g. rough or diffuse), we consider the case where the change in refractive index across an interface is not abrupt, but is described instead by an interface profile function \( p(z) \), as shown in Fig. (2-3) [18], [19].

![Figure 2-3: Sketch of the interface profile function \( p(z) \), which describes a rough or diffuse interface between two materials [18].](image)

Following the formalism developed by Stearns, the interface profile function \( p(z) \) is defined as the normalized, average value of the dielectric function \( \varepsilon(x) \) along the \( z \) direction, where \( n = \sqrt{\varepsilon} \).

\[
p(z) = \frac{\iint \varepsilon(x) dx dy}{(\varepsilon_i - \varepsilon_j) \iint dx dy} \quad ; \quad \varepsilon(x) = \begin{cases} \varepsilon_i, & z \to +\infty \\ \varepsilon_j, & z \to -\infty \end{cases}
\] (2-3)

Stearns has shown that in the case of non-abrupt interfaces, the resultant loss in specular reflectance can be approximated by multiplying the Fresnel coefficient by the function \( \tilde{w}(s_i) \), which is the Fourier transform of \( w(z) = dp/dz \). That is, the modified Fresnel reflection coefficients \( r'_{ij} \) are given by:

\[
r'_{ij} = r_{ij} \tilde{w}(s_i)
\] (2-4)

where \( s_i = 4\pi \cos \theta_i / \lambda \) and \( \lambda \) is the wavelength of light. Note that the loss in specular reflection only depends on the average variation (over \( x \) and \( y \)) of the refractive index across the interface. Consequently, the reflectance can be reduced just as well by a rough or diffuse interface (or by some combination of the two cases) [19].

Stearns presents four interface profiles and the associated Fresnel coefficient modifiers for modeling the loss in specular reflection from a rough or diffuse interface. These are listed in
Table (2-1). The width of each interface profile function is characterized by the parameter $\sigma$ (Fig. 2-3), which can either be a measure of the 1) root mean square (RMS) roughness, in the case of a purely rough interface or 2) an interface width, in the case of a purely diffuse interface or 3) as mentioned before, by some combination of the two properties [19].

It can be seen from Table (2-1), that when the wavelength is much greater than the interfacial roughness or width ($\lambda >> \sigma$) that the values of the associated functions $\tilde{\omega}(s_i)$ approaches unity ($\tilde{\omega}(s_i) \rightarrow 1, s\sigma \rightarrow 0$). In other words, when the wavelength is much greater than the interfacial roughness, we can treat the interface as ideal. In this work we use LEDs of wavelengths $\lambda = 360$ and 460 nm with a typical bandwidth of 20 nm; assuming a maximum wavelength of 480 nm, for 1-2% variation in reflectance to be negligible, we can consider any interface with roughness up to 10 nm as ideal.

<table>
<thead>
<tr>
<th>Table 2-1: Interface profile functions, $p(z)$ and the associated Fresnel reflection coefficient modification factors $\tilde{\omega}(s)$ [18], [19].</th>
</tr>
</thead>
</table>
| **Error Function**                      | $p(z) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}z^2} \sigma^2 dt$ | \begin{align*} \tilde{\omega}(s) &= e^{-s^2\sigma^2/2} \\
\end{align*} |
| **Exponential**                         | $p(z) = \begin{cases} \frac{1}{2} \exp\left(\frac{z}{\sqrt{2}\sigma}\right), & z \leq 0 \\
1 - \frac{1}{2} \exp\left(\frac{z}{\sqrt{2}\sigma}\right), & z > 0 \end{cases}$ | \begin{align*} \tilde{\omega}(s) &= \frac{1}{1 + s^2 \sigma^2 / 2} \\
\end{align*} |
| **Linear**                             | $p(z) = \begin{cases} 0, & z < -\sqrt{3}\sigma \\
\frac{1}{2} + \frac{z}{2\sqrt{3}\sigma}, & |z| \leq \sqrt{3}\sigma \\
1, & z > -\sqrt{3}\sigma \end{cases}$ | \begin{align*} \tilde{\omega}(s) &= \frac{\sin(\sqrt{3}\sigma s)}{\sqrt{3}\sigma s} \\
\end{align*} |
| **Sinusoidal**                         | $p(z) = \begin{cases} \frac{1}{2} + \frac{1}{2} \sin\left(\frac{\pi z}{2a\sigma}\right), & |z| \leq \sqrt{3}\sigma \\
1, & z > a\sigma \end{cases}$ | \begin{align*} \tilde{\omega}(s) &= \frac{\pi}{4} \left( \sin(a\sigma - \frac{\pi}{2}) + \frac{\sin(a\sigma + \frac{\pi}{2})}{a\sigma - \frac{\pi}{2}} + \frac{\sin(a\sigma - \frac{\pi}{2})}{a\sigma + \frac{\pi}{2}} \right) \\
a &= \frac{\pi}{\sqrt{\pi^2 - 8}} \\
\end{align*} |
2.2.3 Reflection and Transmission in a Multilayer Stack

Here we consider the case of a plane wave incident on a multilayer stack (i.e. a series of \( N \) layers and \( N+1 \) interfaces), where the \( i^{th} \) layer has thickness \( d_i \), roughness/diffuseness \( \sigma_i \), and optical constants \( n_i \); as shown in Fig. (2-4).

![Diagram of a multilayer stack containing \( N \) layers, where the optical constants, thickness, propagation angle, and interface roughness/diffuseness of the \( i^{th} \) layer are \( n_i \), \( d_i \), \( \theta_i \) and \( \sigma_i \), respectively. The superstrate (i.e. region above the multilayer stack) has optical constants \( n_s \), and the substrate (i.e. region below the multilayer stack) has optical constants \( n_s \).]

By series summation of the successive reflected or transmitted beams in a multilayer film stack, it can be shown that the net reflection and transmission amplitude coefficients of the \( i^{th} \) layer are given as:

\[
\begin{align*}
    r_i &= \frac{r_{ij} + r_i e^{2i\beta_i}}{1 + r_i^* r_j^* e^{2i\beta_j}} \quad \text{(2-5a)} \\
    t_i &= \frac{t_{ij} t_i e^{2i\beta_i}}{1 + r_i^* r_j^* e^{2i\beta_j}} \quad \text{(2-5b)}
\end{align*}
\]

where \( \beta_i = 2\pi n_i d_i \cos \theta_i / \lambda \) accounts for the optical path length in the film [15], [18]. The reflection (\( r_{ij} \)) coefficients are computed using Eqs. (2-1a) and (2-1c); the transmission coefficients (\( t_{ij} \)) from Eqs. (2-1b) and (2-1c); \( r_i \) and \( t_i \) are the net reflection and transmission coefficients of the \( i^{th} \) interface, respectively. The procedure to obtain the reflectance or transmission of a multilayer stack is to apply Eqs. (2-5a) and (2-5b) recursively, starting with the bottom-most layer i.e. \( i = N \), \( j = s \), with separate computations for the \( s- \) and \( p- \) polarizations.
For interest in modeling film roughness or diffuseness, Eq. (2-4) can be used instead. The reflected and transmitted energy of a multilayer stack is computed in the same manner as before with Eqs. (2-2a) and (2-2b).

2.2.4 Polarization

For an incident light beam on a film composed of a mixture of both s and p-polarizations, it is necessary to determine the average values of the optical functions $R$ and $T$ due to the mixture of polarizations and the detector polarization sensitivity. We define the incident polarization factor $f$ as:

$$ f = \frac{I^s - I^p}{I^s + I^p} $$

(2-6)

where $I^s$ and $I^p$ are the incident intensities for s- and p-polarization, respectively. A $f$ value of 0, +1, or -1 indicates equal polarizations, all s-polarization, or all p-polarization, respectively. We also define the detector polarization sensitivity $q$ as the ratio of s-polarization to p-polarization. A value of $q$ other than 1 can be used to specify a detector that is more or less sensitive to s-polarization than to p-polarization. The average reflectance $R_{avg}$ due to a mixture of polarizations and detector sensitivity is given as:

$$ R_{avg} = \frac{R^s q(1+f) + R^p (1-f)}{f(q-1) + (q+1)} $$

(2-7)

with equivalent expressions for the transmittance $T_{avg}$ and the average intensity $I_{avg}$ [18]. For the (In,Ga)N light emitting diode (LED) and silicon PIN photodetectors used in this study, $f = 0$ and $q = 1$, therefore we have:

$$ R_{avg} = \frac{R^s + R^p}{2} $$

(2-8)

If for example, the LEDs or photodetectors used in this study have been modified with optical polarizing films, $q$ can be designed to vary depending on the orientation of the photodiode, therefore we can select $R^s$ or $R^p$ and the average reflectance would be either $R_{avg} = R^s$ or $R_{avg} = R^p$. This has the added advantage of simplifying the optical function and therefore the computation for the optical properties of samples.

2.2.5 Effective Medium Approximation

The optical properties of a material are determined by a complex dielectric function and a complex magnetic permeability which are both functions of position. The dielectric constant $\varepsilon$ is related to the complex refractive index by:
\[ \varepsilon = \varepsilon_1 - i\varepsilon_2 = (n - i\kappa)^2 \]  

(2-9)

where the real term \( \varepsilon_1 \) is the ratio of the permittivity of the medium to that of free space and the imaginary term \( \varepsilon_2 \) is proportional to the frequency dependent conductivity. Conversion between the refractive index and dielectric constant is done by the following expressions [20]:

\[ \varepsilon_1 = n^2 - \kappa^2 \]  

(2-10a)

\[ \varepsilon_2 = 2n\kappa \]  

(2-10b)

\[ n = \left( \frac{\sqrt{\varepsilon_1^2 + \varepsilon_2^2} + \varepsilon_1}{2} \right)^{\frac{1}{2}} \]  

(2-10c)

\[ \kappa = \left( \frac{\sqrt{\varepsilon_1^2 + \varepsilon_2^2} - \varepsilon_1}{2} \right)^{\frac{1}{2}} \]  

(2-10d)

Determining the optical properties of an inhomogeneous medium composed of a mixture of dielectric inclusions requires one to know the exact geometrical arrangement of the components, a rather difficult proposition experimentally. However, if the wavelength of radiation is much larger than the feature sizes, one can treat the inhomogeneous medium as a homogeneous material with an effective optical function. For this case, one merely needs to know the sizes of the material inclusions and their volume fractions [21].

There are several effective medium approximations (EMA), each of them being more or less accurate in distinct conditions. Regardless, they all assume the macroscopic system is homogeneous and encounter difficulty at predicting the optical properties when long range correlations are introduced. Three EMA theories can be expressed jointly by:

\[ \frac{\varepsilon - \varepsilon_h}{\varepsilon + 2\varepsilon_h} = \sum_j f_j \frac{\varepsilon_j - \varepsilon_h}{\varepsilon_j + 2\varepsilon_h} \]  

(2-11)

where \( \varepsilon \) is the material constant of the effective medium, \( \varepsilon_h \) is the dielectric function of the host, and \( f_j \) is the volume fraction of the \( j^{th} \) material. The underlying assumptions are spherical inclusion geometry and dipole interactions [22].

To obtain the Lorentz-Lorentz (LL) model developed for polarizable inclusions in vacuum; one sets \( \varepsilon_h = 1 \) for a vacuum host material. The LL model can be a reasonable approximation for island formation in thin film growth up to 20% volume fraction [22]. For
inclusions in a host material other than vacuum one gets the Maxwell-Garnett (MG) model and
$\varepsilon_h = \varepsilon_1$ for the host material occupying the largest volume fraction. Like the LL model, the MG model can be acceptable for small volume fractions. For larger volume fractions, the Bruggeman (BG) model treats all material fractions with equal weight and the host material is the effective medium by setting $\varepsilon_h = \varepsilon$ [21]-[23]. A simpler but empirical approach is to consider volume averaging (VA); for a two material system we have:

$$\varepsilon = f_a \varepsilon_a + (1-f_a)\varepsilon_b$$  \hspace{1cm} (2-12)

where $f_a$ is the volume fraction of material $a$ and $\varepsilon_a, \varepsilon_b$ are the dielectric constants of material $a$ and $b$ respectively. To show how these various effective medium approximations compare, the effective index of refraction for a two-material system composed of air and a-SiO$_2$ is calculated for the MG, BG and VA models and shown as Fig. (2-5) (the LL model is not shown since the MG model degenerates to the LL model for air). The exact choice of which model to use will depend on the system in question and any underlying assumptions; what approximation works for a particular case may not work for another [13]. For example, Aspnes and Fujiwara have indicated by spectroscopic ellipsometry that the BG model gives good agreement to modeling surface roughness as a discrete layer with effective optical properties [23], [24]. While nanoporous cylinders and wires have been numerically validated with Maxwell’s equations to agree with VA theory by workers Garahan and Braun et al. [25], [26].

![Figure 2-5: Values of the effective index of refraction for a two material system composed of air and a-SiO$_2$ for varying volume fractions as calculated with the Maxwell-Garnet (MG), Bruggeman (BG), and volume average (VA) effective medium approximations.](image)

2.3 General Case Studies

With the framework provided by the Fresnel equations and effective medium approximations; one has a selection of tools to approach the modeling and computation of
optical functions for a wide range of samples and conditions. We consider three case studies for the reflectance of a thin film above the optical window with a fixed wavelength and incident angle.

### 2.3.1 Refractive Index Monitoring

If the refractive index of a film above the optical window changes while all other optical constants remain constant, then by monitoring the reflectance changes one can deduce the change in the refractive index and ultimately changes in the material properties. This is an important feature for monitoring low-k curing dielectrics where the value of the dielectric constant is essential to the performance of integrated circuits or photo resist curing, where solvent must be driven off before proceeding to the next lithography step. For reference, the relation between the dielectric constant and the index of refraction was previously given as Eqs. (2-9) and (2-10). As an example, Fig. (2-6) shows the reflectance as a function of the refractive index for a fixed angle and wavelength. For simplicity, the film is assumed infinitely thick.

![Reflectance as a function of refractive index](image)

**Figure 2-6:** Average reflectance as a function of refractive index at 460 nm for an incident angle of 45 degrees. Shown are plots for extinction coefficients $k = 0, 0.5, \text{ and } 1$. A 650 nm thick $\text{Si}_3\text{N}_4$ window is used for the calculation.

### 2.3.2 Dielectric Film Monitoring

Alternatively, if the refractive index does not change but the film thickness varies as is the case for most film growth or etch processes, the reflectance changes periodically with the thickness. This is due to the constructive and destructive interference of light as the film thickness approaches integer multiples of the optical path length. Fig. (2-7) shows a periodic change in reflectance as a function of $\text{a-SiO}_2$ thickness with a wavelength of 460 nm and various incident angles.
2.3.3 Metal Film Monitoring

Similar to dielectric films, we can also monitor changes in the thickness of a metal film. This is useful for end-point etch monitoring of copper – often used as a metallization layer in IC fabrication. Fig. (2-8) shows the reflectance as a function of copper thickness for various incident angles with probe wavelength of 460 nm. When the copper thickness is above 50 nm, the reflectance is constant. Below 50 nm, the reflectance of copper tends to decrease. Unlike the periodic reflectance observed with dielectric films, metals tend to show a “half-cycle,” this is due to the high absorption losses.
2.4 General Methodology for the Metrology Wafer

In order to obtain accurate optical properties of sample films under study it is essential to develop a measurement methodology for our optical system to eliminate sources of error such as component alignment, external photon sources, and variations in the photon engine or detector circuitry. To meet these requirements, a methodology has been developed for a generic optical sensor cell, as illustrated in Fig. (2-9). The methodology presented here is based on previous work by Luo and contains several improvements [1]. The essential idea presented here involves using a calibration as a reference point to correct for and modulation of the photon source intensity to eliminate unwanted influence on the sample and drift in the detector signal.

\[
S = AI_T = A(I_W + I_C + I_B)
\]  

(2-13)

where \( A \) contains all the factors relating to the opto-electrical conversion factor of the detector and associated circuits; \( I_W, I_C \) and \( I_B \) are the reflected intensities from the optical window, internal sensor cell walls and any background sources, respectively. Eq. (2-13) is a linear relation; therefore it is important to verify that any sensor used for the sensor cell should also have a linear response to the light intensity e.g. a photodiode should be operated in photoconductive region rather than the photovoltaic region.
Generally speaking, for a given incident beam angle $\theta_{inc}$ by the LED, the reflected intensity $I_i$ is related to the incident intensity $I_o$ by:

$$
I_i(\theta_{inc}, \lambda, \{n\}_i, \{d\}_i) = I_o g \left( \frac{\pi}{2} - \theta_{inc}, \lambda \right) R_i(\theta_{inc}, \lambda, \{n\}_i, \{d\}_i)
$$

(2-14)

where $g$ is the emission spectrum and angle distribution of the LED, $R_i$ is the reflectance of the window/sample film or cell walls which includes all the refractive index terms $\{n\}_i$ and thickness terms $\{d\}_i$ associated with the optical window/sample film or cell walls. For example, we write the window/sample reflectance as:

$$
R_w(\theta_{inc}, \lambda, \{n\}_w, \{d\}_w) = R_w(\theta_{inc}, \lambda, n_{ambient}, n_{window}, n_{sample}, d_{window}, d_{sample})
$$

(2-15)

Similarly, for the cell reflectance $R_C$, we write:

$$
R_C(\theta_{inc}, \lambda, \{n\}_c, \{d\}_c) = R_C(\theta_{inc}, \lambda, n_{ambient}, n_{cell}, d_{cell})
$$

(2-16)

For brevity in the rest of the presentation, we will use the shorthand notation $\{n\}$ and $\{d\}$ in the left-hand side of the above equations to represent the refractive index and thickness terms. The reflected intensity from the optical window $I_w$ to the detector can be expressed as the sum over all the emitted LED wavelengths and the incident/reflected angles $\theta$:

$$
I_w = \int_{\lambda} \int_{\Omega_w} I_R(\theta, \lambda, \{n\}_w, \{d\}_w) d\Omega d\lambda = \int_{\lambda} \int_{\Omega_w} I_o g \left( \frac{\pi}{2} - \theta, \lambda \right) \cdot R_w(\theta, \lambda, \{n\}_w, \{d\}_w) d\Omega d\lambda
$$

(2-17)

where $\lambda$ denotes the LED spectrum and $\Omega_w$ denotes the angle spread of the LED as seen by the photodiode from the window. Similarly the reflected intensity from the non-window area $I_C$, i.e. reflection from the internal walls of the sensor cell, can be expressed as:

$$
I_C = \int_{\lambda} \int_{\Omega_c} I_R(\theta, \lambda, \{n\}_c, \{d\}_c) d\Omega d\lambda = \int_{\lambda} \int_{\Omega_c} I_o g \left( \frac{\pi}{2} - \theta, \lambda \right) \cdot R_C(\theta, \lambda, \{n\}_c, \{d\}_c) d\Omega d\lambda
$$

(2-18)

where $\Omega_c$ denotes the angle spread of the LED as seen by the photodiode from the internal sensor cell walls. The background intensity reaching the detector from sources other than the LED, e.g. ambient, is simply noted as $I_R$. According to the second mean value theorem for integrals, if two functions $f(x)$ and $g(x)$ are continuous on the interval $[a, b]$ and that $g(x) \geq 0$ for any $x \in [a, b]$, then there exists a value $c \in [a, b]$ such that:

$$
\int_a^b f(x) g(x) dx = f(c) \int_a^b g(x) dx
$$

(2-19)
where $f(c)$ can be considered the $g(x)$-weighted average of $f(x)$ on the interval $[a,b]$. Since optical functions in general are continuous and differentiable, except in regions of high absorption, we are assured of satisfying the conditions for the mean value theorem. We can rewrite Eqs. (2-17) and (2-18) in terms of the average reflectance:

$$I_W = I_o R_W \left( \theta_{avg}, \lambda_{avg}, \{n\}_W, \{d\}_W \right) \int \int g \left( \frac{\pi}{2} - \theta, \lambda \right) d\Omega d\lambda$$  \hspace{1cm} (2-20a)

$$I_C = I_o R_C \left( \theta_{avg}, \lambda_{avg}, \{n\}_C, \{d\}_C \right) \int \int g \left( \frac{\pi}{2} - \theta, \lambda \right) d\Omega d\lambda$$  \hspace{1cm} (2-20b)

Caution must be exercised at this point, the mean value theorem only tells us there will be at least one value that will satisfy the average reflectance; there can be more than one due to the behavior of optical reflectance functions. To find the reflectance value $R_W$ of the window and sample one divides out the opto-electrical and geometrical factors by using the calibration procedure outlined next.

### 2.4.1 Calibration Procedure

In order to obtain a reflectance value from experiments, it is necessary to calibrate the sensor cell to correct for the opto-electrical and geometrical factors and also to determine an effective angle. If we intentionally vary the intensity $I_o$ of the LED to the extent that the intensity change is large enough for the detector to register, but small enough to keep the LED spectrum and angle distribution unchanged, assuming these do not change with time for the same ambient temperature, we can approximate the integral terms in Eq. (2-20) to be constant:

$$I_W = I_o R_W \left( \theta_{avg}, \lambda_{avg}, \{n\}_W, \{d\}_W \right) G_W \left( \theta_{avg}, \lambda_{avg} \right)$$  \hspace{1cm} (2-21a)

$$I_C = I_o R_C \left( \theta_{avg}, \lambda_{avg}, \{n\}_C, \{d\}_C \right) G_C \left( \theta_{avg}, \lambda_{avg} \right)$$  \hspace{1cm} (2-21b)

where $G_W$ and $G_C$ are the geometrical factors for the window and internal cell walls, respectively. Substituting Eq. (2-21) into Eq. (2-13), the total detector signal as a function of the intensity contribution from the window reflection, sensor cell wall reflection, and any background sources present can be written as:

$$S = A(I_W + I_C + I_B) = A I_o (R_W G_W + R_C G_C) + A I_B$$  \hspace{1cm} (2-22)

where we have omitted the function variables for conciseness. There are two particular cases of interest:
1) For the case with no sample on the window, we get:

\[ \frac{\Delta S_o}{\Delta I_o} = AR_c G_C \]  

(2-23)

This assumes the window itself has negligible reflectance, and the window should be designed with this in mind.

2) For the case of a sample with a sample film on the optical window, we get:

\[ \frac{\Delta S}{\Delta I_o} = A(R_w G_w + R_c G_C) \]  

(2-24)

This requires one to know the geometrical constants in order to extract a film reflectance \( R_w \). However, if we vary the LED intensity quickly enough such that the time to complete an intensity sweep and record the detector signal is much shorter than the interval that the ambient light could change substantially or by adjusting the LED intensity \( I_o \) adjustment such that it is much greater than the background \( I_B \) (\( I_o \gg I_B \)), the difference in the two signals will eliminate the signal resulting from the reflection off the internal sensor cell walls and any background source influences:

\[ \frac{\Delta S}{\Delta I_o} - \frac{\Delta S_o}{\Delta I_o} = AR_w G_w \]  

(2-25)

The sample and window reflectance \( R_w \) is then obtained by dividing out the opto-electrical and geometrical factors:

\[ \frac{1}{AG_w} \left( \frac{\Delta S}{\Delta I_o} - \frac{\Delta S_o}{\Delta I_o} \right) = R_w \]  

(2-26)

Due to component placement accuracy and electrical variations in photon engine or detector during the fabrication of a sensor cell, determining the opto-electrical and geometrical factors is problematic since one is required to know the effective angle for \( R_w \) or \( G_w \) before computing Eq. (2-26). However, if we take the ratio of Eq. (2-26) to itself the geometrical factor \( G_w \) is eliminated:
\[
\frac{\frac{\Delta S}{\Delta I_\omega} - \frac{\Delta S_{w}}{\Delta I_{\omega}^{\text{REF}}}}{\frac{\Delta S}{\Delta I_\omega} - \frac{\Delta S_{w}}{\Delta I_{\omega}^{\text{REF}}}} = \frac{R_w}{R_{\text{REF}}}
\]

(2-27)

where the subscript \( \text{REF} \) denotes the reflectance of the reference sample, e.g. aluminum mirror and the measured signal with the reference sample. In other words, the reflectance of the sample can be stated as the ratio of the signal difference for the unknown sample and the reference sample with a multiplying factor to correct the value. The expression in Eq. (2-27) is nearly equivalent to the final expression provided by Luo’s methodology; however it differs as it provides an explicit relation to the reflectance of the window and sample in terms of the measured signals.

Due to the behavior of the optical reflectance function, it is highly likely calibration by one reference can result in several solutions for the effective reflectance angle. The case is shown in Fig. (2-10) for the reflectance of aluminum/copper and copper/silicon. It would be prudent to calibrate with more than one reference sample to obtain the best estimate for the effective angle. Calibration with a single reference may yield more than one possibility, but cross referencing with another calibration should yield a value that agrees with both.

**Figure 2-10:** Ratios of the average reflectance for copper/aluminum and silicon/aluminum with 460 nm probe wavelength on 650 nm Si₃N₄ window. A single reflectance ratio can result in more than one possible angle, as denoted by the horizontal dashed line which crosses the optical functions at several points for both samples. Cross referencing both yields an angle that agrees with both (vertical dashed line).

Thus, the calibration procedure is as follows. One uses three reference samples of known reflectance in conjunction with Eq. (2-27) to solve for an effective angle (numerical methods can be used quickly). Once the effective angle is known, Eq. (2-27) can be used again
to solve for the reflectance of an unknown sample. The choice of which reference sample to use in the final computation is arbitrary, however a metal film of sufficient thickness would maximize the sensitivity and avoid any thin film interference effects.

Using the methodology presented here, important parameters such as the refractive index and thickness can be solved for by fitting the appropriate reflectance model to the acquired $R_w$ data, where the framework for constructing a reflectance model has been covered previously.

### 2.4.2 Comparisons to Prior Methodology

In presenting the above methodology for an optical sensor cell, a number of improvements have been made on the prior work and they are enumerated below:

1) Prior methodology implied photovoltaic operation i.e. forward biasing of photo diode [1]. Analysis of the ideal diode equation shows that forward biasing leads to an exponential and therefore non-linear response to illumination intensity. The ideal diode equation is expressed as:

$$I = I_s \left( \exp\left( \frac{qV}{kT} \right) - 1 \right) - I_p$$

where $I_s$ is the saturation current, $q$ is the electron charge, $V$ is the voltage across the diode, $k$ is the Boltzmann constant, $T$ is the temperature, and $I_p$ is the photocurrent induced from illumination [27]. Here, we specify photoconductive operation is necessary for linear operation.

2) Previously, a primary and a reference photo detector were used to eliminate geometrical and electrical constants by taking the ratio of the two signals [1]. This can introduce measurement error as the primary and reference photodiode occupy different spatial locations in the sensor cell and do not have the same geometrical factors. In this work, a reference photo detector is no longer required. This also confers an advantage in reducing the number of components for assembling a sensor cell.

3) The prior methodology invoked an “$F$” function in addition to taking a ratiometric measurement for computing the optical reflectance functions of the sample [1]. Using the “$F$” function approach required computing four reflectance functions, while the approach proposed here solves for the optical function using only two reflectance functions. The method presented here simplifies the computation.

4) It was also proposed to use tunable refractive index liquids e.g. mineral oils for calibration of the sensor cell effective angle [1]. This introduces concern over the control
of the liquid thickness and reproducibility. With the improved methodology, one can avoid this uncertainty and use metallic or mirror-like reflectance calibration standards.

2.4.3 Summary

To summarize our discussion so far; prior work has established the concept of a zero-footprint optical metrology wafer useful for in situ reflectance measurements in hostile environments. A general theoretical frame work for the optical modeling of film stacks and composite material systems was presented. In this context, a methodology for extracting the reflectance information from measurements by the optical sensor cell was developed and improved upon.

2.5 Design and Fabrication

To implement the methodology discussed previously and to keep our model assumptions valid, the optical window material and dimensions should be chosen such that it optimizes the signal sensing and remains intact without deflection, distortion, or fracture during processing and handling [1], [2].

2.5.1 Optical Window Size and Placement

As much as possible, the reflection signal should originate from the window and sample film stack rather than from the sidewall reflection. In order to maximize the signal from the window, one needs to arrange the LED, detector, and window such that the window geometrical factor $G_W$ is greater than the cell geometrical factor $G_C$ (i.e. $G_W > G_C$). In other words, the detection window should be larger than the active area of the detector. For our prototype, we use silicon PIN photodiodes with an active area of 0.84 mm$^2$ [28], [29], therefore a square detection window of 1 mm$^2$ is used.

2.5.2 Optical Window Material and Thickness

Using the recursive relation Eq. (2-5) for a film stack consisting of a free standing film in ambient, it can be shown that the reflectance at the ambient side is:

$$R = \frac{r_{12}^2 + r_{23}^2 + 2r_{12}r_{23}\cos 2\beta}{1 + r_{12}^2r_{23}^2 + 2r_{12}r_{23}\cos 2\beta}$$

(2-29)
where $\beta = 2\pi n_2 d_2 \cos \theta_2 / \lambda$ and the indices 1, 2, and 3 denote the ambient, free standing film and ambient, respectively. Ideally, the window should have no effect on the optical beam, based on an “it isn’t there” concept, thus we wish to determine the optical thickness of the window where the reflection is a minimum. If we define $H = n_2 d_2$ and solve the differential equation $dR/dH = 0$ we get:

$$H = \frac{m\lambda}{4 \cos \theta_2} \quad (m = 0, 1, 2, \ldots) \quad (2-30)$$

This result indicates that whenever the detection window thickness satisfies Eq. (2-30), the reflectance at the ambient side reaches a maximum or a minimum. There are two cases to distinguish here:

1) When $m$ is odd, i.e. when $H$ has the values:

$$H = \frac{\lambda}{4 \cos \theta_2}, \quad H = \frac{3\lambda}{4 \cos \theta_2}, \quad H = \frac{5\lambda}{4 \cos \theta_2}, \ldots \quad (2-31)$$

Then the term $\cos 2\beta = -1$ and Eq. (2-29) reduces to:

$$R = \left( \frac{r_{12} - r_{23}}{1 - r_{12} r_{23}} \right)^2 \quad (2-32)$$

In the case of normal incidence, the above expression reduces to:

$$R = \left( \frac{n_1 n_3 - n_2^2}{n_1 n_3 + n_2^2} \right)^2 \quad (m = 0, 1, 2, \ldots) \quad (2-33)$$

2) when $m$ is even, i.e. when $H$ has the values:

$$H = \frac{\lambda}{2 \cos \theta_2}, \quad H = \frac{\lambda}{\cos \theta_2}, \quad H = \frac{3\lambda}{2 \cos \theta_2}, \ldots \quad (2-34)$$

Then the term $\cos 2\beta = 1$ and Eq. (2-29) reduces to:

$$R = \left( \frac{r_{12} + r_{23}}{1 + r_{12} r_{23}} \right)^2 \quad (2-35)$$

For the case of normal incidence, the above expression reduces to:
and is seen to be independent of the window film refractive index $n_2$. For oblique incidence, all the $n_j$ terms are replaced by $n_j \cos \theta_j$; therefore a window film which has optical thickness $n_2 d_2 = m \lambda / 2 \cos \theta_2$ ($m = 1, 2, 3, \ldots$) has no influence on the reflected or transmitted radiation [14].

Therefore, to design the optical window, one chooses from a technological and material standpoint the thickness and dimensions that can withstand the intended hostile environment. From there, adjusts that thickness value to correspond to an integer that will satisfy the equation $n_2 d_2 = m \lambda / 2 \cos \theta_2$ ($m = 1, 2, 3, \ldots$) to maximize the sensitivity to optical changes.

### 2.5.3 Optical Window Deflection and Bending

Residual stress studies show LPCVD Si$_3$N$_4$ is the best candidate for our application as opposed to oxide (Fig. 2-4). LPCVD nitride remains flat due to the residual tensile stress. Prior work by Luo has shown that a free-standing nitride window up to 1 mm square and 650 nm thick will exhibit no fracture when subjected to a differential pressure of ±2 atmosphere [1]. In addition, nitride films known to be are resistant to many etchants used in micro fabrication [30].

![Figure 2-11: Optical micrographs by Luo of windows after substrate removal. (Top) 650 nm thick nitride windows with dimensions 80, 280, 420, and 700 um square. (Bottom) 60 nm nitride/700 nm oxide windows with dimensions 60, 100, 170, and 360 um square. The 60 nm nitride/700 nm oxide stack shows severe distortion due to the large residual compressive stress in the oxide film, whereas the 650 nm LPCVD nitride shows excellent flatness due to the residual tensile stress. All nitride windows were tested by Luo to ±2 atmosphere before failure [1].](image-url)
If the optical metrology is intended to be used in vacuum, it is useful to know the minimum thickness required for acceptable flatness. Senturia [31] presents an analytical solution for describing the pressure-deflection of a uniformly loaded, clamped square membrane with a built-in residual stress:

\[
p = C_r \left( \frac{\sigma t d}{a^2} \right) + C_b \left( \frac{E t^3 d}{(1-\nu^2)a^4} \right) + C_s f_s(\nu) \left( \frac{E t d^3}{(1-\nu)a^4} \right)
\]  \tag{2-37}

where \( p \) denotes applied pressure, \( d \) is the deflection of the membrane at the center, \( a \) is half the membrane edge length, \( t \) is the membrane thickness, \( \sigma \) is the residual stress, \( \nu \) is Poisson’s ratio, and \( E \) is the Young’s modulus, the constants \( C_r, C_b, \) and \( C_s \) are given as:

\[
C_r = \frac{3\pi^2}{2} ; \quad C_b = \frac{2\pi^4}{3} ; \quad C_s = \frac{\pi^4}{4}
\]  \tag{2-38}

and the function \( f_s(\nu) \) is given as:

\[
f_s(\nu) = \frac{(7-2\nu)(5+4\nu)}{32(1+\nu)}
\]  \tag{2-39}

The three terms in Eq. (2-37) account for the linear stiffness, proportional to the residual stress-thickness term \( \sigma t \), a second linear stiffness term for bending, proportional to the cubed thickness \( t^3 \) and to Young’s modulus \( E \), and a final cubic stiffness term, proportional to the thickness \( t \) and Young’s modulus \( E \) [31]. For a sufficiently thin membrane, the bending term can be neglected, and the pressure-deflection relation of Eq. (2-37) simplifies to:

\[
p = C_r \left( \frac{\sigma t d}{a^2} \right) + C_s f_s(\nu) \left( \frac{E t d^3}{(1-\nu)a^4} \right)
\]  \tag{2-40}

Using the mechanical properties of hot-pressed nitride (Si₃N₄), \( E = 310 \text{ GPa}, \nu = 0.27 \), with a residual stress of 0.2 GPa [31], the pressure-deflection of the window at the center is estimated using Eq. (2-40) as:

\[
p = 2.96 \left( \frac{td}{a^2} \right) + 8704.88 \left( \frac{td^3}{a^4} \right) \quad \text{(GPa)}
\]  \tag{2-41}

For given window sizes of 1 mm square and 650 nm thick, a center membrane deflection of 7.67 μm is estimated under 1 atmospheric differential pressure \( p = 1 \text{ atm} = 10^4 \text{ GPa} \). If one desires less deflection, one sees from Eq. (2-41) that the most effective way is to reduce the window size. For a window of 400 um square, one gets a deflection of 1.71 um under 1 atmospheric pressure.
Since the calibration methodology relies on canceling out the geometrical factors \( G_W \) and \( G_C \) (Eq. 2-21) which in turn depend on the integral bounds of the window and the sensor cell (Eq. 2-20), there is concern that the pressure-deflection or tilt of the window could introduce a source of error. We consider a simplified geometrical model (Fig. 2-12) to estimate the effect of the window tilt angle \( \theta_{\text{tilt}} \) due to assembly error and the bending angle \( \theta_{\text{bend}} \) due to pressure differential.

\[ \tan \theta_{\text{bend}} = \frac{d}{AB/2} \quad (2-42) \]

where \( AB \) is the window length and \( d \) is the membrane deflection. The window tilt angle \( \theta_{\text{tilt}} \) arising from assembly or placement error is:

\[ \cos \theta_{\text{tilt}} = \frac{AD}{AB} \quad (2-43) \]

where \( AD \) is the effective window length after tilt. For the window size of 1000 um used in this study \((AB = 1000 \text{ um})\), at 1 atm pressure the deflection \( d \) is 7.67 um, thus the bending angle \( \theta_{\text{bend}} \) is computed to be < 1 degree. For a window tilt angle \( \theta_{\text{tilt}} \) causing a change in the geometrical bounds of the window of 1% \((AD = 1000 \text{ um} \pm 10 \text{ um})\), one computes a tilt angle \( \theta_{\text{tilt}} \) of 8.1 degrees. The geometrical factors \( G_W \) and \( G_C \) from Eq. (2-21) are essentially the solid angles computed from Eq. (4-20). By definition the solid angle is:
\[ \Omega = \frac{A}{r^2} \cos \theta \]  

(2-44)

where \( A \) is the area of the window, \( r \) is the distance to the window from the LED and \( \theta \) is the angle between the distance \( r \) and the window surface normal. Thus, assuming the distance to the window and window area do not shift appreciably, we can estimate the error from the tilt or pressure-deflection of the window as:

\[
\text{tilt error} = \frac{\cos(\theta \pm \theta_{\text{tilt}}) - \cos \theta}{\cos \theta} \times 100\% 
\]  

(2-45)

\[
\text{deflection error} = \frac{\cos(\theta \pm \theta_{\text{bend}}) - \cos \theta}{\cos \theta} \times 100\% 
\]  

(2-46)

One sees that the error will depend on the angle of window normal \( \theta \), but if we assume a modest angle of 45 degrees, we can numerically estimate our tilt and deflection errors. Using the tilt and deflection angles of 8.1 degrees and 1 degree, respectively, we obtain a tilt error of 13\% and a deflection error of 1.7\%. In other words, this is the estimated error on the optical signal. Since the window tilt error is much greater than the window deflection angle, that any error arising from the deflection of the membrane can be considered negligible.

### 2.5.4 Prototype Fabrication

With the methodology and design developed previously, a 100 mm diameter prototype zero-footprint optical metrology wafer with an array of 3x3 metrology cells has been demonstrated. Fig. (2-13) shows the optical images of the prototype metrology wafer.

**Figure 2-13:** Optical images of a completed 100 mm diameter prototype optical metrology wafer showing a 3x3 array of sensor cells for mapping. Bottom wafer (left) with detail showing the integrated
sensor cell, top wafer (middle) with detail of the free standing nitride window and the final bonded wafer pair (right) [1].

High-brightness (In,Ga)N blue LEDs (peak wavelength 460 nm) donated by SemiLEDs [32], [33] and silicon PIN photodiodes purchased from Advanced Photonix [28], [29] were integrated inside of a lithographically defined wafer pair. A detailed cross section of the process flow for the zero-footprint optical metrology wafer is shown in Fig. (2-14). The detailed process flow begins with: a) two bare silicon wafers prepared with a wet oxidation followed by a nitride deposition; b) defining the initial cavities on both the top and bottom wafers; c) further definition of the wafer cavities on the bottom wafer and a though wafer etch to release the free standing nitride windows on the top wafer; d) contact pad definition, integration of the excitation/detection units, wire bonding, then finally align and seal the wafer pair.

**Figure 2-14:** Process flow for the zero-footprint optical metrology wafer. a) Starting with 2x Si wafers < 500 um thick, wet oxidation followed by nitride deposition; b) define and etch cavities on both top and bottom wafer via KOH bulk machining; c) repeat wet oxidation/nitride deposition with an additional cavity definition for top wafer window and bottom wafer self-alignment features also by KOH bulk machining; d) last, define the metal interconnect, integrate the photon engine and detection units, perform wire bonding, align and seal the wafer pair.
2.6 Application to Optical Metrology

To demonstrate utility of the zero-footprint metrology wafer as a robust and versatile platform for process control and development. Six experiments were conducted in different application areas: 1) refractive index monitoring, 2) plasma etching, 3) CMP, 4) photoresist curing, 5) copper end-point etch detection, and 6) nanopore wetting phenomena.

2.6.1 Refractive Index Monitoring

Experiments were performed by Luo to verify the linearity between a primary photodiode and a reference photodiode signal with air, water, and photoresist on top of the optical window. Plots of the primary photodiode signal versus the reference photodiode signal exhibit excellent linearity. Least-square fitting of the slopes indicates the reflectance methodology can differentiate the refractive index of the overlying film layer by one part in a thousand. Figure (2-15) shows the experimental sample and a plot of the photodiode signal. The results also indicate that the assumptions made in the development of the methodology are valid [1].

![Figure 2-15: Plot of the primary photodiode signal versus the reference photodiode signal with air, water, and photo resist on top of the nitride window. The slopes of the plots are related to the refractive indices of the nitride window and sample film over layer. The refractive index sensitivity is better than 1/1000 [1].](image)

2.6.2 Oxide Plasma Etching

Compatibility of the metrology wafer with the plasma etching environment was demonstrated by Luo. This was accomplished by depositing 180 nm thick silicon oxide film onto
the wafer surface using electron cyclotron resonance (ECR) plasma enhanced chemical vapor deposition (PECVD), (PQECR, Plasma Quest). The thickness of the oxide film was measured with a Dektak 3030 profilometer (Dektak). After measuring the reflectance, the wafer was put into a parallel plate plasma etcher (Plasma-Thermal Inc.) for several etch cycles. Each etch lasted 30 seconds at 100 W RF power with 100 sccm SF₆ and after each cycle the wafer was fetched out for reflectance and thickness measurements. The experimental setup and results is shown as Fig. (2-16). The reflectance data and physical thickness measurements show excellent agreement with the interferometry model [1].

![Figure 2-16: a) Plasma etching and measurement setup; b) measured reflectance (circles) from several 30-second plasma etching cycles of SiO₂ with SF₂. The dashed line is fitted reflectance to the SiO₂ thickness measurements [1].](image)

### 2.6.3 Chemical Mechanical Polishing

Application to chemical mechanical polishing (CMP) was first demonstrated by Loryuenyong. Diamond suspensions with particle sizes 250 nm, 3 um, 6 um, and 45 um from South Bay Technologies Inc. (DS002-16, DS030-16, DS060-16, and DS450-16) [34] were prepared on a CMP platen with various heights. It was found that the sensor wafer can distinguish between the various slurries on the polish pad due to the light scattering from different particle sizes [35]. Fig. (2-17) shows the demonstration setup and a plot of the results.
Figure 2-17: a) Chemical mechanical polishing demonstration setup and b) measured reflectance of H$_2$O and several diamond suspensions with particle sizes 250 nm, 3 um, 6 um, and 45 um from South Bay Technologies as a function of the slurry height [34], [35].

2.6.4 Photoresist Curing and Stripping

Photoresist cure monitoring was demonstrated; a layer of S1818 resist was cured on top of the optical window via UV light. As the cure process proceeds, both the refractive index and thickness of the film changes which translates to a change in the reflectance. When the cure process is complete, the refractive index and thickness remains unchanged, as a result the reflectance converges a steady-state value. The reflectance data agrees with simulated model that both the refractive index and resist thickness changes exponentially with a characteristic time of 40 minutes (Fig. 2-18a) [36].

We expand upon the original application area of photoresist process monitoring with a demonstration of photoresist stripping end-point detection. Cover slip glass slides were prepared with 1-2 um hard-baked S1818 resist and PRS-3000 solution was used to strip the resist. Fig. (2-17b) shows a decrease in reflectance as the photoresist dissolves due to the PRS-3000 solution. It was also found that the end-point detection of photoresist stripping is observable even with ambient lighting. We observed a factor of 16 improvement in the signal-to-noise with the HB LED over prior work with a low brightness LED (Fig. 2-18b) [37]. This is demonstrated advantage of the HB LED.
2.6.5 Copper End-Point Etch Detection

For end-point etch detection of copper, we perform copper etching using Cyantek CR-7 solution on 150-200 nm of copper samples prepared by sputtering onto cover glass slips. Samples are placed on the window and optical signals are captured as a function of time. Fig. (2-19) shows distinct etching regimes of the copper etching mechanisms as thickness approaches zero (<50 nm). A multistage etch phenomena was observed, possibly due to interfacial phenomena.
2.6.6 Nanopore Wetting Phenomena

Experiments were conducted to determine if the sensor can distinguish wetting of nanopores i.e. filled with a liquid, partially filled, or not at all. The purpose is to demonstrate potential application in monitoring nanometer feature cleaning efficacy e.g. contact hole clearing before metallization or liner deposition. To facilitate this investigation, porous (40-50% surface porosity) aluminum oxide (Al$_2$O$_3$) 45 um-thick with 200 nm average pore diameter was placed on top of the optical detection window and a droplet of deionized water (DI H$_2$O), methanol, or isopropanol applied. Optical signals are then captured as a function of time. Fig. (2-20) shows the SEM image of the porous Al$_2$O$_3$ sample used and the reflectance signal as a function of time [38].

For the DI H$_2$O droplet, the reflectance signal does not vary with time. First hand observation leads to the conclusion that the DI H$_2$O droplet does not wet the porous Al$_2$O$_3$. For methanol and isopropanol, the reflectance decreases to a minimum and then increases. Correlation with observation indicates the porous sample becomes wetted as the liquid penetrates the pores and at some time after, the alcohol evaporates giving us a return to the original reflectance signal [38].
Figure 2-20: a) SEM image of the porous Al₂O₃ sample used in this investigation [39], [40]; b) Nanopore absorption/desorption data with methanol, isopropanol, and DI H₂O. The sensor can detect changes in the 0.5-1% range [38].

2.7 Additional Developments

While this work focuses exclusively on the development and methodology of the optical sensor cell rather than the specifics of power and communication. There has been some effort to explore integration of power and data transmission. We will mention them here briefly before continuing onto the next chapter.

To demonstrate the feasibility of the metrology wafer as a standalone wireless unit, Cho encapsulated a 2 cm by 2 cm, 300 um thick LiPON polymer battery [5], [6], an IR-sensitive optical switch, and a 460 nm blue LED inside a wafer pair. A top view schematic is shown in Fig. (2-21) along with an infrared micrograph image of the encapsulated battery and switch. The power unit can be switched on and off with remote IR illumination. If required, the polymer battery can be charged by inductive coupling or by the use of through-silicon via (TSV) contact pads [3], [4], [41].
Figure 2-21: Layout (left) and infrared transmission micrographs (right) of a 100 mm diameter metrology wafer prototype with an encapsulated thin-film polymer battery, optical switch and LED. The optical switch can be turned on/off with a remote infrared beam [3], [4], [41].

More recently, the standalone wireless unit concept has been demonstrated further with the addition of a data acquisition (DAQ) board donated by KLA-Tencor. The DAQ board measures approximately 3 cm diameter with a thickness of 1 mm and was mounted to the surface of the prototype metrology wafer. With the collaboration of Dr. Mason Freed from KLA-Tencor, the DAQ was enabled to store and readout to PC a copper etching experiment. Fig. (2-22) shows the DAQ and the acquired reflectance data as a function of time for the copper etching [42], [43].

Figure 2-22: a) Optical photograph showing the KLA-Tencor data acquisition (DAQ) module mounted to the surface of a prototype metrology wafer and b) plot of a 200 nm copper film etching by CR-7 (perchloric based) as acquired by the KLA-Tencor DAQ [42], [43].
2.8 Summary

We have introduced the concept of the zero-footprint optical metrology wafer for in situ, real-time process monitoring and study. The metrology wafer is dimensioned as a regular wafer so that it can accommodate all processing equipment typically found in the fab. The optical metrology wafer relies on reflectance information from the optical window from which important parameters such as film thickness, refractive index, and density can be probed. To ensure accurate and precise measurement across the wafer, a framework for modeling the reflectance functions and measurement methodology was presented. A prototype wafer with 3x3 sensor cells was successfully fabricated and the sensor cells tested in various hostile environments. Reflectance measurements with different refractive index films showed the linear operation and validity of the methodology. Application of the optical metrology wafer was demonstrated with a plasma etching of silicon oxide, CMP slurry particle size monitoring, photoresist cure and dissolution, copper end-point etch detection and nanopore wetting phenomena.

It is expected that with further development that the concepts and potential applications presented here would not be limited to just the semiconductor industry. With the appropriate modeling and calibration the metrology sensor cell can be used in places where the reflectance is indicative of material changes or solution concentrations. With appropriate modeling and calibration, the metrology sensor cell can expand its application areas far beyond what we presented. The remainder of this dissertation will now focus on efforts to extend the capability of the optical sensor platform to multiple wavelength sensing.

2.9 References


[34] South Bay Technology, Inc., San Clemente, California.
[40] SEM courtesy of Evan Stateler.
[42] DAQ courtesy of KLA-Tencor Corporation, Milpitas, CA.
3 Image Sensor as a Three-Channel Spectrometer

3.1 Introduction

Previously, we had discussed an interferometry-based optical sensor cell in the context of the zero-footprint optical metrology wafer. With this chapter, we discuss our efforts to expand the optical sensor platform to three-channel colorimetric sensing by using a filter-based solid-state image sensor. These solid-state image sensors are often used as a colorimetric sensor element for scientific, medical, and industrial process control applications. Example applications are: analysis of water samples [1], dermatology [2], food quality monitoring [3], [4], printed circuit board quality control, and paper pulp monitoring [5]. Color measurements can help correlate with other physical and chemical controls since color is related to the spectral reflectance/emission caused by the physical or chemical states of an object. Typically the color spectrum of a sample is measured in terms of the red (R), green (G) and blue (B) components of the reflected or emitted light and the image sensor output is given as a digital triplet of RGB values ranging from 0 to 255 for an 8-bit system. This transformation of spectral information to the RGB triplet is a many-to-one mapping and is generally not invertible or unique. However, if one characterizes the spectral sensitivities of the image sensor channels and subsequently partitions the spectrum into three defined color bands, it becomes possible to invert the RGB triplet values to acquire a unique solution corresponding to the weighted values of the three color bands. It is the goal of this paper to show a methodology to convert the measured RGB values from an image sensor to weighted color band values. First we describe our image sensor characterization setup and the methodology to extract the spectral sensitivities of the RGB channels using known photon sources. After defining the wavelength ranges of the three color bands, any arbitrary spectrum will be approximated as a linear combination of the three color bands. As a demonstration of this technique, we have analyzed the in-situ reflectance/emission spectra from the etchings of copper and aluminum thin films using this methodology.

3.2 The Image Sensor

The image sensor is an off-the-shelf dual mode web camera manufactured by Sakar [6]. The camera board was detached from the case and the lens assembly removed to expose the image sensor. The image sensor consists of a red, green, and blue Bayer filter array [7] with the cover glass bonded to the sensor die (3 x 4 mm², 1 mm thick). Removal of the cover glass was not possible without destroying the image sensor so it was left intact. The camera operates with VGA resolution (640 x 480 pixels) at 30 frames per second and data acquisition is made possible by the use of the accompanying 8-bit software with USB connection to a personal computer. After disassembly, the camera board was modified to mount a high brightness blue LED (1 mm sq, 150 um thick) [8] adjacent to the image sensor for illuminating samples. The blue LED emits at 460 nm with a bandwidth of 20 nm and a peak optical power output of 250 mW [9]; it is used for interrogating the sample and is not used for the image sensor characterization step. A plastic retainer ring is fixed around the perimeter of the image sensor and LED so that a
sample can be placed on top for collecting spectra. The plastic retainer ring is about 1 cm square with a thickness of 2 mm. The system design utilizes the small form factor of the photon emitter and the detector array so that it can be used as a self-contained remote sensor platform. Fig. 3-1a shows the top view of the image sensor and mounted LED on the circuit board with sample stage. Fig. 3-1b shows a cross-sectional schematic of Fig. 3-1a to show the sample placement and reflection geometry.

![Image](image.png)

**Figure 3-1**: a) Top view of the modified image sensor board with insert showing detail of the 1 mm square, 150 um thick high-brightness blue LED and sample stage. b) Cross-sectional schematic view of the image sensor, LED and sample stage to show sample placement and reflection geometry.

### 3.3 Model of Image Sensor Output

The digital RGB triplet output from the image sensor contains quantitative information for the red, green and blue channels. This output can be described in terms of a sensor transfer function ‘$F$’ which accounts for any linear or non-linear mapping of the photon generated signal to the digital output that could be attributed to automatic gain and/or conversion beyond experimental control. For example, the digital output ‘$R$’ of the red channel can be written as:

$$
R = F(R')
$$

(3-1)
where $R'$ is a quantity proportional to the electron-hole pairs created in the sensor from illumination. We model $R'$ as an integration of all wavelength contributions to the sensor response as:

$$R' = k \int_{0}^{\infty} S_R(\lambda) I(\lambda) d\lambda$$

(3-2)

where $S_R(\lambda)$ is the spectral sensitivity of the red channel, $I(\lambda)$ is the photon irradiance, and $k$ is a proportionality constant of the image sensor. Analogous expressions can be written for the green (G) and blue (B) outputs.

### 3.4 Image Sensor Characterization Setup

To characterize the response of the image sensor and verify our model, we used a monochromatic light created by passing a tungsten-halogen source through an American ISA H10-VIR optical grating monochromator [10]. The monochromator output is coupled to an integrating sphere to emulate a uniformly illuminated area for sensor characterization. Intensity control was achieved with the addition of a neutral density filter placed in the light path. The band pass of the monochromator was determined to be 10 nm at 535 nm and 633 nm with laser sources, which is sufficient for our purposes to approximate as a narrow band source with a constant band pass. Since our sensor model (Eq. 3-2) implies linear superposition, we also performed a separate experiment to verify the digital output dependence from various wavelength sources. Narrow-band 430, 570, and 660 nm LED sources are coupled to an integrating sphere and illuminated on the image sensor so that we can independently control the intensity of the three wavelengths to investigate whether superposition holds. The background noise of the image sensor is estimated by placing the lens cap over the image sensor and capturing the output with ambient lights off.

### 3.5 Image Sensor Characterization Methodology

A monochromator with a narrow line aperture will yield a Gaussian spectral distribution. With a sufficiently narrow aperture opening, we can treat the input spectra $I_i(\lambda)$ as a delta function which simplifies the computation of the spectral sensitivity of the three RGB channels:

$$I_i(\lambda) = \frac{I_i}{\sqrt{2\pi}\sigma_i^2} \exp\left(-\frac{(\lambda - \lambda_i)^2}{2\sigma_i^2}\right) \rightarrow \lim_{\sigma \to 0} I_i(\lambda) = I_i \delta(\lambda_i)$$

(3-3)

Applying the narrowband stimulus to the linear image sensor model given in Eq. (3-2), we get:
The results are similar for the blue and green channel. The digital output $R$ of the image sensor for the red channel Eq. (3-1) is rewritten using the results of Eq. (3-4):

$$R' = k \int_{0}^{\infty} S_{R}(\lambda) I_{i} \delta(\lambda_{i}) d\lambda \rightarrow R' = k S_{R}(\lambda_{i}) I_{i} \Delta \lambda_{i}$$

(3-4)

where the effective spectral sensitivity $S_{R}(\lambda)$ (digital units/irradiance) indicates the product of the spectral sensitivity function, proportionality constant, and the spectral bandwidth term. This will simplify computation of the integral in Eq. (3-2) to a simple summation when we invoke a box approximation for the input spectra $I(\lambda)$ in a later section.

The effective spectral sensitivity can be solved once one knows the sensor transfer function $F$ and the corresponding irradiance, digital output and background noise values. To accomplish this, we map the image sensor response by varying the monochromator irradiance on the sensor from 5 to several hundred nW for wavelengths between 400 and 800 nm in 10 nm steps. The irradiance at the sensor was measured with a Newport optical power meter [11] at the same geometrical location that the sensor was placed at. Each measurement is captured as an image file and ImageJ software [12] used to extract the average RGB response. We subsample an area of no less than 200 x 200 pixels in the center of the image to remove any edge effects and artifacts present at the edges of the sensor. Forty data sets are collected per channel with a minimum of 10 data points per set for a total of 1200 data points. Plots of the sensor channel responses (y-axis) in digital units (d.u.) as a function of the photon irradiance (x-axis) in photons/sec·m² are shown in Fig. (3-2). For brevity, we only show the RGB responses at 430, 550, and 630 nm. The sensor response is approximately linear between $1 \times 10^{14}$ and $3 \times 10^{15}$ photons/sec·m² for all three channels, after which it becomes saturated and insensitive to changes in the photon irradiance.
3.6 Verification of Superposition Assumption

We check the validity of our superposition assumption implied by Eq. (3-2) by investigating a subset of the response space with three LEDs of wavelengths 430, 570, and 660 nm simultaneously illuminating the sensor. The bandwidths of all three LEDs were found to be 40-60 nm and can be considered to be monochromatic. Using our linear model, with three sources illuminating the sensor one should get a digital response equal to the sum of the individual responses. We express this for each of the sensor channels as:

\[
\begin{align*}
R_{660+570+430} &= R_{660} + R_{570} + R_{430} \\
G_{660+570+430} &= G_{660} + G_{570} + G_{430} \\
B_{660+570+430} &= B_{660} + B_{570} + B_{430}
\end{align*}
\]

3.6 Figure 3-2: RGB sensor output in digital units (d.u.) as a function of monochromator photon irradiance at 430, 550, and 630 nm for the a) red, b) green, b) and blue channels. The three wavelengths were chosen to correspond to the peak spectral responses of the image sensor channels. The sensor response is approximately linear between $1 \times 10^{14}$ and $3 \times 10^{15}$ photons/sec/m², after which it becomes saturated and insensitive to changes in the irradiance.
where the subscripts indicate the sensor measurements with all three sources (660, 570 and 430 nm, left hand side) or individual measurements (660, 570 and 430 nm, right hand side). Fig. (3-3) shows a plot of the measured RGB response (clear symbols) from our triple source illumination compared to the predicted RGB values (filled symbols). The results indicate, barring fluctuations in the digital output arising from the photon source or sensor circuitry, that a linear model is adequate to describe the sensor digital output within the intensity range of $1 \times 10^{14}$ and $3 \times 10^{15}$ photons/sec-$m^2$.

![Figure 3-3](image)

**Figure 3-3:** Verification of superposition assumption by comparing the measured RGB response (clear diamond) to the predicted RGB values (filled diamond) for various combinations of illumination with 660 nm (circle), 570 nm (triangle) and 430 nm (square) LED photon sources. Figs 3a, 3b, and 3c show the R (red channel), G (green channel), and B (blue channel) digital outputs respectively. Some plot symbols have been slightly offset to the side of another symbol for clarity.

### 3.7 Extraction of the RGB Spectral Sensitivity Functions

From Fig. (3-2), we approximate the sensor response as a linear model for photon irradiance between $1 \times 10^{14}$ and $3 \times 10^{15}$ photons/sec-$m^2$. It can be shown that using a linear transfer function that the slope and intercept of the measured digital response is related to the effective spectral sensitivity at that wavelength and the background noise:

$$R = F(R') = F(S_R(\lambda_i)I_i) = a_i I_i + b$$  \hspace{1cm} (3-7)
where \(a_i\) and \(b\) are the linear fit values to the experimental data. The background noise values were estimated from a dark frame measurement to average 0.01, 4.03, and 0.02 digital units for the red, green and blue channels respectively. We extract the effective spectral sensitivity values using a linear fit to each digital response data set at each wavelength using our background noise estimate as the intercept. The \(S'_R\), \(S'_G\), and \(S'_B\) plots versus wavelength \(\lambda\) are summarized in Fig. (3-4).

![Figure 3-4: Plots of the extracted effective spectral sensitivities \(S'_R\), \(S'_G\), and \(S'_B\) versus wavelength \(\lambda\).](image)

### 3.8 Box Approximation of Unknown Reflectance/Emission Spectra

Since the image sensor only gives three numerical values corresponding to the RGB outputs, one can in principle solve for an unknown intensity \(I(\lambda)\) which is characterized by three parameters. We adopted a three-box function to represent \(I(\lambda)\) as a weighted response of three spectral bands:

\[
I(\lambda) = I_R \text{Box}_R(\lambda) + I_G \text{Box}_G(\lambda) + I_B \text{Box}_B(\lambda)
\]  

(3-8)

where the coefficients \(I_R\), \(I_G\), and \(I_B\) are the heights or the weighted response of the box functions over their respective spectral bands. As an example of this approach, Fig. (3-5) illustrates a box approximation for an arbitrary spectrum.
Figure 3-5: Graphical diagram of the box approximation for an arbitrary spectrum \( I(\lambda) \) in photon/sec. The measured digital RGB sensor output is multiplied by the inverse matrix \( C^{-1} \) to obtain the effective intensity distribution values \( I_R, I_G, \) and \( I_B. \) The elements of matrix \( C \) are determined by summation of the effective spectral sensitivity functions over the defined spectral bands.

Inserting the box function expression for \( I(\lambda) \) into our sensor model it can be shown:

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} =
\begin{bmatrix}
\sum_{i} S_R(\lambda_i) & \sum_{i} S_G(\lambda_i) & \sum_{i} S_B(\lambda_i) \\
\sum_{i} S_R(\lambda_i) & \sum_{i} S_G(\lambda_i) & \sum_{i} S_B(\lambda_i) \\
\sum_{i} S_R(\lambda_i) & \sum_{i} S_G(\lambda_i) & \sum_{i} S_B(\lambda_i)
\end{bmatrix}
\begin{bmatrix}
I_R \\
I_G \\
I_B
\end{bmatrix}
\]

where each matrix element becomes the summation of the sampled effective spectral sensitivity values over the wavelength ranges \( \Delta \lambda_R, \Delta \lambda_G, \) and \( \Delta \lambda_B \) used to define the box functions. We define our spectral band boundaries as the cross over points where the red/green, green/blue spectral sensitivity functions are equal and cut off the spectral bands at the lower limit of 400 nm and the upper limit of 675 nm. The numerical values for the spectral bands are hence defined as:

\[
\Delta \lambda_R = [585, 675] \\
\Delta \lambda_G = [495, 585] \\
\Delta \lambda_B = [400, 495]
\]

One can compute the \( I_R, I_G, \) and \( I_B \) values in Eq. (3-9) by simple matrix inversion (i.e. \( Cx = a \rightarrow C^{-1}a = x \)) or by numerical iteration methods. The advantage of this approach is one can transform the changes in the RGB digital values to an effective intensity distribution \( I_R, I_G, \) and \( I_B \) associated with the defined spectral bands of \( I(\lambda). \) In addition, once the spectral
bands are defined the solution for $I_R$, $I_G$, and $I_B$ will also be unique. With the defined wavelength bounds, the matrix $C$ for our image sensor used for the $I_R$, $I_G$, and $I_B$ extraction is:

$$
C = \begin{bmatrix}
69.72 & 15.95 & 4.25 \\
16.62 & 59.36 & 18.26 \\
6.19 & 28.96 & 58.22 \\
\end{bmatrix} \cdot 10^{-14}
$$

(3-11)

where a $1 \times 10^{-14}$ in digital units/photon has been factored out for clarity.

3.9 Application to Copper End-Point Etch Monitoring

Our first three channel spectrometer attempt is to quantify the spectral reflectance/emission of a copper end-point etch monitoring experiment. Copper samples were prepared by sputtering 200 nm of copper onto glass cover slips. Our copper etchant was CR-7 chromium etchant (Cyantek). CR-7 consists of 6% perchloric acid and 9% ceric ammonium nitrate by weight in water solution. It is generally used to etch chrome, but also etches copper at appreciable rates ~280 nm/min [13]. The copper samples are placed on top of the sample stage and a drop of CR-7 is applied to the sample surface. The LED is powered on prior to the acid application and illuminates the underside of the sample while the image sensor records the reflectance/emission at 30 frames per second. All measurements were done with ambient lights off. Post image processing is done by extracting an image frame every 0.5 seconds and then tabulating the time evolved digital RGB triplet values. With the spectral response of the image sensor modeled, we solve the system of equations in Eq. (3-10) by numerical iteration for the $I_R$, $I_G$, and $I_B$ values associated with each set of time evolved RGB values. The results are plotted as a function of time in Fig. (3-6a) and a box approximation of the spectra is shown in Fig. (3-6b). We observed a 40.5% increase in intensity for $I_R$ (585-675 nm), a 33.8% decrease for $I_G$ (495-585 nm), and a 44.5% decrease for $I_B$ (400-495 nm). As expected, the total intensity decreases with etching time due to copper becoming transparent when the thickness is reduced to 50 nm and below [14]. The $I_G$ (495-585 nm) and $I_B$ (400-495 nm) intensity components are caused by the 460 nm source reflection and decrease when the copper thins down [15]. The $I_R$ (585-675 nm) signal increases to a steady state value which can be explained by the higher $I_R$ (585-675 nm) reflectance of the CR-7 etching solution when the thinned copper allows higher transmission of the probe beam into the etching solution. The higher $I_R$ component of the CR-7 etching solution is shown in Fig. (3-7) which contains the box spectra of the pure CR-7 solution on a glass cover compared to the pre-etch and final steady state spectra of the copper etch.
Figure 3-6: a) Plots of the time evolved $\mathbf{I}_R$ (585-675 nm), $\mathbf{I}_G$ (576-800 nm), and $\mathbf{I}_B$ (495-585 nm) spectral band versus etching time during a copper etch as determined using our methodology and b) box approximation of the spectra at etch times $t = 0$ sec (thin line), $t = 5$ sec (dashed line), and $t = 10$ sec (thick line). Arrows indicate the shift in the box spectra over time. Circles in a) indicate the sampled time for box spectra and arrows in b) indicate the shift in the box spectra over time.

Figure 3-7: Plots of the box spectra of copper pre-etch ($t = 0$ sec, thin line) and final steady state etch ($t = 10$ sec, thick line) compared to the box spectra of pure CR-7 on glass slide (dashed line). Initially the blue/green regime of the spectrum has high reflection from the copper. As copper thickness decreases, the reflectance will sample more intensity from the etchant solution. Arrows indicate the shift in the box spectra over time.
3.10 Application to Aluminum End-Point Etch Monitoring

A similar investigation to the copper end-point etch monitoring was conducted for aluminum. Aluminum samples were prepared by sputtering 200 nm of aluminum onto glass cover slips. The same etchant and procedure was used as before with the copper example. The results as a function of time are shown in Fig. (3-8a) and the box approximation of the spectra is shown in Fig. (3-8b).

![Figure 3-8](image)

**Figure 3-8:** a) Plots of the time evolved $I_R$ (585-675 nm), $I_G$ (576-800 nm), and $I_B$ (495-585 nm) spectral band versus etching time during an aluminum etch as determined using our methodology and b) box approximation of the spectra at etch times $t = 0$ sec (thin line), $t = 15$ sec (dashed line), and $t = 35$ sec (thick line). Circles in a) indicate the sampled time for box spectra and arrows in b) indicate the shift in the box spectra over time.

Here we see a similar trend to the copper etching before. A 13.6% increase in the intensity for $I_R$ (585-675 nm), a 31.5% decrease for $I_G$ (495-585 nm), and a 42.7% decrease for $I_B$ (400-495 nm). We observed that the transient behavior of the spectral bands vary during the etching in a similar fashion to the copper etching, but with different characteristic peaks; this may be an indication of a different etching mechanism.

3.11 Summary

We report on a novel approach to utilize a paper-thin LED photon source and a commercial image sensor as a three channel spectrometer to collect real-time data for hostile environment processing such as chemical etching. We verify the linearity of the image sensor photo response and extract the spectral sensitivity functions for the $R$, $G$, and $B$ sensor channels. We then establish a matrix relationship between the digital RGB triplet values and the absolute intensity $I_R$, $I_G$, and $I_B$ components by defining three specific spectral bands. As a demonstration of this method, we analyze the in-situ reflectance/emission spectra from wet
etches of copper and aluminum thin films. The time evolution of the spectral band intensity values $I_R$, $I_G$, and $I_B$ of the reflectance/emission spectra of thin-film copper and aluminum etching both show an unexpected rise of the $I_R$ component near the end point of the etching process which we attribute to a higher $I_R$ reflectance from the CR-7 etching solution.

3.12 References


4 A Fully Integrated Microspectrometer with a Photon Engine

4.1 Introduction

In this chapter we describe the design, fabrication, and demonstration of a fully integrated, chip-sized microspectrometer with a photon engine. The microspectrometer is realized using standard planar microfabrication techniques and bulk silicon micromachining. Hybrid integration is employed for the final system integration. This approach is advantageous in that it facilitates batch production and decouples potential process compatibility issues (e.g. chemical, material, and/or temperature constraints) of one component from another.

The essential problem to solve is the miniaturization of what has been traditionally a desktop based instrument. Miniaturization confers two design constraints: 1) we are limited in the vertical dimensions to the thickness of a typical silicon wafer (< 1 mm thick) and to a lesser extent the lateral dimensions (e.g. die size); and 2) our geometry is restricted to shapes achievable by planar microfabrication techniques, including the crystal planes of the substrate. These limitations force a down-scaling of the optical components and the optical path length, which in turn will affect the overall performance. Despite these challenges, we will demonstrate the feasibility of a chip-sized micro spectrometer that can operate in the visible region of the electromagnetic spectrum (400-700 nm).

4.2 Conventional Spectrometer Construction

Before we discuss the details of the microspectrometer design, it is useful to cover the basics of a conventional spectrometer. In general, a spectrometer consists of the following components, as shown in Fig. (4-1):

a) a photon source,
b) an entrance slit,
c) collimating lens,
d) demultiplexing element,
e) focusing lens,
f) and a detector.
The principle behind the operation of a spectrometer follows; a) a photon source illuminates b) the entrance slit which serves to condition the light beam by reducing the size and divergence of the source; c) the collimating lens transforms the divergent light beam from the entrance slit into a parallel light beam, so that plane waves arrive at d) the demultiplexing element, which acts to separate the incident light into its components of interest. In the case of a grating based spectrometer, the incoming light beam is deflected at angles depending on the wavelength and period of the grating. Since each angle corresponds to a particular wavelength, images of the entrance slit are formed at angles corresponding to the wavelengths present in the incoming radiation. The collimated, monochromatic beams then pass through e) the focusing lens which projects the image of the entrance slit onto the detector plane. Finally f) a detector at the image plane measures the intensity of the spectral components as a function of position; where each position corresponds to a specific wavelength [1]. There is considerable latitude in the types of spectrometer designs with many options for the demultiplexing and detector elements [2]. Given the scope of this thesis, the above description will suffice.

4.3 Lensless Spectrometer Design

In order to realize a fully integrated micro spectrometer and to keep assembly to a functional minimum, we only consider the most essential components. This includes the photon engine, the collimator, the demultiplexing element, and the detector. To achieve a spectrometer with the form factor constraints, we resort to a folded optical path design with a reflection grating as the demultiplexing element. A folded optical design allows us to conform to the vertical form factor constraint by using mirror reflection to extend the optical path. Fig. (4-2a) shows the cross section of the design architecture we used for the integrated micro spectrometer and Fig. (4-2b) shows the top-down view of the architecture.
Figure 4-2: Architecture of the microspectrometer design: a) cross-section and b) top-down view. The optical path is folded by use of a reflection mirror, effectively doubling the optical path length available for collimation. A high-brightness LED (HB LED) illuminates molecules at the free-standing optical window. The molecules absorb/emit photons which propagate to the diffraction grating by mirror reflection. The collimation function is fixed by the position of the top wafer relative to the bottom wafer. A photodiode array performs readout of the spatially dispersed wavelengths.
The micro spectrometer design embeds the following components between two bonded silicon wafer pairs: a high brightness LED (HB LED), a reflecting mirror, a diffraction grating, and a photodiode array. The bottom wafer has recessed cavities which are sized to the dimensions of the components to allow for drop-in, self-aligned assembly. The top wafer contains a free standing nitride window and a recessed cavity for accommodating the diffraction grating. The recessed cavities are fabricated using multi-step potassium hydroxide (KOH) bulk silicon etches and form mesas with 54 degree angles from the plane due to the <100> preferential etch. The active area of the micro spectrometer measures 2 mm x 3 mm, however the actual chip is conveniently made larger (16 mm sq.) to facilitate an array of electrical connections for purposes of prototyping and readout. In addition, we introduce a new photon engine to be used here and in subsequent chapters – a high brightness UV LED (HB UV LED) to be used instead of the blue HB LED used previously.

Operation of the micro spectrometer is as follows: 1) a HB UV LED (peak wavelength 360 nm) illuminates molecules at the free-standing nitride window; 2) The molecules then absorb and/or emit characteristic photons which some will propagate to the grating by mirror reflection off the bottom wafer. The propagation and collimation angle is inherently fixed by the <111> preferential etch by KOH and the position of the top wafer relative to the bottom wafer. After diffraction, a photodiode array completes the readout of the spatially separated wavelengths. In order to analyze the design in depth, we will begin with estimating the propagation and collimation angle formed by the geometry of the crystal planes exposed by the KOH etch.

4.3.1 Geometric or Ray Theory Model

Here we introduce an idealized ray optics treatment of the microspectrometer. Ray-tracing gives an approximate solution on how light will propagate through the system and is only valid as long as the wavelength is very small compared to the size of the object. The drawback is that ray theory will not describe diffraction or interference phenomena which require wave theory. This approach will suffice to give a general quantitative understanding of how the microspectrometer works before delving into the wave theory approach.

In general, the design revolves around the collimation geometry formed by the placement of the top wafer relative to the bottom wafer (Fig. 4-3). Once the degree of collimation $\Delta \theta$ and propagation angle $\theta_{inc}$ is known, the spatial dispersion, component placement and resolution estimate follows.
Figure 4-3: a) Schematic of the collimator geometry formed by the top and bottom wafer. Light rays from the LED cavity have many exit angles, but only a small range (to first order) can pass through to the grating/photodiode cavity. The propagation angle $\theta_{inc}$ is fixed by the 54 degree angle formed by KOH etch. b) Redrawing of a) to show that the collimation angle is determined by the effective length $l_{sidewall}$ and slit width $l_{slit}$ between the top and bottom wafer. Not shown in the diagram is the thin compliant polymer seal used to bond the top and bottom wafers.

The following derivation for the collimation is based on geometrical ray-trace and does not consider the additional broadening that can occur from edge diffraction effects. Nevertheless, it will suffice as an estimate. From Fig. (4-3) one sees that the ray propagation angle $\theta_{inc}$ is fixed by the 54 degree angle formed by the KOH etch. The collimation angle $\Delta\theta$ is determined by the effective sidewall length $l_{sidewall}$ and slit width $l_{slit}$ between the top and bottom wafer; we express this as:

$$\tan\left(\frac{\Delta\theta}{2}\right) = \frac{l_{slit}}{l_{sidewall}} \quad (4-1)$$

where the slit width $l_{slit}$ is given in terms of the gap $l_{gap}$ between the top and bottom wafer as:

$$l_{slit} = \frac{l_{gap}}{\cos 36^\circ} \quad (4-2)$$

and the sidewall length $l_{sidewall}$ is given as:

$$l_{sidewall} = \frac{t_{top} + t_{bottom} + t_{seal}}{\sin 54^\circ} \quad (4-3)$$

where $t_{top}$ and $t_{bottom}$ are the thickness of the top and bottom wafers; the compliant polymer seal is given as $t_{seal}$. After algebraic rearrangement Eq. (4-1) can be rewritten as:
\[ \Delta \theta = 2 \tan^{-1} \left( \frac{l_{\text{gap}}}{t_{\text{top}} + t_{\text{bottom}} + t_{\text{seal}}} \right) \] (4-4)

From Eq. (4-4), one sees that for a fixed form factor thickness \( t_{\text{top}} + t_{\text{bottom}} + t_{\text{seal}} \) the degree of collimation is adjustable by the gap formed between the top and bottom wafer placement. If the form factor thickness has some design latitude, one can generate design curves for estimating the desired degree of collimation based on the relative gap width between the top and bottom wafer (Fig. 4-4).

\[ m \lambda = d \left( \sin \theta_{\text{inc}} + \sin \theta_{m} \right) \] (4-5)

Once the incident angle is known, we can estimate the diffraction angle \( \theta_{m} \) from the grating equation and ultimately the spatial position on the photodiode array:

\[ x = h \tan \theta_{m} \] (4-6)

where \( h \) is the height of the cavity. Fig. (4-5) shows a plot of the wavelength position of the \( m = -1 \) diffracted order for given form factor heights \( h = 500, 1000, \) and 1500 um. A grating period of 1 um is assumed. The effect of a) 1°, b) 5°, and c) 10° collimation is shown to broaden the wavelength position. For a form factor height of 1000 um, the full width at half maximum
(FWHM) of the wavelength broadening is found to average 30 um, 200 um, and 400 um respectively. Since the final resolution will be proportional to the FWHM, this will necessitate a detector pitch on the order of the FWHM.

Figure 4-5: Wavelength positions of the $m= -1$ diffracted order for given form factor heights $h = 500$, 1000, and 1500 um. Positions are given relative to the zero-order diffraction position and a grating period of 1 um is assumed. The effect of a) $1^\circ$, b) $5^\circ$, and c) $10^\circ$ collimation is shown to broaden the wavelength position.
4.3.3 Additional Design Considerations

There are additional design considerations for the micro spectrometer; they are enumerated below:

1) Since the microspectrometer operates by reflection from the window (Fig. 4-2), one designs the optical window dimension larger than the gap \( (l_{\text{gap}}) \) between the top and bottom wafer and positions it such that it does not limit the throughput of the light rays. Additionally, the window material should be mechanically robust and transparent to the wavelengths of interest (400-700 nm). We invoke the same design principles for the nitride window discussed in Chapter 2.

2) The mirror should be optically smooth (i.e. surface roughness \( \sigma \ll \lambda \)) and highly reflective to the wavelengths of interest (e.g. aluminum for 400-700 nm). Optical simulation of the reflectivity using the formalism set forth in Chapter 2 estimates that the surface roughness should be < 10 nm for the lowest wavelength of interest (400 nm) to maintain < 2% reflection loss from the roughness. In principle, we could do without the mirror as long as the bottom cavity surface is of sufficient surface quality and reflectance. However, the use of an independent mirror component allows us to circumvent any surface roughness issues from the bulk micromachining process used to form the cavities.

3) The grating, like the mirror, should also be reflective and optimized for the wavelengths of interest (400-700 nm) e.g. aluminum coated reflection grating.

4) Placement of the components is straightforward – one ensures that the placement of the LED, window, mirror, grating, and photodiode do not obstruct the ray path. By using a folded spectrometer geometry, we also take advantage of limiting any direct light ray propagation from the LED/window cavity to the grating/photodiode cavity, thus one hopes this design will help minimize the background.

5) The detector element should be sensitive to the wavelengths of interest and have sufficient pitch to resolve the spatial separation of wavelengths. For our purposes, we will design and fabricate a silicon pn junction array with a 30 um pitch between elements to correspond to the best case scenario of 1° degree collimation (Fig. 4-5). Silicon is chosen since its bandgap of 1.1 eV allows the generation of electron-hole pairs from visible light.

6) Last, but most importantly, all components should be as thin as possible in order to maximize the optical path length; this will require paper-thin substrates.
4.3.4 Wave Theory Based Model

Here we present a more rigorous treatment of the light path through the microspectrometer using diffraction theory. We begin with the analysis of the diffraction pattern of the slit formed by the collimator geometry.

4.3.4.1 Diffraction Pattern of a Slit

The Huygens-Fresnel principle governs diffraction phenomena – where every point on a wave front can be considered as a source of secondary spherical wavelets. The field beyond a wave front is the result of the superposition of these wavelets taking into account their amplitudes and phases. The intensity pattern that results changes as one moves away from the aperture can be characterized by three regions, as shown by Fig. (4-6). In the shadow or geometric region, close to the aperture, the boundary of the transmitted light is sharp and resembles the aperture in shape. In the Fresnel region, the intensity distribution remains comparable to the aperture but narrow fringes begin to appear at the edges. In the Fraunhofer region, the beam spreads to widths much greater than the aperture and is flanked by many weaker fringes [3].

![Diffraction Pattern of a Slit](image)

Figure 4-6: A succession of diffraction patterns at increasing distance from an aperture; from geometric (left) to Fresnel (middle) towards Fraunhofer (right) [3].

Here we introduce a dimensionless parameter $F$, called the Fresnel number:

$$F = \frac{a^2}{\lambda z}$$  \hspace{1cm} (4-7)

where $a$ is the characteristic size of the aperture, $\lambda$ is the wavelength, and $z$ is the distance from the aperture to the image screen. Depending on the value of the Fresnel number, diffraction phenomena can be simplified into two special cases: Fraunhofer diffraction for
\( F \ll 1 \), and Fresnel diffraction for \( F \geq 1 \). In the case of \( F \gg 1 \), the laws of geometrical optics can be applied [3].

A more quantitative description of the disturbance at a point \( P \) from an aperture is contained in the Fresnel-Kirchhoff integral theorem (Fig. 4-7).

![Figure 4-7: Diffraction geometry for a point source at \( P_o \), a plane screen with aperture, and an observation point at \( P \). The distance from the point \( Q \) in the aperture to the points \( P_o \) and \( P \) are defined as \( r \) and \( s \), respectively [4].](image)

Since we make no attempt to control the polarization of the LED source or sample emission, it will suffice for our purposes to use the scalar approach. The solution provided by the integral theorem for a time-harmonic, monochromatic source is:

\[
U(P) = -\frac{1}{4\pi} \int_{A_o} \frac{e^{iks}}{s} \left[ ikU_o(r)\cos(n,s) + \frac{\partial U_o(r)}{\partial n} \right] dS
\]

(4-8)

where \( U(P) \) is the complex amplitude of the scalar field at the point \( P \), \( k \) is the wavenumber \((k = 2\pi/\lambda)\), and \( s \) is the distance from \( P \) to the surface [5]. It is assumed that the values of \( U \) and \( \partial U/\partial n \) are zero on the surfaces \( A_2 \) and \( A_3 \) are zero (Kirchhoff boundary conditions). It also is assumed that the \( 1/s \) and \( 1/r \) terms arising from the derivative of the field on the normal is negligible compared to \( k \), since \( r \) and \( s \) are much greater than the wavenumber. This assumption is justified as it can be estimated from Fig. (4-2) that the minimum distance from the window to the aperture is approximately 1500 um (3 wafers), and the minimum distance from the aperture to the grating is approximately 500 um (1 wafer). This is a worst case approximation; the actual distances will be longer due to the off-normal reflection geometry used. We approximate the extended source as:

\[
U_o(r) \approx a(r)e^{-ikr}
\]

(4-9)
where \( a(r) \) is the magnitude of the disturbance at the point \( r \) in the aperture. Additionally, we get:

\[
\frac{\partial U_n(r)}{\partial n} = -i k A(r) \cos(n, r)
\] (4-10)

where \( A(r) \) has absorbed the exponential term. Inserting Eqs. (4-9) and (4-10) into Eq. (4-8) we get:

\[
U(P) = -\frac{i}{2\lambda} \int_S \left[ A(r) \frac{e^{iks}}{s} \left[ \cos(n, r) - \cos(n, s) \right] \right] dS
\] (4-11)

If we make the further assumption that the light from the window has a well defined direction and uniformly illuminates the aperture, which is the case when the distance between the source and aperture is much greater than the wavelength \( \{r, s \gg \lambda\} \), then we can pull the \( A(r) \) term out of the integral and write:

\[
U(P) = -\frac{iA}{2\lambda} \int_S e^{iks} \left[ \cos(n, r) - \cos(n, s) \right] dS
\] (4-12)

Since the aperture dimension is small compared to the distance to the source and grating, we approximate the obliquity factor in the bracket with:

\[
\left[ \cos(n, r) - \cos(n, s) \right] \approx 2 \cos \gamma
\] (4-13)

where \( \gamma \) is the angle between the line \( \overrightarrow{P_0P} \) and the normal to the screen. The integral (Eq. 4-12) reduces to:

\[
U(P) = -\frac{iA}{\lambda} \cos \gamma \int_S \frac{e^{iks}}{s} dS
\] (4-14)

We use a Cartesian reference system with origin \( O \) in the aperture with the \( x \)-axis in the plane of the aperture and choose +\( z \) to point into the half-space that contains the observation point \( P \). We express the distance from a point \( Q \) in the aperture to a point \( P \) of observation in Cartesian coordinates as:

\[
s^2 = (x - x')^2 + z^2
\] (4-15)

where \( x' \) is the coordinate of a point in the aperture, and \( (x, z) \) is the coordinate of the point \( P \). If the linear dimensions of the aperture are small compared to \( s \), we can expand as a power series:
\[ s = z \left[ 1 + \frac{(x-x')^2}{2z^2} - \frac{1}{8} \left( \frac{(x-x')^2}{z^2} \right)^2 + \ldots \right] \]  

(4-16)

The range of variation on \( s \) in the denominator of Eq. (4-14) is much less sensitive than the exponential, thus for large \( z \) in comparison to the field of interest we can approximate as \( z \) and remove the denominator to outside the integral:

\[ U(P) = -\frac{iA}{\lambda z} \cos \beta \int_{S} e^{i\phi} dS \]  

(4-17)

We have reduced the problem of determining the disturbance at \( P \) to the evaluation of the integral (Eq. 4-17). When one truncates the quadratic terms, one gets the case of Fraunhofer approximation; when the quadratic terms cannot be neglected, one gets the Fresnel approximation. To determine the range of validity for truncation, the next higher order term in the exponent must be small compared to \( 1 \). Computing the Fresnel number (Eq. 4-7) for an aperture to screen distance of 500 um (1 wafer est. from Fig. 4-2) for source wavelength of 400 nm, one sees that for very narrow slit widths of 0.01 to 100 um one quickly transitions from Fraunhofer to geometric regimes (Fig. 4-8). Therefore instead of performing a truncation for Fresnel or Fraunhofer diffraction case, we evaluate the integral given by Eq. (4-17) numerically for various slit sizes at normal incidence (\( \cos \gamma = 1 \)). The results are presented as Fig. (4-9).

![Figure 4-8: Fresnel number as a function of aperture width for a screen distance of 500 um and a wavelength of 400 nm.](image-url)
From Fig. (4-9), as one transitions from slit sizes 10 um, 50 um, to 100 um, one gets Fraunhofer diffraction, Fresnel diffraction, and the geometric case. The oscillatory behavior observed for the geometric and Fresnel case is due to the much more sensitive phase variations in the exponent as the integral explores the region of the aperture.

![Graphs showing diffracted intensity profiles](image)

**Figure 4-9:** Diffracted intensity profiles on a screen 500 um away for apertures widths a) 10 um, b) 50 um, and c) 100 um. An incident wavelength of 400 nm is used for computations. The respective Fresnel numbers are a) \( F = 0.5 \), b) \( F = 12.5 \), and c) \( F = 50 \).

In review, we have derived an approximation for the intensity at a distance away from the collimating slit using a time-harmonic, monochromatic wave. We have assumed that due to the large distance on the source to slit side, that the incident waves will be approximately planar and uniformly illuminated. However, on the slit to grating side, the distances are sufficiently short enough that one must use caution in determining the intensity pattern – as one can arrive at very different results. In actuality, the experimental conditions may be much closer to non-time harmonic, broadband wave conditions which will smear out the oscillatory intensity patterns. Despite approximation, this approach serves to aid the design in estimating the number of illuminated grating grooves for purposes of determining the resolution.
4.3.4.2 Diffraction Pattern of a Grating

Here we consider the diffraction pattern of the grating. A grating consists of a periodic array of elements, either apertures or obstacles, which has the desired effect of producing periodic alternations in the phase, amplitude, or both of an emergent wave. The grating can be considered as an array of \( N \) identical grooves of width \( a/2 \) and equally spaced period \( a \) (Fig. 4-10) [3].

![Cross section of rectangular grating structure with period \( a \), height \( h \) and 50% duty cycle.](image)

**Figure 4-10:** Cross section of rectangular grating structure with period \( a \), height \( h \) and 50% duty cycle.

Computation of the diffraction pattern of a grating is similar to that of the slit, with the exception that one sums over the contributions from \( N \) slits [3], [6]. Similar to our discussion of the diffraction pattern from a slit, we start with the Fresnel-Kirchhoff integral. The contribution of the \( j^{th} \) slit to the amplitude \( U_j \) at a point \( P' \) on the detector plane at a distance \( s' \) from the grating is given as:

\[
U_j(P') = -\frac{1}{4\pi} \int_G 0 \ e^{i k s'} e^{i G m' x} \left[ ik U(P) \cos(n, s) + \frac{\partial U(P)}{\partial n} \right] dS
\]  

(4-18)

where we have introduced the grating wavenumber \( G = 2\pi/d \) and the grating profile function \( f(x) \) to account for the additional phase change as one moves along the grating profile; \( m \) is the diffraction order; \( U(P) \) is the complex field amplitude on the grating from the source. The integral is conducted over one grating period \( a \). For a square wave grating, the profile function \( f(x) \) is given as:

\[
f(x') = \begin{cases} 
    h & 0 \leq x' \leq a/2 \\
    0 & a/2 \leq x' \leq a 
\end{cases}
\]  

(4-19)

The effective phase of the resulting pattern on the detector \( U_T(P') \) is obtained by summing the contributions from the secondary waves of \( N \) grating periods [3], [6]:

\[
U_T(P') = -\frac{1}{4\pi} \sum_{j=0}^{N-1} e^{i k s'} e^{i G m' x} \left[ ik U(P) \cos(n, s) + \frac{\partial U(P)}{\partial n} \right] dS
\]  

(4-20)
The inclusion of the general complex field amplitude $U(P)$ here allows one to compute the effect on the resulting grating pattern for various source conditions, such as a divergent source from the collimator as computed with Eq. (4-18).

For the sake of arriving at an analytical expression, we make the following assumptions; 1) the grating is uniformly illuminated by the sources in the aperture, thus the source strength over the grating area $U(P)$ is approximated as constant ($U(P) \approx A$); 2) the illumination has a well defined direction ($s, s' \gg \lambda$); 3) the aperture dimensions are small compared to the distance $s'$ to the grating $[[\cos(n, r) - \cos(n, s)] \approx 2\cos\gamma$; and 4) that the grating profile $f(x')$ is thin ($e^{ikf(x')} \approx 1$). With these assumptions and approximations we can simplify Eq. (4-20) to:

$$U_T(P') = -\frac{IA}{\lambda} \cos \gamma \sum_{j=0}^{N-1} \int_{0 \leq ja} e^{iks'} \frac{e^{iGmx}}{s'} dS$$

where the distance from the grating to the detector plane $s'$ is given as:

$$s'^2 = (x - x')^2 + z'^2$$

Provided that the range of variation on $s'$ in the denominator of Eq. (4-21) is much less sensitive than the exponential terms, we can further approximate the denominator ($s' = z'$) and remove it from the integral:

$$U_T(P') = -\frac{IA}{\lambda z'} \cos \gamma \sum_{j=0}^{N-1} \int_{0 \leq ja} e^{iks'} e^{iGmx} dS$$

Provided that our diffracting elements (grating grooves) are small compared to the distance $z'$ to the detector plane we can resort to the Fraunhofer approximation; that is, we drop all the quadratic terms in the expansion of $s'$ (Eq. 4-16):

$$s' \approx z' \left[ 1 - \frac{xx'}{z'^2} \right]$$

Alternatively, in terms of the diffracted angle:

$$s' \approx z' - x' \sin \theta$$

We are now in a position to evaluate the integral in Eq. (4-23). We rewrite Eq. (4-23) with our approximations thus far as:
\[
U_f(P') = -\frac{iA}{\lambda z'} e^{ikz'} \cos \gamma \sum_{j=0}^{N-1} \left[ e^{-ikx'\sin \theta} e^{iG_{mx}} dS \right]
\]  

(4-26)

Evaluating the integral in the bracket \([...]\), performing the summation for \(N\) grooves, and squaring the result we obtain the result for the diffracted intensity pattern:

\[
\frac{I}{I_o} = \left( \frac{\sin \beta}{\beta} \right)^2 \left( \frac{\sin N\alpha}{\sin \alpha} \right)^2
\]  

(4-27)

where:

\[
\alpha = \frac{1}{2}ka \sin \theta \quad ; \quad \beta = \frac{1}{4}ka \sin \theta
\]  

(4-28)

It can be found that the maximum intensity occurs at:

\[
\frac{I}{I_o} = \left( \frac{\sin \beta}{\beta} \right)^2
\]  

(4-29)

when the following condition is satisfied:

\[
\alpha = m\pi \quad ; \quad m = 0, \pm 1, \pm 2, \pm 3...
\]  

(4-30)

By substitution of Eq. (4-28), the grating equation follows:

\[
m\lambda = a \sin \theta
\]  

(4-31)

The resultant intensity pattern \(I/I_o\) can be considered as the interference pattern of \(N\) point-sources equally spaced at a distance \(a\) which is confined within an envelope equal to the diffraction pattern of a single slit with width \(a/2\) (Fig 4-11a). It can also be shown that the interference pattern becomes much sharper with an increase in the number of illuminated grating grooves \(N\) (Fig. 4-11b).
**Figure 4-11:** (Solid dark line) Multiple-slit diffraction patterns for a) $N = 2$ and b) $N = 10$ grooves. The various contributions of Eq. (4-27) yield a multiple-wave interference (light gray line) modulated by the intensity pattern of a single slit (dashed line). An increase in the number of illuminated grooves $N$ results in a sharper intensity distribution.

### 4.3.4.3 Ultimate Resolving Power of a Grating

According to Rayleigh’s criterion, two spectral lines with a wavelength difference $d\lambda$ can be distinguished or resolved for a specific order if the principal maximum of the first wavelength falls on the first zero on either side of the principal maximum of the second wavelength. The angular distance between two spectral lines and their angular width is found by differentiating the grating equation (Eq. 4-31) with respect to the diffraction angle [3], [6]:

$$
\frac{d\theta}{d\lambda} = \frac{m}{a \cos \theta}
$$

(4-32)

The angular distance between two spectral lines with wavelength difference $d\lambda$ is found by rearranging the above equation:

$$
d\theta = \frac{md\lambda}{a \cos \theta}
$$

(4-33)

From Eq. (4-27) it is easily verified that the value changes from the maximum to the minimum when the argument $N\gamma$ changes from 0 to $\pi$. We then get:

$$
\frac{1}{2} \ kN \cos \theta \ d\theta' = \pi
$$

(4-34)
Applying the Rayleigh criterion which states two spectral lines are resolved if their angular separation $d\theta$ is equal to or larger than their separation between their peaks and the adjacent minimum $d\theta'$ of either spectral line, we set $d\theta = d\theta'$ and yield:

$$\frac{\lambda}{d\lambda} = mN$$  \hspace{1cm} (4-35)

$$R = \frac{\lambda}{d\lambda} = mN$$  \hspace{1cm} (4-36)

Thus the ultimate resolving power of a grating is determined by the number of illuminated grooves $N$ and the diffraction order. It can be improved by increasing $N$ or $m$. While the resolving power is independent of the grating shape, note that increasing the number of illuminated grooves requires increasing the collimator slit width and will result in a decrease in the spectrometer resolution as the incident waves will no longer be planar/parallel. In practice, the final spectrometer resolution will not approach the theoretical maximum. The primary factor limiting the resolution is the finite entrance slit which results in a wider FWHM.

Employing a higher order to increase the resolution is feasible as long as the intensity is high enough as the intensity of the maximum drops off rapidly with increasing order. The efficiency ($eff$) of a square wave grating can be estimated using the following:

$$eff \propto \left| \frac{1}{a} \int_0^a e^{-iGmx} e^{ikf(x')} dx' \right|$$  \hspace{1cm} (4-37)

where $f(x')$ is the grating profile function given by Eq. (4-19). Evaluating Eq. (4-37) for the general case of a grating of period $a$ with groove width $w$ we get:

$$eff \propto \begin{cases} 
\cos^2 \left( \frac{\pi h}{\lambda} \right) & m = 0 \\
\frac{4}{\pi^2 m^2} \sin^2 \left( m \frac{\pi w}{a} \right) \sin^2 \left( \frac{\pi h}{\lambda} \right) & m = 1, 2, 3, \ldots 
\end{cases}$$  \hspace{1cm} (4-38)

For a 50% duty-cycle grating ($w=a/2$), the above reduces to:
\[
\begin{cases}
\cos^2\left(\frac{\pi h}{\lambda}\right) & m = 0 \\
\frac{4}{\pi^2 m^2} \sin^2\left(\frac{m \pi}{2}\right) \sin^2\left(\frac{\pi h}{\lambda}\right) & m = 1, 3, 5, \ldots \\
0 & m = 2, 4, 6, \ldots
\end{cases}
\]

One sees that using the higher diffraction orders 2\textsuperscript{nd} or 3\textsuperscript{rd} would increase the resolving power by a factor of 2 or 3, but would also decrease the intensity by a factor 1/4 or 1/9 of the first order intensity. An interesting case also occurs if \( \frac{mw}{a} \) is an integer then the even diffraction orders are suppressed, this is useful to mitigate overlapping of the diffraction pattern of the first order with the second. With this in mind, our microspectrometer is designed to operate in the first diffraction orders.

4.3.5 The Photodiode Array

The final component in the microspectrometer is the photodiode array, where the intensity of spectral components diffracted by the grating is measured as a function of position. For our purposes we utilize a silicon pn junction array architecture so that we may extract a position dependent signal, where each position corresponds to a specific wavelength. Silicon is widely used for the fabrication of solar cells and photodetectors. This choice is based on a number of favorable properties of silicon: the bandgap of 1.1 eV allows the generation of electron-hole pairs from visible light, the starting material is relatively inexpensive and with availability of process technology for silicon, it is relatively easy to fabricate photodetectors [7]-[10].

4.3.5.1 Photodiode Operation

Photodiodes are semiconductor light sensors that operate by absorption of photons or charged particles and generate a flow of current proportional to the incident power. Fig. (4-12) shows the cross section of a typical planar photodiode.
The P+ layer at the surface and the N-type substrate form PN junction. The P+ layer is usually formed by selective implantation and diffusion of boron to a thickness of less than 1 um. By controlling the thickness of the diffusion layer and the doping concentration of the photodiode, the spectral and frequency response can be engineered. Due to the concentration gradient at the metallurgical junction i.e. the intersection of the P- and N-layer, free electrons in the N-layer diffuse across the junction and combine with holes to form negative ions. In doing so, the electrons leave behind positive ions at the donor impurity sites. A space charge builds up, creating a depletion region that inhibits further electron transfer, unless an external forward bias is placed on the junction. When the PN junction is reverse biased, the depletion region widens, exposing more positive and negative ions [7]-[10].

When light strikes a photodiode, the electrons within the crystal structure are stimulated. If the energy of light is greater than the band gap energy, electrons transition to the conduction band leaving holes in the valence band. If this process occurs in the depletion region, the electric field accelerates the electrons towards the N-layer and the holes towards the P-layer, creating a photocurrent [7]-[10].

The upper cut-off wavelength $\lambda_g$ for photo generated absorption is determined by the bandgap energy $E_g$ of a semiconductor, using ($E = h\nu = hc/\lambda$) [7]-[10]:

$$\lambda_g = \frac{1234 \text{ eV} \cdot \text{nm}}{E_g (\text{eV})}$$  (4-40)

For silicon, $E_g = 1.12$ eV and $\lambda_g = 1110$ nm, or 1.11 um, well into the infrared region of the visible spectrum. Incident photons with wavelengths shorter than $\lambda_g$ get absorbed as they travel through the semiconductor and the intensity decays exponentially with distance into the semiconductor. The light intensity $I$ at a distance $x$ from a semiconductor surface is given by:

$$I(\lambda, x) = I_o \exp \left(-\alpha(\lambda)x\right)$$  (4-41)
where $I_o$ is the intensity of the incident radiation and $\alpha$ is the absorption coefficient which depends on wavelength $\lambda$ [7]-[10]. Fig. (4-13) shows the penetration depth versus wavelength for silicon. From Fig. (4-13), the minimum cutoff wavelength occurs around 400 nm.

![Penetration depth of light into silicon for various wavelengths](image)

**Figure 4-13:** Penetration depth of light into silicon for various wavelengths [11].

### 4.3.5.2 Photodiode Spectral Response

The responsivity $\mathcal{R}$ of a silicon photodiode is a measure of the sensitivity to light; it is defined as the ratio of the photocurrent $I_{ph}$ to the incident light power $P_o$ at a given wavelength $\lambda$:

$$\mathcal{R}(\lambda) = \frac{I_{ph}(\lambda)}{P_o(\lambda)}$$  \hspace{1cm} (4-42)

The responsivity of a photodiode can be influenced by the applied reverse bias, temperature, as well as the geometry and the quality of the material of the device. The responsivity of a photodiode increases slightly with increased reverse bias due to the widening of the depletion region which leads to increased charge collection. Fig. (4-14) shows the spectral responsivity of several commercial photodiodes made by Hamamatsu [8].
4.4 Prototype Microspectrometer Fabrication and Integration

We now describe the fabrication and integration of the micro spectrometer. Fabrication of the micro spectrometer is functionally divided into several parts – the top and bottom cavity wafers, and the individual components i.e. mirror, grating, and photodiode array. Fig. (4-15) shows the cross section of the micro spectrometer at key process steps.

The detailed process flow for the overall device follows: 1) starting substrate – 2 silicon wafers < 500 um thickness each; 2) cavity definition – oxidation and nitride deposition followed by pattern transfer and bulk silicon machining via potassium hydroxide (KOH); 3) further cavity definition for optical window – additional oxidation and nitride deposition followed by pattern transfer and bulk silicon machining via KOH; 4) metallization – deposit aluminum and pattern; 5) integrate the HB LED [12]-[14], mirror, grating, and photodiode using conductive silver epoxy and cure; 6) finally, we wire bond the components, align and seal the wafer pair. Optical photographs of the completed cavity chips prior to integration are shown in Fig. (4-16).
Figure 4-15: Cross section of the micro spectrometer at key process steps. 1) starting substrate – 2 silicon wafers < 500 um thickness each; 2) cavity definition– oxidation and nitride deposition followed by pattern transfer and bulk silicon machining; 3) further cavity definition for optical window – additional oxidation and nitride deposition is followed by another pattern transfer and bulk silicon machining; 4) metallization – deposit aluminum and pattern; 5) integrate the HB LED, mirror, grating, and photodiode via conductive silver epoxy and cure; 6) finally, we wire bond the components, align and seal the wafer pair. Wire bonds are not shown and are typically into or out of the figure plane.

Figure 4-16: Optical photograph of a) the bottom cavity chip and b) the top cavity chip with optical window. The die measure 16 mm sq. and 10 mm sq. for the bottom and top cavity chips, respectively.
The fabrication of the mirror is straightforward: 1) starting substrate – 50 um thick D263 glass donated by SCHOTT [15], [16]; 2) clean and sputter coat with aluminum twice for a pinhole free film; and 3) singulate die. Due to the thin substrate and the desire for a quality mirror reflector, special process steps are taken. They involve affixing the 50 um thick D263 glass to a handle wafer so that it may be handled like a regular wafer. Prior to dicing, the substrate is coated with photoresist to protect the surface finish from chipping. An optical photograph of the final mirror die is shown in Fig. (4-17).

![Figure 4-17: Optical photograph of the fabricated mirror die. The die measure 1 mm square and are 50 um thick.](image)

To fabricate the grating, we follow a similar process flow to that of the mirror: 1) starting substrate – 100 um thick polymer transmission grating [17]; 2) clean and evaporate aluminum [18]; and 3) singulate. Evaporation is chosen as the film deposition method to avoid excessive heating of the substrate which can cause deformation of the polymer stamped grating grooves. An optical photograph of the final grating prior to singulation is shown in Fig. (4-18).

![Figure 4-18: Optical photograph of the polymer grating substrate under fluorescent room illumination prior to singulation.](image)
The process steps for the photodiode array is as follows: 1) starting substrate – 200 um thick phosphorus doped n-type prime silicon wafers with 0.3-0.1 Ω-cm resistivity (5x10^{15} to 2x10^{16} cm^{-3}); 2) grow thick field oxide (1 um) for oxide cut isolation; 3) deposit 180 nm nitride hard mask; 4) clear backside nitride and oxide; 5) backside n++ contact diffusion via POCl_3 doping; 6) topside active area pattern transfer; 7) active area ion implantation BF_2 with dose 1x10^{15} cm^{-2} and energy 30 keV; 8) rapid thermal anneal (RTA) for dopant activation; 9) sputter coat aluminum and define metal contacts; 10) forming gas anneal; 11) final die singulation and electrical characterization. The essential process flow steps, mask layout and optical photograph of the fabricated diode array is shown in Fig. (4-19), Fig. (4-20), and Fig. (4-21) respectively.

Figure 4-19: Cross section of the key photodiode process steps for a single photodiode strip showing ACTV, CONT, and METL steps.
Figure 4-20: a) Mask layout of the photodiode array. Green – ACTV (implanted area), black – CONT (contact hole definition), and blue – METL (metal definition). The photodiode chip measures 2 mm square. The scribe area includes verniers and checker patterns for mask alignment. b) Detail of the contact scheme to the active area. The contact holes are 2 um square and the metal contact line is 10 um wide with 2 um overlap of contacts. The active area is 20 um with a 10 um gap, or 30 um pitch between diode strips. c) Detail of the bond pad scheme. Adjacent photodiodes are paired out with neighboring bond pads for optional connection to double the active area. Alternating pairs are connected at the other end of the array. A total of 48 photodiodes are on-chip.

Figure 4-21: a) Optical photograph of the fabricated photodiode array. The die measures 2 mm square and 200 um thick; b) SEM detail of the metal contacts to the photodiode strips [19].

Integration of the micro spectrometer is done in parts: 1) the LED, mirror, and photodiode array are affixed to the appropriate cavities on the bottom chip using EpoTek silver conductive epoxy (EpoTek H2Oe) and cured [20]; 2) the LED and photodiode array are wire bonded out to the bond pads on the bottom chip (Fig. 4-22); 3) the grating is affixed to the top cavity chip; 4) a compliant polymer seal is applied to the top cavity chip and then placed on the bottom cavity chip for sealing (Fig. 4-23); 5) finally, we affix and wire bond the completed package onto a FR-4 based circuit board for interfacing to the data acquisition (Fig. 4-24). Prior to assembly, the electrical components e.g. LED and photodiode array are tested to confirm proper operation.
Figure 4-22: Optical photographs showing a) the integrated UV LED/mirror and b) the photodiode array.

Figure 4-23: Optical photograph of the final integrated micro spectrometer placed next to a USA penny for form factor comparison. The various components i.e. LED, mirror, grating, and photodiode array are shown on the penny. The total micro spectrometer thickness is < 1 mm thick.

Figure 4-24: Optical photograph of the final integrated micro spectrometer mounted on a readout circuit board for connection to the data acquisition system. (Left) Without optical window and (right) with optical window and protective plastic cover.
4.5 Optical and Electrical Characterization

We have covered the design, layout, and fabrication of the fully integrated microspectrometer. Here we discuss the optical and electrical characterization of the fabricated device. Each component is characterized prior to assembly to ensure a functional prototype – an advantage of the hybrid integration approach. After assembly, the completed device is tested for the dispersion performance.

4.5.1 Photon Engine Characterization

The current-voltage characteristics of the integrated UV LEDs are measured in order to determine operation points and to estimate the optical power output in conjunction with the LED datasheet values (Fig. 4.25) [13], [14].

Figure 4.25: Current-voltage characteristics and optical output of the UV (peak wavelength 360 nm) and high brightness blue (peak wavelength 460 nm) LED for comparison [12]-[14].

4.5.2 Mirror Reflectance

The aluminum mirror is characterized pre- and post-dice to confirm that the dicing procedure did not damage the surface finish. We measured the aluminum mirror reflectance using a NanoSpec®/210 Film Thickness System as a function of wavelength for normal incidence (Fig. 4.26a). Both pre- and post-dice reflectance measurements are within the ±2% repeatability specifications of the NanoSpec [21] and shows a maximum of -5% reflectance deviation from literature [22]. The surface roughness is characterized post-dice by AFM (Fig. 4-26b) and shows a RMS roughness of 2.55 nm [23].
4.5.3 Collimator Function

To characterize the collimator function, a dummy spectrometer chip is prepared with only the mirror and modified to allow light to exit the substrate where the photodiode array would be positioned. A CCD is placed at the exit to capture the light intensity passing through the chip while an input fiber from a light source is rotated about the window in 5 degree increments from 0 to 90 degrees. The CCD digital count is recorded and plotted as a function of angle (Fig. 4-27). A peak propagation angle of 53 degrees and a standard deviation of 6 degrees is extracted from Gaussian fit to the data. This agrees with the predicted estimate of 54 degrees for the propagation angle.
4.5.4 Grating Reflectance

Since the grating response space depends on many variables, e.g. the incident light angle, polarization, wavelength and diffraction order. For brevity, it suffices to do a simple test to confirm proper grating operation. The grating was mounted on a rotary stage with the monochromator [24] output focused to a 5 mm diameter spot on the grating. We measure the optical power incident and diffracted with an optical power meter [25] and compute the ratio to obtain the unpolarized efficiency of the m = -1 diffraction order for the case of normal and 45 degree incidence. The results are shown as Fig. (4-28). The grating efficiency was found be roughly 30% across the visible spectrum.

![Figure 4-28](image.png)

Figure 4-28: Plot of the measured grating efficiency for the diffraction order m = -1 at normal incidence and 45 degrees incidence for unpolarized light.

4.5.5 The Photodiode Array

The diode electrical characteristics and optical reponsivity were measured using an HP4145B Semiconductor Parameter Analyzer [26]. The instrument has full-scale ranges from 50 fA to 100 mA and 4 digit resolution. A tunable broadband LED source [27] coupled to a UV-VIS ISA 1/8 m monochromator [24] served as the light source. The monochromator has a bandwidth of 10 nm as measured with a HeNe laser (632 nm). The light source was coupled to the photodiode array by a glass fiber optic bundle. The output of the light source/fiber was calibrated using an optical power meter.

The spectral response of the photodiodes was measured across the wavelength range 400-700 nm in 20 nm increments at normal incidence. The photodiode IV response was also measured under dark conditions to determine the leakage current. Fig. (4-29) shows the measured photodiode spectral response at 1 V reverse bias and Fig. (4-30) shows the current voltage characteristics of the photodiode array under dark conditions.
Figure 4-29: Spectral response of the fabricated photodiode array at 1 V reverse bias.

Figure 4-30: Reverse current-voltage characteristics of the photodiode array under dark conditions. The diodes are paired out and show an average dark current of 30 ± 14 pA at the zero bias point and 19 ± 26 nA at 5V reverse bias.

Up to a reverse bias voltage of 5V the dark current increases to a 19 ± 26 nA. The high leakage current indicates the presence of traps in the depletion region. No breakdown was observed up to 10V reverse bias. At the zero bias point, the diode current averages 30 ± 14 pA across 20 channels. Due to the high leakage observed, we use 100 mV reverse bias for all subsequent measurements. It was previously estimated that the photodiode signal would be on the order of nA, therefore keeping the leakage in the pA range (factor of 10⁻³ less) will help improve discerning the signal over the background.
4.5.6 Micro Spectrometer Characterization

Final testing of the micro spectrometer device was performed with a completely assembled device mounted on a custom read-out circuit board for convenient extension of the electrical connections to the data acquisition system.

Fig. (4-31) shows the apparatus used for the optical characterization of the fabricated micro spectrometer device and Fig. (4-32) shows the block diagram of the readout system with detail on the amplifier circuit. The apparatus consists of a tunable LED source with an optical fiber for input into the spectrometer. A rotary stage allows for angular control of the light source input. A National Instruments NI-6210 data acquisition module (NI-6210 DAQ) [28], [29] with a transimpedance amplifier board enables readout via USB connection to a personal computer (PC).

Figure 4-31: A schematic of the optical and electrical measurement apparatus. The spectrometer device is coupled to the NI-6210 USB data acquisition (NI-6210 DAQ) via an amplifier board consisting of an array of transimpedance amplifiers. A tunable LED source coupled to a fiber and rotary stage allows for angular control of the incident beam. Data collection and control of the tunable LED source is enabled by a personal computer (PC).
Figure 4-32: (Top) Block diagram of the readout system. The spectrometer device is connected to a transimpedance amplifier board which is then connected to the National Instruments NI-6210 USB data acquisition module. Readout is accomplished via USB to PC by the use of LabVIEW SignalExpress software. (Bottom) Transimpedance amplifier circuit used for converting the photo current signal to a usable voltage signal.

NI-6210 DAQ offers 16 analog inputs with a 16-bit, 250 kS/s aggregate sample rate. The tunable LED source has 3 peak wavelengths at 460 nm, 510 nm, 630 nm which are independently adjustable. Both the NI-6210 DAQ and tunable LED source are controlled by a PC [27]-[29].

The transimpedance amplifiers allow us to convert the photocurrent to a voltage signal that can be read by the DAQ and also helps prevent loading of the DAQ. A schematic of the transimpedance amplifier circuit is shown in Fig. (4-32). The voltage output $V_{out}$ of the circuit is given as [30]:

$$V_{out} = -R_f (I_{\text{photo}} + I_{\text{dark}} + I_{\text{offset}})$$  \hspace{1cm} (4-43)

Where $R_f$ is the feedback resistor, $I_{\text{photo}}$ is the photo current, $I_{\text{dark}}$ is the leakage current with ambient lights off, and $I_{\text{offset}}$ is the current draw resulting from the non-ideal op amp inputs.

Operation of the apparatus is as follows; 1) optical input to the spectrometer device under test via the fiber guide results in a photocurrent signal from the integrated photodiode array; 2) the photo current signal is amplified by a transimpedance amplifier and then acquired by the NI-6210 DAQ; 3) readout is accomplished by USB connection to PC running LabVIEW SignalExpress software.
With ambient lights off, the photodiodes are biased and the offset voltage resulting from the photodiode dark current and op amp current offset are nulled. Then with our monochromator input as stimulus, we record the photodiode signals.

During measurement of the micro spectrometer, three different inputs of wavelengths of 460, 520, and 630 nm were used and the resulting photocurrent is recorded as a function of diode position. Fig. (4-33) shows a plot of the diode array signal for the different wavelength inputs.

![Figure 4-33: a) The photodiode signal of the integrated spectrometer illuminated with 630 nm, 520 nm, and 460 nm. The dashed lines are least square fitted Gaussians used to extract the peak positions and spread. b) The extracted peak positions and spread. The solid lines correspond to the classical grating equation fitted to the geometry of the spectrometer device with a grating period of 1 um, an incident angle of 53 degrees, and a height of 700 um.](image)

Least square fitting of Gaussians was used to extract the peak photocurrent position; peaks were recorded on diode channels 2, 3, and 4 for wavelengths 630, 520, and 460 nm, respectively. The appearance of a Gaussian-like intensity pattern indicates that the device is likely operating in the Fraunhofer diffraction regime, however due to the pixel resolution, further verification is suggested.

The instrumental bandpass or \( FWHM \) is approximately given by the greater of the size of a pixel \( \Delta x_{\text{pixel}} \) or the width of the image size \( w \) multiplied by the dispersion \( \Delta \lambda / \Delta x \):

\[
FWHM = \left( \frac{\Delta \lambda}{\Delta x} \right) \cdot \max( \Delta x_{\text{pixel}}, w) \tag{4-44}
\]

Referring to Fig. (4-31), the width of the diffraction pattern is approximately 3 pixels or 180 um for 460-630 nm wavelength range with a image widths of 2 pixels or 120 um. Applying
these values to Eq. (4-44), we obtain an effective spectral resolution of 120 nm. An effective spectral resolution of 120 nm results in a 2 or 3 channel device with poor fidelity. However, as a proof-of-concept device, these results show that an integrated microspectrometer is possible and there is certainly room for improvement. We enumerate some possible approaches for improvements:

1) Inspection of Eq. (4-47) shows that one could decrease the FWHM to improve the wavelength resolution. This can come about by an increase in the optical path length e.g. thicker wafers and an adjustment of the slit size.

2) One can also increase the spatial dispersion $\Delta \lambda/\Delta x$ by increasing the grating constant, since it follows from the grating equation (Eq. 4-5) that the dispersion is proportional to the grating constant.

3) Alternatively, one can decrease the pixel size for improved resolution, but this must be accompanied with an improvement in the dispersion or image width.

For our fixed geometry design with a short optical path length, it is somewhat problematic to improve the FWHM without changing the geometric design. However, the increasing the grating constant and changing the pixel size is more readily accessible with a simple replacement of components – this is the focus of our discussion in Chapter 5.

4.6 Summary

In this chapter, we presented the design, fabrication and prototype demonstration of a fully integrated, chip-size micro spectrometer with a photon engine. This was accomplished by using standard microfabrication techniques for each of the components. Using the hybrid integration approach, the process flows for each component was decoupled from the other. The final device form factor measured < 1 mm thick and demonstrated a resolution of 120 nm over the visible spectrum 400-700 nm.

4.7 References


[21] Marvell Nanofabrication Laboratory, "Nanospec/DUV Microspectrophotometer (NanoDUV),"
   University of California, Berkeley, Lab Manual 2012. [Online].
   http://microlab.berkeley.edu/labmanual/chap8/nanoduv.pdf


[23] AFM courtesy of Patrick Bennett.


[27] DiCon FiberOptics, Inc., Richmond, California.

[28] National Instruments Corporation, Austin, Texas.


5 An Improved Microspectrometer

5.1 Introduction

In Chapter 4, we covered the design and fabrication of a fully integrated microspectrometer with a photon engine using conventional microfabrication techniques. The proof-of-concept prototype has shown the working principle of spatial dispersion. However, with only three spectral channels demonstrated, the prototype in its current iteration does not show significant advantage over the three-channel RGB sensor approach described in Chapter 3. In this chapter we present the subsequent modification and improvement of the grating based microspectrometer to realize a minimum of 5 channels. We end the chapter with a quantitative demonstration of the microspectrometer in distinguishing three different phosphor powders.

5.2 Overview of Improvements

To improve the performance of the microspectrometer, the following modifications were made:

1) The 1000 line/mm grating was replaced with a 1200 line/mm grating for increased dispersion since it follows from the grating equation that increasing the grating density is proportional to the dispersion.

2) The 60 um pixel photo diode array was replaced with an RGB image sensor array consisting of 5 um pixels for improved resolution.

We now cover the details of the modifications, the characterization, and the results of the improved microspectrometer.

5.3 The Grating

A standard reflection grating (product number SLG-C12-5030A-Al) with line density 1200 lines/mm was purchased from LightSmyth Technologies, Inc. [1]. They are patterned straight-line binary silicon substrates with aluminum coating and measures 50 mm x 30 mm by 0.7 mm thick. The grating groove depth and duty cycle is optimized to maximize the first order diffraction with a peak wavelength at 580 nm (s-polarization) and 1000 to 1550 nm (p-polarization) [2]. In order to integrate the 0.7 mm thick off-the-shelf grating, the thin silicon remaining of the top cavity chip was carefully removed with a diamond scribe such to create a free-standing silicon frame. The LightSmyth grating was then cleaved to dimensions approximately 3 mm x 4 mm and placed to cover the exposed hole. Epoxy is used to affix the grating permanently and to form a light-tight seal around the perimeter.
5.4 The Image Sensor

The image sensor is an off-the-shelf dual mode web camera manufactured by Sakar [3]. The camera board was detached from the case and the lens assembly removed to expose the image sensor (3 mm x 4 mm, 1 mm thick). The image sensor consists of a red, green, and blue Bayer filter array [4]. The image sensor here differs from the one used in Chapter 3 as this one does not have a cover glass bonded to the sensor die. The camera operates with VGA resolution (640 x 480 pixels) at 30 frames per second and data acquisition is made possible by the use of the accompanying 8-bit software with USB connection to a personal computer. Like the grating modification, the thin silicon of the bottom cavity chip was carefully removed with a diamond scribe to create a free-standing silicon frame. The silicon frame is placed on a plastic retainer ring around the perimeter of the image sensor to accommodate the wire bonds already present on the sensor. The camera board was modified to supply external power to the UV LED. Accommodating both the grating and image sensor increased the internal form factor to approximately 1.5 mm. Fig. (5-1) shows a cross sectional diagram of the modified microspectrometer.

![Cross section of the modified microspectrometer showing the addition of a diffraction grating and RGB image sensor. The internal form factor is approximately < 1.5 mm thick.](image)

5.5 Model of Microspectrometer Sensor Output

With the addition of an RGB image sensor, the microspectrometer now has a digital output containing quantitative information about the input spectra which we desire to extract. The approach that follows is similar to that presented in Chapter 3 with few additions. Proceeding in like fashion, we describe the digital output in terms of the sensor transfer function $F$ which accounts for any linear or non-linear mapping of the photon generated signal. For example, the digital output $D$ of the $i^{th}$ channel can be written as:
\[ D_i = F(D_i') \]  

where we have introduced the total digital response \( D \), defined as the sum of the RGB triplet in order to simplify computation:

\[ D_i = R_i + G_i + B_i \]  

Like before, \( D_i' \) is a quantity proportional to the electron-hole pairs created in the sensor from illumination. We model \( D_i' \) as an integration of all wavelength contributions to the sensor response as:

\[ D_i' = k \int_{0}^{\infty} S_i(\lambda) I(\lambda) \exp\left(-\frac{(x - x_i(\lambda))^2}{2\sigma_i^2}\right) d\lambda \]  

where \( S_i(\lambda) \) is the spectral sensitivity of the channel, \( I(\lambda) \) is the photon irradiance, and \( k \) is a proportionality constant of the image sensor. Here we have added a Gaussian term to account for the spreading of the intensity over the image sensor pixels where the peak position as a function of wavelength is \( x_i(\lambda) \) and \( \sigma_i \) is the characteristic spread. A graphical representation of Eq. (5-3) is shown in Fig. (5-2).

**Figure 5-2:** Graphical diagram of the image sensor model given by Eq. (5-3). We illustrate two different wavelength stimuli (\( \lambda_1, \lambda_2 \)) resulting in two similar but different pixel responses (shift in peak position \( x(\lambda) \), height \( kS(\lambda)I(\lambda) \), and characteristic spread \( \sigma \)).

### 5.6 Characterization Setup

The characterization methodology is conducted in similar fashion as presented in Chapter 3. The optical bench setup is unchanged from that shown in Chapter 4. A monochromatic source is created by passing a high power DiCon tunable LED source (400-700 nm).
97 nm) [5] or a tungsten halogen lamp (400-900 nm) though an American IS H10-VIR optical grating monochromator [6]. The high power LED source with peak wavelengths 460, 520, and 640 nm is used for characterizing the dynamic range of the device; the low power tungsten source with a wider bandwidth is used for determining the wavelength positions. The monochromator output is coupled to an optical fiber bundle and aligned with a rotary stage to illuminate the microspectrometer window. The band pass was verified to be 10 nm at 535 nm and 633 nm with laser sources, which is sufficient for our purposes to approximate as a narrow band source with a constant band pass. Since our device operates by spatial separation of the wavelengths, we find it unnecessary to repeat the superposition experiment previously discussed in Chapter 3. The background noise of the device is estimated by placing the lens cap over the device and capturing the image sensor output with ambient lights off. A personal computer served as both control and data acquisition for the LED source and image sensor.

5.7 Characterization Methodology

A monochromator with a narrow line aperture will yield a Gaussian spectral distribution. With a sufficiently narrow aperture opening, we can model the input spectra \( I_i(\lambda) \) as a delta function which simplifies the computation of the spectral sensitivity of the \( D_i \) channels:

\[
I_i(\lambda) = \frac{I_i}{\sqrt{2\pi}\sigma_i^2} \exp\left(-\frac{(\lambda - \lambda_i)^2}{2\sigma_i^2}\right) \rightarrow \lim_{\sigma \to 0} I_i(\lambda) = I_i \delta(\lambda_i)
\]  (5-4)

Applying the narrowband stimulus to the linear image sensor model given in Eq. (5-3), we get:

\[
D_i' = k \int_0^\infty S_i(\lambda) I(\lambda) \exp\left(-\frac{(x - x_i(\lambda))^2}{2\sigma_i^2}\right) d\lambda \quad \rightarrow \quad D_i' = kS_i(\lambda_i) I_i \exp\left(-\frac{(x - x_i(\lambda_i))^2}{2\sigma_i^2}\right) \Delta\lambda_i
\]  (5-5)

The digital output \( D_i \) of the image sensor Eq. (5-1) is rewritten using the results of Eq. (5-5):

\[
D = F(D') = F\left(kS_i(\lambda_i) I_i \exp\left(-\frac{(x - x_i(\lambda_i))^2}{2\sigma_i^2}\right) \Delta\lambda_i\right) = F\left(I_i S_i'(\lambda_i) \exp\left(-\frac{(x - x_i(\lambda_i))^2}{2\sigma_i^2}\right)\right)
\]  (5-6)

where the effective spectral sensitivity \( S_i'(\lambda) \) (digital units/irradiance) indicates the product of the spectral sensitivity function, proportionality constant, and the spectral bandwidth term. Again, like Chapter 3, this approach simplifies the computation of the integral in Eq. (5-3) to a simple summation when we invoke a box approximation in solving for the input spectra \( I(\lambda) \) later on.

The effective spectral sensitivity, peak wavelength position, and characteristic spread can be determined once one knows the sensor transfer function \( F \) and the corresponding irradiance, digital output, and background noise values. To determine the dynamic range, we
map the microspectrometer response by varying the monochromator intensity on the optical window from several nW to several uW at the peak wavelengths of the LED source (460 nm, 520 nm, and 640 nm). Fifteen intensity steps were used per wavelength. The irradiance was measured with a Newport optical power meter at the same geometrical location of the optical window [7]. To characterize the wavelength position, we replace the LED source with the tungsten halogen lamp and vary the wavelength in 20 nm steps. Each measurement step is captured as an image file and ImageJ software [8] is used to extract the average digital response along the lateral direction of the image sensor. Fig. (5-3) shows an example of the microspectrometer response under 460, 520, and 640 nm illumination. The \( m = 0, -1, \) and \(-2\) diffraction orders are observed.

![Example data set of the microspectrometer response.](image)

**Figure 5-3:** Example data set of the microspectrometer response. (Top) The average response along the lateral direction of the image sensor is shown for 460, 520, and 640 nm illumination. The \( m = 0, -1, \) and \(-2\) diffraction orders are observed and are labeled accordingly along the top horizontal axis. (Bottom) The RGB-based JPEG image as captured from the image sensor showing simultaneous illumination by all three wavelengths for comparison.

### 5.8 Characterization of the Dynamic Range

From Fig. (5-3) it is apparent that we can approximate the response with a Gaussian model. Assuming a linear transfer function, it can be shown that the measured digital response is related to the effective spectral sensitivity, the peak wavelength position, the characteristic spread, and the background noise:
\[ \mathbf{D} = F(\mathbf{D}') = F\left( S'_i(\lambda_i) I_i \right) \approx a_i \exp \left( \frac{-(x-c_i)^2}{2b_i^2} \right) + d_i \]  

(5-7)

where \( a_i, b_i, c_i, \) and \( d_i \) are the fit values to the experimental data. We extract the effective spectral sensitivity, peak wavelength position, characteristic spread, and background simultaneously using Gaussian fits to the \( m = -1 \) diffraction order. Plots of the peak sensor response (y-axis) in digital units (d.u.) as a function of the photon irradiance (x-axis) in photos/sec·m\(^2\) are shown in Fig. (5-4a). The characteristic spread in pixels (px) as a function of irradiance is shown in Fig. (5-4b), and the background is shown in Fig. (5-4c).

From Fig. (5-4) we make several observations:

1) The sensor response was found to be approximately linear for photon irradiances between \( 4 \times 10^{16} \) and \( 1 \times 10^{18} \) photons/sec·m\(^2\) for all three wavelengths (460, 520, 640 nm).
2) The characteristic spread was observed to increase monotonically from 5 pixels at $4 \times 10^{16}$ photons/sec-m$^2$ to 20 digital units at $5 \times 10^{17}$ photons/sec-m$^2$. At irradiances above $5 \times 10^{17}$ photons/sec-m$^2$ the characteristic spread reaches an asymptote at approximately 22 digital units. The spread is roughly independent of wavelength.

3) The background count was also found to have a dependence on wavelength and increased above a threshold irradiance of $3 \times 10^{17}$ photons/sec-m$^2$. However, below this threshold the background remains a constant at 60 digital units.

With these observations we can make some simplifications to our model. As long as one ensures that the irradiance at the optical window does not exceed $5 \times 10^{17}$ photons/sec/m$^2$, we can fix the characteristic spread and background for worst case values of 10 pixels and 60 digital units, respectively.

5.9 Extraction of the Wavelength Position and Form Factor Height

With a tungsten halogen lamp as the input stimulus, we extract the wavelength pixel position using the approach described before (Eq. 5-7). Figure (5-5a) shows the results of the extracted wavelength pixel position and Fig. (5-5b) shows a contour plot constructed from slices of the captured images along the lateral axis of the image sensor at each wavelength. The improved microspectrometer is observed to exhibit a wavelength to spatial dispersion of approximately 1.2 nm/um ($\Delta \lambda = 500$ nm, $\Delta x = 400$ um) for the $m = -1$ diffraction order. There is no overlap between the $m = -1$ and $m = -2$ diffraction orders up to 900 nm, giving us a free spectral range of 900 nm ($\Delta \lambda = \lambda_{max}/m$).

With the calibrated wavelength pixel positions, we also extract the vertical distance between the grating and the image sensor or the form factor height. Simple trigonometry yields the relation for the height $h$ as a function of the wavelength position $x(\lambda)$ and diffraction angle $\theta_m$:

$$\tan \theta_m = \frac{x(\lambda) + x_{\text{offset}}}{h}$$

(5-8)

where $x_{\text{offset}}$ accounts for the relative shift between the grating and image sensor; the offset is computed at the $m = 0$ diffraction order ($\theta_m = \theta_{\text{inc}}$). The diffraction angle is derived from the grating equation:

$$\theta_m = \sin^{-1}\left(\frac{m\lambda}{d} - \sin \theta_{\text{inc}}\right)$$

(5-9)
Inserting known parameters into the above equation \((\theta_{in} = 54\ degrees, \ d = 0.83\ \text{um})\) and fitting to the wavelength positions yields a form factor height \(h\) of 1.2 mm, a value in agreement with the initial estimate of 1.5 mm.

![Figure 5-5: a) Contour map of the normalized pixel response to the stimulus wavelength using a tungsten-halogen lamp and b) extracted peak positions from the intensity maxima. Symbols correspond to the extracted peak values and solid lines correspond to the grating equation fitted to the form factor of the microspectrometer with grating period 0.83 um, incident angle 53 degrees, and height 1200 um. Pixel position has been converted to units of micron (5 um/pixel).](image)

### 5.10 Extrapolation of the Spectral Sensitivity Function

From Fig. (5-4a), we approximate the sensor response as linear for the irradiance range \(4 \times 10^{16}\) and \(1 \times 10^{18}\) photons/sec·m². It can be shown that using a linear transfer function at the peak wavelength of our model (Eq. 5-3) that the slope and intercept of the measured digital response \(D\) is related to the spectral sensitivity at that wavelength and the background:

\[
D = F(D') = F(S(\lambda_i)I_i) \approx a_i I_i + b_i
\]  

(5-10)

where \(a_i\) and \(b\) are the linear fit values to the experimental data. We extract the effective spectral sensitivity values using a linear fit to the digital response at wavelengths 460, 520, and 640 nm using our background estimate of 60 digital units as the intercept. We then extrapolate the response over the wavelength range 400 to 900 nm using a piece-wise linear fit with bounds set for zero responsivity at 300 nm and 1100 nm, corresponding to the approximate band gap and absorption range of silicon. The extrapolated spectral sensitivity function is shown in Fig. (5-6). The piece-wise defined spectral sensitivity function \(S(\lambda)\) is defined as:
\[ S(\lambda) = \begin{cases} 3.95 \times 10^{-19} \lambda - 1.19 \times 10^{-16} & 400 \leq \lambda \leq 460\text{nm} \\ 4.01 \times 10^{-18} \lambda - 1.78 \times 10^{-15} & 460 \leq \lambda \leq 520\text{nm} \\ -3.41 \times 10^{-19} \lambda + 4.81 \times 10^{-16} & 520 \leq \lambda \leq 640\text{nm} \\ -5.71 \times 10^{-19} \lambda + 6.28 \times 10^{-16} & 640 \leq \lambda \leq 900\text{nm} \end{cases} \] (5-11)

Figure 5-6: Plot of the effective spectral sensitivity where the symbols correspond to the extracted sensitivity for 460, 520, and 640 nm. The solid line corresponds to the interpolated spectral sensitivity function and the shaded area indicates the usable wavelength range as 400 to 900 nm in our spectral extraction.

5.11 LED Operation Considerations

Due to the high intensity UV LED source used in this study [9], [10], it is essential that we operate the LED at an operating point low enough to avoid saturating the image sensor, but also at an operating point high enough so an excitation signal is obtainable. We estimate the LED/sample irradiance reaching the image sensor as:

\[ I_{\text{sample}} = k \frac{P_{\text{window}} RG(\sigma N l)}{4\pi r^2} \quad \text{(photons/sec/m²)} \] (5-12)

where \( P_{\text{window}} \) is the optical power incident on the window from the LED, \( R \) is the reflectance of the mirror, \( G \) is the grating efficiency, and the term \( \sigma N l \) is the fluorescence probability computed from the absorption cross section and density of a sample with a path length \( l \). The term in the denominator approximates the emission of a sample at the window as spherical with intensity fall-off proportional to the inverse of the distance squared. We omit the functional dependence on wavelength and angle for simplicity. The \( k \) term is the conversion from optical power to the number of photons per second derived from the Planck relation [11]:
\[ k = 5.34 \times 10^{15} \lambda \text{(nm)} \quad \text{(photons/sec/Watt)} \quad (5-13) \]

By approximating the LED as a Lambertian emitter [9], [10] and ignoring any reflection from the silicon sidewalls that may otherwise distort the emission angles, the optical power \( P_{\text{window}} \) reaching the window from the LED can be written to first order as:

\[ P_{\text{window}} = \int_{\phi_{\text{min}}}^{\phi_{\text{max}}} \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} P_o(\lambda_i) \frac{\cos \theta \sin \theta d \theta d \phi}{\pi} \]

where \( P_o(\lambda_i) \) is the optical power output of the LED at the peak wavelength \( \lambda_i \), and the integral bounds are over the maximum and minimum angles between the LED and the optical window. We use the prior collimator results for the zenith angle 48 \( \leq \theta \leq 60 \) degrees, and estimate the azimuthal angles for our geometry to be no greater than \( \pm 45 \) degrees or \( -45 \leq \phi \leq 45 \) degrees. Computing the above integral yields \( P_{\text{window}} = 0.05 P_o(\lambda_i) \).

If we approximate reasonable values for the mirror reflectivity of 0.9, a grating efficiency of 0.3, and a distance from window to image sensor of 3 mm, we get an expression for the operation range as a function of the LED power and the probability of the sample fluorescence:

\[ 4 \times 10^{16} \leq 1.3 \times 10^{20} P_o(\sigma N \lambda) \leq 2 \times 10^{17} \quad \text{(photons/sec/m}^2) \quad (5-15) \]

In order to keep the microspectrometer device within the bounds given by the above expression, the product of the LED power and sample fluorescence probability should have a minimum of \( 10^{-4} \) for a detectable signal and at a maximum of \( 10^{-3} \) to avoid saturating the sensor.

### 5.12 Box Approximation of Unknown Reflectance/Emission Spectra

With the microspectrometer spectral response mapped, we are now in a position to determine the spectral function \( I(\lambda) \) of unknown samples. In a similar fashion to the RGB sensor, we adopt a multi-box function to represent \( I(\lambda) \) as a weighted response of pre-defined spectral bands. It will suffice to demonstrate 5 channels as:

\[ I(\lambda) = \sum_{j=1}^{5} I_j \text{Box}_j(\lambda) \quad (5-16) \]

where the coefficients \( I_j \) are the heights or the weighted response of the box functions over their respective spectral bands. Inserting the box function expression for \( I(\lambda) \) into our sensor model it can be shown:
\[ D_{i,j} = \sum_{i} S'_{i}(\lambda_{i}) \exp \left( \frac{-(x-x_{i}(\lambda_{i}))^2}{2\sigma^2} \right) \sum_{j=1}^{5} I_{j} \]  
(5-17)

The above expression represents a matrix in condensed form. Each matrix element becomes the summation of the sampled effective spectral sensitivity values over the wavelength ranges \( \Delta \lambda_{j} \) used to define the box functions. We define our spectral boundaries over the 400 to 900 nm at roughly equal intervals in order to ensure a stable solution. The numerical values for the spectral bands are hence defined as:

\[
\begin{align*}
\Delta \lambda_{1} &= [400, 530] \\
\Delta \lambda_{2} &= [530, 610] \\
\Delta \lambda_{3} &= [610, 710] \\
\Delta \lambda_{4} &= [710, 810] \\
\Delta \lambda_{5} &= [810, 900]
\end{align*}
\]  
(5-18)

Once the spectral bands are defined the solution for the coefficients \( I_{j} \) will be unique. One computes the \( I_{j} \) values in Eq. (3-17) by simple matrix inversion (i.e. \( CX = a \rightarrow C^{-1}a = x \)) or by numerical iteration methods. The matrix \( C \) used for the spectral extraction is:

\[
C = \begin{bmatrix}
3.60 & 1.66 & 0 & 0 & 0 \\
2.17 & 4.06 & 1.11 & 0 & 0 \\
0 & 0.97 & 4.65 & 0.79 & 0 \\
0 & 0 & 0.69 & 2.88 & 0.60 \\
0 & 0 & 0 & 0.52 & 2.18 \\
\end{bmatrix} \times 10^{-15}
\]  
(5-19)

where a \( 1 \times 10^{-15} \) in digital units/photon has been factored out for clarity.

### 5.13 Design Curves

By inspection and solution of the matrix equation given by Eq. (5-17) for different characteristic spreads we are able to estimate the channels \( N \) for a given design by the following:

\[
N = \frac{\Delta x}{2\sigma}
\]  
(5-20)

where \( \Delta x \) is the dispersion width in pixels and \( \sigma \) is the characteristic spread in pixels. Design curves for the number of possible channels as function of the characteristic spread for various dispersion widths is shown as Fig. (5-7).
5.14 Demonstration of Spectral Identification

Our demonstration of the microspectrometer is to distinguish the spectral emission of inorganic phosphor powders. Phosphor samples with a characteristic color emission of red, yellow, and green were donated by Phosphor Technology Ltd. [12]. They carry the product designation FL63/S-D1 (red), QUMK58/F-D1 (yellow), and HPL63/F-F1 (green) and consist of Ca5:Eu, (Y,Gd)3Al5O12:Ce, SrGa2S4:Eu in powder form, respectively [13]-[15]. Samples were prepared by affixing the phosphor powder to a piece of Scotch Tape\textsuperscript{TM} and the photoluminescence spectra under UV LED excitation independently measured by our monochromator setup. The emission peaks were found to be 650, 600, and 550 nm for the red, yellow, and green phosphor samples, respectively (Fig. 5-8).
Samples were then placed on the window and the UV LED was driven appropriately to yield an optical output of 5 mW to 95 mW. The image sensor is used to capture the sample emission as an image file. In addition, the signal from the UV LED in the absence of a sample is captured at each power step; this is used to determine the relative change in spectra for our samples. All measurements are conducted with ambient lights off. Post-image processing is done by extracting the pixel values corresponding to the calibrated wavelength positions. With our prior knowledge of the system response, we solve the system of equations in Eq. (5-17) by numerical iteration for the box function heights $I_j$ at each power step. Since prior knowledge of the sample emission and LED power product is not known, we plot the extracted box function heights as a function of the UV LED power to ensure we are operating the device in the linear regime without saturation (Fig. 5-9).

Figure 5-8: Measured photoluminescence spectra for the a) red (CaS:Eu) [13], b) yellow ((Y,Gd)₃Al₅O₁₂:Ce) [14], and c) green (SrGa₂S₄:Eu) [15] phosphors used in this study. Spectra are normalized by total signal and scaled. The emission peaks are 650, 600, and 550 nm, respectively.
Figure 5-9: Extracted box spectra heights for the a) red, b) yellow, and c) green phosphor samples as a function of the UV LED optical power; d) extracted box spectra heights with no sample. The response is approximately linear for 40-100 mW UV LED optical power, indicating we are operating in the linear regime for the microspectrometer. Below 40 mW optical power, we have a non-linear response due to the current-voltage characteristic of the UV LED.

We observe an approximate linear response when the UV LED output is between 40 to 100 mW. Below 40 mW the response is non-linear due to the current-voltage characteristic. With confirmation that we are operating the microspectrometer in the linear regime, we compute the relative spectral change by subtracting the UV-only spectra from the phosphor sample spectra at a UV LED output of 95 mW. The box functions are shown as Fig. (5-10). For comparison, we also normalize our extracted spectra by the total signal (Fig. 5-11).
Figure 5-10: Extracted box spectra in terms of the relative change from the UV LED spectra at 95 mW optical power for the red, yellow, and green phosphor samples on Scotch Tape\textsuperscript{TM} [12]-[15].

Figure 5-11: Plots of the extracted a) red, b) yellow, and c) green phosphor box spectra normalized by the total signal [12]-[15].
From Fig. (5-11) we make some general observations. For the red phosphor we observe a peak at the 610-710 nm spectral band. For the yellow phosphor, a broader emission is found to be over the 530-610 nm and 610-710 nm spectral bands. For the green phosphor, a peak is observed at the 530-610 nm spectral band. The peaked band position corresponds to the independently measured photoluminescence spectra shown in Fig. 5-8. However, in all three cases, the extracted spectra are broader than the original spectra and show some distortion. Inspection of the inverse matrix $C^{-1}$ used for the spectral extraction reveals the cause of the spectral broadening and distortion:

$$
C^{-1} = \begin{bmatrix}
0.38 & -0.16 & 0.04 & 0.01 & 0 \\
-0.21 & 0.35 & -0.09 & 0.03 & -0.01 \\
0.05 & -0.08 & 0.24 & -0.07 & 0.02 \\
-0.01 & 0.02 & -0.06 & 0.38 & -0.11 \\
0 & 0 & 0.01 & -0.09 & 0.48 \\
\end{bmatrix} \cdot 10^{-15}
$$

(5-21)

where a $1 \times 10^{-15}$ in digital units/photon has been factored out for clarity. Here we can see that the underlying cause of this distortion is the unequal channel weighting (diagonal matrix terms) due to the spectral sensitivity function (Eq. 5-10) and also the nearest neighbor channel interactions (off-diagonal matrix terms). There is little to no effect (1-5%) from the far channels. Physically, these interactions come from the overlap of pixel responses. Despite this effect, the five-channel approach is still able to distinguish differences between the three phosphor samples.

In case of a perfectly uniform spectral input stimulus, more weight will be placed on the 710-810 nm and 810-900 nm spectral bands, leading to an artificially high signal. Given this, one should use caution when interpreting results derived using this approach. To alleviate this issue, one can optimize the truncation of the matrix (e.g. adjustment of the spectral bands) to give a more regular, diagonal matrix without sacrificing solution stability. As an example, we manually re-define our spectral boundaries as to give a more regular matrix:

$$
\Delta \lambda_1 = [470, 550] \\
\Delta \lambda_2 = [550, 630] \\
\Delta \lambda_3 = [630, 690] \\
\Delta \lambda_4 = [690, 790] \\
\Delta \lambda_5 = [790, 880]
$$

(5-22)

The new inverse matrix $C^{-1}$ used for the spectral extraction is:
\[
C^{-1} = \begin{bmatrix}
0.43 & -0.28 & 0.15 & -0.05 & 0.01 \\
-0.30 & 0.57 & -0.35 & 0.13 & -0.01 \\
0.15 & -0.33 & 0.60 & -0.26 & 0.03 \\
-0.05 & 0.11 & -0.24 & 0.38 & -0.04 \\
0 & -0.01 & 0.02 & -0.04 & 0.30
\end{bmatrix} \cdot 10^{-15} 
\]  

where a $1 \times 10^{-15}$ in digital units/photon has been factored out for clarity. Using the re-defined spectral bounds we extract the box spectra of the three phosphor samples (Fig. 5-12). Comparison of Fig. (5-11) and Fig. (5-12) shows that the manual adjustment of the spectral boundaries has improved the asymmetry of the original extracted box spectra and made the characteristic peaks sharper. Future work could involve investigating algorithms to optimize the extraction matrix and/or extending the number of channels to larger than 5 with tighter collimator designs.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5-12.jpg}
\caption{Plots of the extracted a) red, b) yellow, and c) green phosphor box spectra using the modified spectral boundaries. Plots are normalized by the total signal.}
\end{figure}
5.15 Summary

We modified the original microspectrometer prototype presented in Chapter 4 with a 1200 line/mm diffraction grating and a 5 um pixel array image sensor for increased resolution. These modifications have enabled us to achieve an improved microspectrometer with 5 channel sensing capability with a spectral range 400-900 nm. Following appropriate calibration procedure; red, yellow and green phosphor powders were used to evaluate the ability of the prototype to conduct spectral identification. The prototype was able to distinguish differences between these phosphor samples and identify characteristic peaks. This result has demonstrated the feasibility of a fully integrated multi-wavelength optical sensor platform with a photon engine.

5.16 References

6 Conclusion

6.1 Dissertation Summary

Recent advances in the laser lift-off (LLO) technique (Fig. 1-1) has resulted in a new genre of optical sources such as ultra-bright LEDs and laser diodes to be mass produced with a form factor of 1 mm sq. and 100 um thick [1]-[4]. Coupled with silicon thinning technologies, multi-chip modules, grid arrays and flip chip technology for 3D integration [5], [6], we envision new architectures with heterogeneous integration of III-V photonics with Si CMOS for a ubiquitous optical microsystem platform [7].

In this dissertation, we have utilized these state-of-the-art ultra-bright LEDs and leveraged a hybrid integration approach to develop miniaturized optical microsystems with various sensing functions. Three specific test vehicles were developed and presented in order of increasing functionality: 1) an interferometry-based sensor cell, 2) an RGB colorimetry cell, and 3) a spectroscopy cell. A schematic overview of various microsystems explored in this work is shown in Fig. (6-1).

**Figure 6-1:** Schematic overview of the anatomy of the ubiquitous optical microsystem platform explored in this dissertation. With appropriate design and hybrid integration of monolithic paper-thin components, one can implement several variations on the optical platform for specific applications such as: a) interferometry, b) RGB colorimetry, and c) spectroscopy with choices for the photo excitation engine.
In Chapter 2, we introduced the concept of the zero-footprint optical metrology wafer based on an interferometric sensor cell for in-situ, real-time process monitoring and study. The interferometry sensor cell relies on the reflected intensity from the embedded LED from which important parameters such as film thickness, refractive index and density can be deduced. To ensure accurate and precise measurement, a framework for modeling the reflectance functions for a wide variety of experimental conditions was presented. In addition, a measurement methodology was presented.

A prototype wafer with 3x3 sensor cells was successfully fabricated and the sensor cells tested in various hostile environments. Reflectance measurements with different refractive index films showed the linear operation and validity of the methodology. Application of the optical metrology wafer for different hostile environments was demonstrated with a plasma etching of silicon oxide, CMP slurry particle size monitoring, photoresist cure and dissolution, copper end-point etch detection and also nanopore wetting phenomena.

In Chapter 3, we discussed research efforts on expanding the optical sensor platform to include multi-wavelength sensing with an off-the-shelf commercial RGB sensor. After modification of the RGB sensor board with a HB LED we were able to establish a method for extracting the absolute intensity of three defined spectral bands from the RGB triplet values. With this method, we were able to demonstrate and quantify the in-situ reflectance/emission spectra from wet etches of copper and aluminum films.

In Chapter 4, we described the development of a fully-integrated microspectrometer with a photon engine. The microspectrometer is realized using standard planar microfabrication techniques and bulk silicon micromachining for three-dimensional geometries. The final device measures < 1 mm thick with an active area of 2 mm x 3 mm and was designed to operate in the visible wavelength region (400-700 nm). Optical and electrical characterization of the microspectrometer was carried out and was shown to exhibit dispersion of wavelengths 460, 520, and 640 nm across the photodiode array. The effective spectral resolution was found to be 120 nm, resulting at best, a 2 or 3 channel device.

In Chapter 5, we described the subsequent modification of the microspectrometer prototype presented in Chapter 4 with a grating of increased line density and an image sensor array with 5 μm pixels for increased resolution. The result was a microspectrometer with 5 channels that can operate in the 400-900 nm wavelength range. With the improved device, we demonstrated the spectral identification capability with red, yellow, and green phosphor powder samples with different characteristic peaks and spreads. The improved prototype microspectrometer was able to distinguish the differences between samples and identify characteristic peaks.
6.2 Future Research Directions

This dissertation has explored the design, fabrication and testing of three different optical sensor platforms for various applications. There are clearly many other sensor types that can be built and many more applications that can benefit from a chip-size optical sensor platform. Several areas of investigation remain for future work:

1) In this work, we explored two probe wavelengths with LEDs: 360 nm and 460 nm. There exists many additional options for the probing wavelength that span the visible wavelength range for LEDs and also laser diodes. One could also make use of phosphors for broadband sources to enable absorption spectroscopy. In addition, intensity modulation techniques and time-domain methods remain another area that can be explored.

2) Here, we demonstrated wavelength demultiplexing using filters and gratings. There are undoubtedly many other options that may be suitable for a particular application. One option could be polarization sensitive sensors to determine the s- and p-components of light from a sample [8], [9]. Another option could utilize the Talbot effect to enable angle and wavelength sensitive pixels in a smaller form factor [10], [11].

3) One may also wish to explore different window geometries or structures such as zero mode waveguides to enhance the signal over the background [12].

4) As our understanding and leverage of MEMS-based technology improves, this would also be another area to explore and may enable more dense optical microsystems with improved function.

While this research focused only on the optical sensor cell as a chip-based concept or a wafer-based array. There is much work to be done on the wireless communication, internal power source, and testing of the environmental limits and isolation schemes to drive this concept to wide-spread industrial and commercial use. It is hoped that with some more research and development, that these optical sensor platforms will become ubiquitous.
6.3 References


