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Thinned, Back-Illuminated CCDs for X-ray Microscopy

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Thinned, Back Illuminated CCDs for X-Ray Microscopy

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1 Introduction

The selection of an image detection system for x-ray microscopy is oriented at the following criteria:

- high sensitivity combined with low system noise
- high dynamic range
- good linearity and known quantum efficiency (for radiometric measurements)
- spatial resolution and image field matched to a given x-ray microscope
- radiation hardness
- practicability (e.g. on-line data acquisition, display and processing)

Thinned, back illuminated CCD cameras promise to meet most of these requirements. We installed such a CCD camera at the Göttingen x-ray microscope, which is operating at the electron storage ring BESSY in Berlin [1]. From the first results we concluded that this thinned, back illuminated CCD seems to be an ideal detector for x-ray microscopy [2]. Subsequently we installed a similar system at the Göttingen x-ray microscope, which uses a pulsed plasma source [3,7].

2 The CCD Camera System

The CCD camera is a commercially build camera that has been mechanically adapted to the x-ray microscope. Normally the CCD sensor is covered with an antireflective coating. This coating was omitted from the CCDs used for x-ray microscopy. The CCD camera system consists of the following parts:
• Photometrics slow scan CCD camera AT200L  
  Readout 16Bit ADC, 40kHz  
  Peltier cooling to −45°C
• Tektronix TK1024AB thinned, back illuminated CCD chip  
  1024 x 1024 pixel, each 24μm x 24μm  
  full well capacity ≈ 5 · 10^6 e−, limited to S_{max} ≈ 4 · 10^6 e− by ADC
• Host computer (80486) for camera controlling and data acquisition

The slow scan readout reduces the readout noise to a few electrons at the cost of an increased data acquisition time (≈ 26s for 1024² Pixel). Cooling the CCD chip reduces the dark current.

3 Characterization of the CCD Camera

3.1 Quantum Yield

We measured the quantum yield of the CCD camera system, defined as the ratio of detected quanta (here: electrons stored in the potential well) per incident quanta (x-ray photons) using the SX-700 radiometric beamline of the PTB-lab at BESSY [4] in the photon energy range from 60eV – 800eV. Fig. 1a represents the data.

![Fig.1a: Quantum yield of the thinned, back illuminated CCD. At λ = 2.4nm, the value for the QY is 90e−/photon](image1)

![Fig.1b: Quantum efficiency of the thinned, back illuminated CCD. The Si_{L_{II}}-edge and the N_{K}-edge can easily be seen.](image2)

A linear function of the quantum yield can be observed, interrupted at the Si_{L_{II}}-absorption edge at 99eV and at the N_{K}-edge at 400eV. The quantum yield is
90\text{e}^-/\text{photon} at 2.4nm(517eV), the wavelength the Göttingen x-ray microscopes are working with. The average energy necessary for creating an electron-hole pair is 3.7eV [5]. The average number of electrons per photon detected in an ideal detector is therefore $n_{\text{max}} = \frac{h \cdot \nu}{3.7eV}$. It is now useful to define an energy related quantum efficiency as the number of detected electrons per incident photon $n_d$ divided by the maximum number $n_{\text{max}}$:

$$QE = \frac{n_d}{n_{\text{max}}} = \frac{n_d \cdot 3.7eV}{h \cdot \nu}$$

Fig. 1b shows the results for the quantum efficiency $QE$ of the CCD as a function of the photon energy $h \cdot \nu$ in the range from 60eV to 800eV. In this energy range, the $QE$ is between 0.56 and 0.72. The accuracy of the measurement is $\approx 10\%$, determined mainly by the stability of the low intensity photon beam used for our measurements.

### 3.2 Readout Noise and Dark Current Noise

The readout noise of the CCD can be measured by acquiring a dark image with exposure time 0s. When the exposure time of the dark image is increased to finite values, the CCD collects electrons thermally created by the dark current, giving an exposure time dependent contribution to the total signal and also to the total system noise of the CCD camera. The average dark signal itself can be measured and subtracted from the image data in order to obtain only the photon induced signal. The dark current is a function of the temperature. At $-45^\circ C$ the dark current was found to be $2.9e^-/(\text{pixel} \cdot \text{s})$. Fig. 2 represents the system noise without irradiation as a function of exposure time. For integration times less than 30s, the readout noise of 10e$^-$ dominates the total noise of the CCD camera. The signal generated by one photon of 517eV is also indicated in fig. 2, showing that for exposure times up to 250s the camera noise is less than the signal from one photon. Exposure times in the Göttingen x-ray microscope are a few seconds, so that the camera noise can be neglected in this application.

### 3.3 Linearity and Dynamic Range

The linearity was measured at $\lambda = 2.4nm$ (517eV); the CCD camera was used in its standard configuration in the x-ray microscope at BESSY without specimen. Fig. 3 shows the quantum yield as a function of the exposure in photons/pixel. Exposures were varied using a shutter and attenuation filters. The absolute value was taken from the measurements at the SX-700. The accuracy of the measurement is 2%, given by the slight move of the BESSY source during the measurements. From the plot the CCD response is linear within these limits until the ADC comes to saturation at an exposure of $\approx 4400\text{photons/pixel}$. At very low exposures, the stochastic character of the photon absorption leads to an increased deviation from the mean.
According to the high quantum yield of the CCD it is convenient to define the dynamic range as the maximum detectable number of x-ray photons:

\[ DR_{\text{photon}} = \frac{S_{\text{max}}}{QY} = \frac{4 \cdot 10^5 e^-}{90 e^-} = 4.4 \cdot 10^3 \quad (\lambda = 2.4 \text{nm}) \]

This is a good value for a dynamic range.

![Graph 1: Camera Noise vs. Integration Time](image1)

![Graph 2: Quantum Yield vs. Exposure](image2)

**Fig. 2:** CCD system noise without irradiation at \( T = -45^\circ C \).

**Fig. 3:** Linearity of the thinned, back illuminated CCD at \( \lambda = 2.4 \text{nm} \).

### 3.4 Radiation Damage

The effect of radiation damage can be observed as an increased dark current (and slightly decreased full well capacity). After \( \approx 2400 \) x-ray microscope images and nearly the same amount of test images taken with the CCD operating at BESSY (the total number of absorbed x-ray photons in the CCD up to now is \( \approx 10^{12} \)), the dark current was found to be

- \( I_{\text{du}} = 2.9 e^-/(\text{pixel} \cdot s) \) unexposed pixels (chip corner)
- \( I_{\text{de}} = 4.0 e^-/(\text{pixel} \cdot s) \) after 2400 x-ray exposures (central region)

No influence of the radiation damage on the x-ray microscope images could be observed, and even if the dark noise increases further with the same rate, the CCD will be usable without a remarkable effect on the image quality for several years.

### 4 Conclusions

The thinned, back illuminated CCD chip in combination with a cooled slow scan CCD camera seems to be the best suited image detector for x-ray microscopy with soft x-radiation available today. It offers high sensitivity, the possibility of making
radiometric measurements and the advantages of digital detection systems like on-line image acquisition, display and processing. Especially the investigation of wet biological specimen in the Göttingen x-ray microscope at BESSY [6] benefits from the advantages of the thinned, back illuminated CCD. With the Göttingen x-ray microscope with the pulsed plasma source, images exposed with only one pulse are now possible [7].

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