Title
Graphene-Base Hot-Electron Transistor

Permalink
https://escholarship.org/uc/item/01t9w07g

Author
Zeng, Caifu

Publication Date
2014

Peer reviewed|Thesis/dissertation
A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Electrical Engineering

by

Caifu Zeng

2014
The exceptional properties of the two-dimensional material, graphene, having high-mobility carriers, deployable on a large area have made it attractive for RF electronic applications. However, the channel mobility in graphene-channel field effect transistors (GFET) is still limited by various external scattering sources and the absence of a bandgap in graphene causes poor current on-off ratio and unsatisfying current saturation in GFETs. Graphene-base hot-electron transistor (GB-HET) uses the single-atomic thick, semi-metallic graphene as the base region of the hot-electron transistor. It provides an alternative way to utilize the unique properties of graphene and solve some problems of the GFETs based on a different operational principle. This dissertation focuses the operational principle, fabrication and characterization of several types of GB-HETs. Current saturation with high current on-off ratio are observed in the current-voltage characteristics of GB-HETs. The influence of the tunnel barrier, filter barrier and emitter/collector area ratio on
the common-base current gain of GB-HET are investigated. The current gain is improved by more than two orders of magnitude by optimizing these device parameters. The results suggest that the quality and choice of the materials are key elements for the implementation of GB-HETs into practical applications. In addition, theoretical studies show that phonon scattering in the dielectrics and reflections at the interfaces may reduce the energy of the hot electrons and suppress the transmission probability, and thus limit the maximum current gain of GB-HETs. Developing mature process, accurate physical models, involving new materials and experiment methods, as well as having a better fundamental understanding of the electron transport in the direction perpendicular to the graphene sheet, are highly desirable to reveal the ultimate performance of GB-HETs for high-speed electronics.
The dissertation of Caifu Zeng is approved.

Robert N. Candler

Ya-Hong Xie

Kang L. Wang, Committee Chair

University of California, Los Angeles

2014
Dedicated to my parents and my wife

for their love and support.
TABLE OF CONTENTS

Chapter 1 Introduction ........................................................................................................ 1

1-1. The Rise of Graphene .................................................................................................. 1

1-2. Electronic Properties of Graphene ............................................................................ 2

1-3. Graphene-Channel Field-Effect-Transistor (GFET) .................................................. 5

1-4. Hot-Electron Transistor (HET) .................................................................................. 8

1-4-1. Operational Principle of HET ............................................................................... 8

1-4-2. A Brief History of HET .......................................................................................... 11

1-5. Synopsis ...................................................................................................................... 15

Chapter 2 GB-HET with Schottky-Barrier as the Filter Barrier ............................. 17

2-1. Introduction: Graphene-Base Hot-Electron Transistor ........................................... 17

2-2. Fabrication of GB-HET1 .......................................................................................... 19

2-2-1. Device Structure ................................................................................................... 20

2-2-2. Making Graphene Visible on Si ............................................................................. 20

2-2-3. Process flow .......................................................................................................... 24

2-3. Electrical Characteristics of GB-HET1 ................................................................. 29

2-3-1. Characterization of the Graphene-Silicon Schottky Contact ................................ 29

2-3-2. I-V Characteristics of GB-HET1 ......................................................................... 32
Chapter 3 GB-HET with High-k Dielectric as the Filter Barrier 

3-1. Device Structure of GB-HET2

3-2. Process flow of GB-HET2

3-3. Electrical Characteristics of GB-HET2

3-3-1. Input I-V Characteristics of GB-HET2

3-3-2. Transfer I-V Characteristics of GB-HET2

3-4. Device Structure of GB-HET3

3-5. Electrical Characteristics of GB-HET3

3-5-1. Input Characteristics of GB-HET3

3-5-2. Transfer Characteristics of GB-HET3

3-5-3. Output Characteristics of GB-HET3

3-5-4. Current Gain of GB-HET3

3-6. Summary

Chapter 4 Optimization of the Device Parameters

4-1. Optimization of the Tunnel Barrier

4-2. Optimization of the Filter Barrier

4-3. Scattering and Reflection Mechanisms in the Dielectrics
4-4. Optimization of the Device Geometry ................................................................. 75

4-5. Summary .............................................................................................................. 77

Chapter 5 Conclusion and Future Works .............................................................. 79

5-1. Conclusion ........................................................................................................... 79

5-2. Suggested Future Works ..................................................................................... 81

References ................................................................................................................. 83
LISTS OF FIGURES

Figure 1-1. Carbon electronic materials in different dimensions ............................................................. 2
Figure 1-2. Schematic band structure of graphene ...................................................................................... 4
Figure 1-3. (a) SEM image of a graphene field-effect transistor (GFET). (b) Ambipolar field-effect behavior of a GFET. ....................................................................................................................... 6
Figure 1-4. Typical output I-V characteristics of a GFET. .......................................................................... 6
Figure 1-5. Energy band diagram of a hot-electron transistor (HET) with a bias applied to the emitter and the collector .................................................................................................................................. 8
Figure 1-6. Energy band diagram of the first HET proposed by Mead ....................................................... 11
Figure 1-7. Energy band diagram for Shannon’s camel HET ................................................................. 12
Figure 1-8. Energy band diagram of the heterojunction HET ................................................................. 13
Figure 2-1. Energy band diagram of a graphene-base hot-electron transistor (GB-HET)......................... 17
Figure 2-2. Schematic device structure of GB-HET1 ............................................................................. 19
Figure 2-3. Optical images of graphene on SOI with different wavelengths of illumination ....... 20
Figure 2-4. (a) Raman spectroscopy of single layer graphene on the SOI substrate and the 300 nm SiO₂ control substrate. (b) Raman spectroscopy of bilayer graphene on silicon substrate .......... 22
Figure 2-5. Schematic process flow of GB-HET1 .................................................................................... 27
Figure 2-6. Optical microscopy image of GB-HET1 ............................................................................... 28
Figure 2-7. Schematic of the experimental setup for measuring GB-HET1 .............................................. 29
Figure 2-8. I-V characteristics of the graphene-Si Schottky barrier at various temperatures ...... 29
Figure 2-9. Plot of \( \ln(I_{\text{sat}} / T^2) \) vs. \( 1 / T \) for extracting the Schottky barrier height .......... 30
Figure 2-10. Schematic of the common-base experimental setup for measuring the I-V characteristics of GB-HET1................................................................................................................................. 31

Figure 2-11. Transfer I-V characteristics (I_C vs. V_BE) at various V_CB for GB-HET1 in the (a) linear scale and (b) logarithmic scale......................................................................................................................................... 32

Figure 2-12. Energy band diagram of the GB-HET1 in the (a) off-state and (b) on-state............. 33

Figure 2-13. (a) Output characteristics (I_C vs. V_CB) at various V_BE for GB-HET1. (b) Energy band diagram of GB-HET1 under different V_CB .......................................................................................................................................... 34

Figure 2-14. The common-base current gain, \( \alpha \), as a function of V_BE for GB-HET1. .............. 36

Figure 2-15. Energy band diagram of GB-HET1 with undesirable current channels .......... 37

Figure 3-1. Schematic diagram of GB-HET2 ............................................................................... 41

Figure 3-2. Schematic diagram of the process flow to fabricate GB-HET2................................. 43

Figure 3-3. Optical microscope image of the completed device GB-HET2................................. 44

Figure 3-4. Schematic diagram of the common-base configuration for the electrical characterization of GB-HET2............................................................................................................................ 45

Figure 3-5. Input characteristics (I_E vs. V_BE at various V_CB) for GB-HET2 ......................... 46

Figure 3-6. Transfer characteristics (I_C vs. V_BE at various V_CB) for GB-HET2 ..................... 48

Figure 3-7. Input and transfer characteristics when a large V_BE is applied ............................... 49

Figure 3-8. (a) Schematic device structure of GB-HET3. (b) Optical microscope image of GB-HET3 .................................................................................................................................................... 50

Figure 3-9. (a) Input characteristics of GB-HET2 at various V_CB. (b) Fowler-Nordheim plot of the emitter current............................................................................................................................ 52

Figure 3-10. Input and transfer characteristics of GB-HET3 .................................................... 53

Figure 3-11. Energy band diagram of GB-HET3 ................................................................. 54
Figure 3-12. (a) Output characteristics of GB-HET3 at various $V_{BE}$. (b) Transfer characteristics of GB-HET3 at various $V_{CB}$.............................................................................................................. 55

Figure 3-13. Energy band diagram of GB-HET3 under different $V_{CB}$ biases ....................... 56

Figure 3-14. The current gain $\alpha$ as a function of $V_{BE}$ in the on-state of GB-HET3............. 57

Figure 4-1. Schematic diagram of the GB-HET4 .................................................................. 60

Figure 4-2. (a) Input I-V characteristics of GB-HET4 at different $V_{CB}$ biases. (b) Fowler-Nordheim plot of the tunneling current through the 25 nm SiO$_2$ tunnel barrier ................................................. 61

Figure 4-3. Transfer I-V characteristics of GB-HET4 at various $V_{CB}$ biases...................... 62

Figure 4-4. $I_C$ and $I_E$ as a function of $V_{BE}$ from 13 V to 20 V for GB-HET4...................... 63

Figure 4-5. $I_C$ and $I_E$ as a function of $V_{BE}$ from 13 V to 20 V for GB-HET5...................... 64

Figure 4-6. Schematic energy band diagrams to illustrate the different filter barrier heights between GB-HET4 and GB-HET5 .................................................................................................. 66

Figure 4-7. Major scattering and reflection mechanisms in GB-HETs ........................................ 67

Figure 4-8. Electron energy distributions at different electric-field obtained from the vacuum emission experiment ..................................................................................................................... 68

Figure 4-9. (a) Schematic energy band diagram of the BEEM experiments. (b) Collector current and transmission probability through SiO$_2$ as a function of the tip bias $V_T$ ............... 71

Figure 4-10. (a) Schematic device structure for GB-HET3-5. (b) Improved structure (GB-HET6) with current confinement .......................................................................................................................... 72

Figure 4-11. (a) Input and transfer I-V characteristics for GB-HET6. (b) The current gain of GB-HET6 after subtracting the base-collector leakage current from the collector current.......... 73
ACKNOWLEDGEMENT

I would like to express my sincere appreciation to Professor Kang L. Wang for his guidance and support throughout the period of this research in UCLA. I have learnt a lot form his vast knowledge, experience and profession.

I also wish to thank Professor Robert Candler, Professor Oscar Stafsudd, and Professor Ya-Hong Xie for their valuable suggestions and helpful insights, and spending their precious time serving in my committee.

As a member of DRL (Device Research Lab), I am honored to work with the talented and hard-working people. I would like to thank all my colleagues for all the long hours we spent in clean room together, for all the late nights stuck with the experiments, for all the sparks from the discussions, and for all the fun we have together in the group events.

Finally, there are no words in the world to express my deepest gratitude to my parents and my wife. Their unlimited love, sacrifice, understanding, support and encouragement guided my life over the years.

VITA

Education

2007-2009  M.S., Electrical Engineering
University of California, Los Angeles, United States

2003-2007  B.S., Electronic Science and Technology
Zhejiang University, Hangzhou, China

Publications

- Journal (*co-first author)


Conference

“In Direct measurement of Dirac point and Fermi level at graphene/oxide interface by internal
Huffaker, D. “High Mobility p-Channel AlSb/InGaSb HFETs Grown on GaAs Substrates with

Patent

M.; Si, R.; Zhang, J. “An ESD protection part for enlarging valid pass area of static current”, China
Chapter 1

Introduction

1-1. The Rise of Graphene

Carbon atoms are able to form a variety of structures with different physical properties because of the flexibility of carbon bonding. Graphene is one of the most interesting members in the carbon family. It consists of a single layer of carbon atoms densely packed in a honeycomb lattice and can be thought of as the source for all other carbon allotropes such as graphite, carbon nanotubes, and fullerenes. (Figure 1-1)

Although graphene is relatively easy to produce by simply writing with a pencil, it is not so easy to find with the naked eye; therefore, it was not discovered until 2004 via a clever approach utilizing its optical contrast with respect to its underlying substrate [1]. Since then, graphene has prompted much excitement and activities in both experimental and theoretical physics communities because of its fascinating novel physical phenomena deriving from the unique energy band structure of this two-dimensional system.
Figure 1-1. Graphene (top) is a honeycomb lattice of carbon atoms. Fullerenes (C60) are molecules consisting of wrapped graphene by the introduction of pentagons on the hexagonal lattice. Carbon nanotubes are rolled-up cylinders of graphene (middle). Graphite (right) can be viewed as a stack of graphene layers held together by van der Waals forces between each of the layers. [2]

1-2. Electronic Properties of Graphene

In graphene, there are four valence electrons in each carbon atom; one from the s-orbital and the other three from the p-orbitals. Three of these valence electrons form an sp2 hybridization, resulting in a trigonal planar structure with the existence of three covalent carbon-carbon bonds (σ-bonds). These σ-bonds have a fully filled shell and hence form a deep valence band, which is responsible for the robustness of this two-dimensional structure. The remaining valence electron,
which extends out-of-plane of the graphene, bonds covalently with neighboring carbon atoms and form a π-bond. The half-filled π-bond is responsible for the conduction in graphene. In contrast, a diamond atom has all four valence electrons forming an sp3 hybridization, which creates four σ-bonds and results in an insulator.

The tight-binding approach can be applied to solve the band structure of graphene by considering hopping between the nearest-neighbor carbon atoms and hopping between the next-nearest-neighbor carbon atoms. The Hamiltonian for electrons can be expressed as

\[
H = -t \sum_{\langle i,j \rangle, \sigma} (a_{\sigma,i}^* b_{\sigma,j} + b_{\sigma,i}^* a_{\sigma,j}) - i' \sum_{\langle\langle i,j \rangle\rangle, \sigma} (a_{\sigma,i}^* a_{\sigma,j} + b_{\sigma,i}^* b_{\sigma,j} + a_{\sigma,i}^* a_{\sigma,j} + b_{\sigma,i}^* b_{\sigma,j})
\]

where \( a_{i,\sigma}(a_{i,\sigma}^*) \) annihilates (creates) an electron with spin of \( \sigma \ (\sigma = \uparrow, \downarrow) \) on site \( R_i \) on sub-lattice A (an equivalent definition is used for sub-lattice B), \( t \) is the nearest-neighbor hopping energy, and \( t' \) is the next-nearest-hopping energy [3].
Figure 1-2. Left: Schematic band structure of graphene with finite hopping energy $t = 2.7 \text{ eV}$ (between the nearest neighbors) and $t' = 0.2t$ (between the next nearest neighbors). Right: Zoomed in picture close to one of the Dirac points, which exhibits linear energy dispersion [3].

The energy bands derived numerically from the above Hamiltonian is shown in Figure 1-2. If we take a close look at the energy dispersion near the Dirac points and ignore the hopping between the next nearest atoms ($t' = 0$), the energy band can be approximated as

$$E = v_F q = v_F \hbar k$$

where $q$ is the momentum relative to the Dirac points, $v_F$ is the Fermi velocity, $\hbar$ is the reduced Planck constant. According to the above expression, the energy near the Dirac points shows a linear dependence on the momentum $q$, which is quite different from the usual case of $E = \frac{\hbar^2 k^2}{2m^*}$ as in traditional parabolic dispersion semiconductors like silicon and gallium arsenide. As a result, the effective mass, defined as $\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2E}{dk^2}$, is zero in linear dispersion graphene near the Dirac points in contrast with a constant value in traditional parabolic dispersion semiconductors. The quasi-particles (i.e. electrons in graphene) also have a constant Fermi velocity of approximately $c/300$, where $c$ is the speed of light, independent of energy and momentum. Therefore, the electrons in graphene are called massless Dirac fermions near the Dirac points.

In addition, the $\pi$-band and $\pi^*$-band of graphene meet exactly at the Dirac points. In neutral (e.g. intrinsic) graphene, the Fermi level crosses exactly at the Dirac point; this means that electrons fill the bottom bands up to the cone center leaving the top cone empty at zero temperature; therefore, the bottom cone is treated as a valence band and the top cone is treated as
a conduction band analogous to a semiconductor. Thus, graphene can be treated as a zero bandgap material or a semimetal.

1-3. Graphene-Channel Field-Effect-Transistor (GFET)

Because the density of states near the Dirac point in graphene is low, the carrier concentration can be modulated by the electric-field effect. This allows the conductance of graphene to be tuned when graphene is used as the channel material in field-effect-transistors (FETs) (see Figure 1-3). Graphene is believed to be a superior material for high-speed FETs, (especially RF FETs), since the two-dimensional planar structure of graphene is compatible with the top-down fabrication procedure of silicon technology and its ultra-high mobility. In addition, according to the Klein paradox, an incoming electron starts penetrating through a potential barrier if its height exceeds the electron’s rest energy. The transmission probability for this type of tunneling (Klein tunneling) approaches the perfect transparency for very high barriers. As electrons near the Dirac point of graphene can be treated as massless Dirac fermions, they can penetrate through a potential barrier without back scattering when they travel through the graphene channel [4]. Therefore, the intrinsic carrier mobility in graphene is by far the highest among materials that exhibit FET-like behavior [5]. Mobility as high as ~200,000 cm²/Vs has been observed in the suspended graphene at room temperature [6]. However, the mobility degrades to below 20,000 cm²/Vs when graphene is placed on the SiO₂ substrate, because of the extrinsic scattering from the surface phonons of the underlying SiO₂ substrate [7]. This extrinsic scattering can be reduced by replacing the SiO₂ substrate by a hexagonal boron-nitride (h-BN) substrate. h-BN has an atomically smooth surface that is relatively free of dangling bonds and charge traps,
and the surface optical phonon modes of h-BN have energies two times larger than the similar modes in SiO₂. As a result, the mobility of graphene on h-BN is three times higher than that on SiO₂ [8].

Figure 1-3. (a) Scanning electron microscope (SEM) image of a graphene field-effect transistor (GFET). The underlying substrate is a 300nm SiO₂ thermally grown on top of a highly-doped silicon substrate. The back Si layer serves as a gate electrode. (b) Ambipolar field-effect behavior of the GFET. The increase of conductivity with gate voltage shows that the carrier concentration (proportional to the conductivity) can be modulated. The minimum conductivity point indicates that the Fermi level is at the Dirac point. [9]

GFETs have shown a high cutoff frequency of several hundred gigahertz [10, 11]. However, the output characteristics of many GFETs either show a linear shape without any saturation or only weak saturation, as shown in Figure 1-4. Some GFETs have an unusual saturation behavior that includes a second linear region [12], which is a consequence of GFETs having zero bandgap channels and carrier type switching at the drain end when a high V_DS is applied [13]. The cutoff frequency of a FET can be expressed as
The cutoff frequency can be maximized by increasing the intrinsic transconductance, $g_m$, and decreasing the drain conductance, $g_{ds}$, and all the capacitances and the resistances. All these values vary with the applied DC biases. Saturation of the drain current is essential to reach the maximum possible operating speeds since the cutoff frequency normally peaks deep in the region of drain-current saturation, where $g_m$ is near its peak and $g_{ds}$ has decreased sufficiently [13]. Therefore, the unsatisfying saturation behavior in GFETs has an adverse impact on the cut-off frequency, the intrinsic gain, and other figures of merit and thus limits the maximum possible operating speeds of GFETs.

\[
f_T = \frac{g_m}{2\pi}\left(\frac{1}{C_{GS} + C_{GD}}\right) + \frac{1}{\left[1 + g_{ds}\left(R_S + R_D\right)\right] + C_{GD}g_m\left(R_S + R_D\right)}
\]

Figure 1-4. Typical output I-V characteristics ($I_D$ vs. $V_D$) of a GFET. The drain current shows a linear dependence on the drain voltage. Saturation of the drain current is essential to reach the maximum possible operating speeds as the cutoff frequency normally peaks deep in the region of drain-current saturation, where $g_m$ is near its peak and $g_{ds}$ has decreased sufficiently. The
unsatisfying saturation behavior in GFETs has an adverse impact on the cut-off frequency, the intrinsic gain, and other figures of merit and thus limits the maximum possible operating speeds of GFETs [13].

In addition, as the bandgap is zero in graphene, it is difficult to completely deplete the carriers in graphene and hence to switch GFETs off. The current on/off ratio is usually smaller than 10 in GFETs (Figure 1.3), which is a huge disadvantage compared to silicon FETs in terms of static power consumption. Several methods have been proposed to improve the current on-off ratio in GFETs. For example, patterning graphene into nanoribbons to open a bandgap of up to 400meV; however, the edge scattering in graphene nanoribbons causes significant degradation of the carrier mobility [14, 15]. As such, GFETs are not yet suitable for high-speed digital logic circuits.

1-4. Hot-Electron Transistor (HET)

1-4-1. Operational Principle of HET

Hot-electron transistors (HETs) have been investigated as a promising candidate for high-speed electronic devices for decades because of their short base transit times. The structure of a HET is similar to a bipolar junction transistor (BJT). Normally, a HET is comprised of three active regions (i.e. emitter, base, and collector) and two potential barriers that separate each active region (i.e. one as a tunneling barrier between the emitter-base and the other as an energy filtering barrier between the base-collector) (Figure 1-5). The carriers in a HET consist of “cold” electrons (the
majority carriers, in thermal equilibrium with the lattice) and “hot” electrons (the minority carriers). The cold electrons provide the conductivity needed in the various regions of the device including the emitter, the base, and the collector, while the hot electrons carry the input signal that is to be amplified.

Figure 1-5. Energy band diagram of a HET with a bias applied to the emitter and the collector. Hot electrons are injected from the emitter to the base via tunneling. They travel across the base region and lose some of their energy due to various scatterings. Finally, they will be selected at the filter barrier.

Hot electrons are generated via tunneling. The base-collector filter barrier is designed so that upon biasing only a small amount of current will flow between base and collector. The barrier between the emitter and the base is designed thin enough to facilitate tunneling, while the barrier between the base and the collector is thick enough to prevent tunneling. These basic features are presented in the energy band diagram of Figure 1-5.
When a base-emitter bias is applied, electrons will tunnel from emitter to base with energies near the Fermi level of the emitter, since the density of electrons decays as the energy is above the Fermi level of the emitter and the tunneling probability drops significantly when electrons are further away from the top of the potential barrier. In the base, electrons suffer various scatterings after a length equal to the mean free path (MFP). These scatterings include electron-electron (e-e), electron-phonon (e-ph), and electron-impurity collisions. The base transit time is one of the most important figures of merit that determines the frequency response of a transistor. A HET utilizes the ballistic carrier transport rather than the drift-diffusion carrier transport to achieve a short transit time.

The ON and OFF states of a HET are determined by the base-emitter bias. In the case when $V_{BE}$ is less than $\phi_c / e$ and $V_{CB} > 0$, electrons incident on the collector-base interface will have a very small probability of tunneling through the collector potential barrier, and hence they will bounce back and be thermalized in the base resulting in $I_E = -I_B$. The collector-base barrier height $\phi_c$ is almost unaffected by $V_{CB}$ and hence the collector current is unaffected by $V_{CB}$. The leakage current $I_{CBO}$ is caused by the tunneling and thermal electrons from the base and is very small. This scenario signifies that the HET device is in the OFF state. In the other case, when $V_{BE}$ exceeds $\phi_c / e$, a substantial fraction of the emitter current will pass through the base and be collected by the collector, resulting in $I_C = -\alpha I_E$, where $\alpha$ is the common-base current gain or the current transfer ratio (similar in principle to the transfer ratio in a BJT). Consequently, the HET device in this scenario is operating in the ON state.
1-4-2. A Brief History of HET

The first hot-electron transistor was proposed by Mead in 1960 [16] and it was named the tunnel-emission amplifier (see Figure 1-6). It consisted of two metal-oxide-metal (MOM) sandwiched structures to form an MOMOM configuration. The oxide in the first MOM structure was thin to facilitate tunneling between emitter and base, while the oxide in the second MOM structure was thick to prevent tunneling, which led to leakage current between the base and the collector. The common M layer (the base) was thin enough, so that carrier transport in this region was quasi-ballistic. However, the mean-free-path (MFP) of hot electrons in metals is quite short and a pinhole-free thin metal is difficult to fabricate, both of which resulted in a low current gain for this kind of transistor.

Figure 1-6. Energy band diagram of the first HET proposed by Mead in 1960. It consisted of two metal-oxide-metal (MOM) sandwiched structures to form an MOMOM configuration. The oxide in the first MOM structure was thin to facilitate tunneling between emitter and base, while the
oxide in the second MOM structure was thick to prevent tunneling, which led to leakage current between the base and the collector. The mean-free-path (MFP) of hot electrons in metals is quite short and a pinhole-free thin metal is difficult to fabricate, both of which resulted in a low current gain for this kind of transistor.

A revival of interest in HETs surged with the introduction of Shannon’s silicon-based camel transistor in 1979 (see Figure 1-7) [17]. A thin, highly doped degenerate semiconductor replaced the common metal layer to serve as the base. This novel base layer was bounded by a potential barrier of a P-N junction forming the collector and an emitter of hot electrons, which was a reverse-biased metal-semiconductor Schottky diode. The collection efficiency was improved because both the base and the collector were made of same semiconductor material, resulting in reduced quantum mechanical reflections.

Subsequently, Heiblum proposed the tunneling hot electron transfer amplifier (THETA) in 1981 (see Figure 1-8) [18]. Compared to the MOMOM, the collector was replaced by a metal-semiconductor Schottky diode, while the emitter was still in the metal-oxide-metal configuration. However, the above devices combines metals, semiconductors and insulators in a sandwiched form. These structures are difficult to fabricate without interface problems, which result from the material mismatch and the exposure to ambient in between layers deposition. Hence, a device which is entirely composed of semiconductor materials with similar lattice parameters is highly desirable. As the development of the molecular-beam-epitaxy (MBE) technology allowed for the emitter, the base, and the collector of THETA to all be made of semiconductor materials, a heterojunction HET structure was proposed by Heiblum in the same year (1981). In this heterojunction HET device structure, all metals were replaced by n+-GaAs (narrower bandgap),
and insulators by undoped AlGaAs (wider bandgap). The device structure consisted of: n+-GaAs—i-AlGaAs—n+-GaAs—i-AlGaAs—n+-GaAs, where the first AlGaAs layer was thin to facilitate tunneling, while the second being thicker to prevent tunneling. The MBE technology allows single atomic-layer control of the material thicknesses, interfaces and band alignment. In addition, the entire device is composed of semiconductors and it stays in the ultra-high vacuum of the MBE system in between layers deposition, which prevents the exposure of interfaces to ambient during the process. Therefore, the current transfer ratio and the cutoff frequency are significantly improved [19-21].
Figure 1-7. Energy band diagram for Shannon’s camel transistor in 1979. (a) In thermal equilibrium. (b) Under operating condition with a bias applied to the base and collector. The collection efficiency was improved because both the base and the collector were made of same semiconductor material, resulting in reduced quantum mechanical reflections at the interfaces.

Figure 1-8. Energy band diagram of the heterojunction HET demonstrated by Heiblum in 1985. The structure consisted of: n+ -GaAs—i -AlGaAs—n+ -GaAs—i -AlGaAs—n+ -GaAs. The MBE technology allows single atomic-layer control of the material thicknesses, interfaces and band alignment. In addition, the entire device is composed of semiconductors and it stays in the ultra-high vacuum of the MBE system in between layers deposition, which prevents the exposure of interfaces to ambient during the process. Therefore, the transfer ratio and the cutoff frequency are significantly improved [19-21].

Following Heiblum’s work, modern HETs normally consists of InAlGaAs-based heterostructures. A number of HETs have been fabricated and tested with different degree of
success so far [22-27]. Among them, Evers et al. have successfully demonstrated an InP-based HET operating at room temperature with $f_t$ in excess of 20 GHz, thus illustrating the potential of HETs for RF applications [24]. However, trade-offs have to be made between the base thickness, base doping concentration and the base series resistance. As the base thickness is reduced and the base doping concentration is lowered in order to achieve a short base transit time and a high current gain, the base series resistance increases and it has an adverse impact on the cutoff frequency. Therefore, new fabrication technology and materials are highly desirable.

1-5. Synopsis

In order to overcome the obstacles that conventional GFETs and HETs have faced, graphene-base hot-electron transistors (GB-HET) have emerged. The principle objective of this dissertation is to demonstrate and optimize the viability of GB-HETs.

Chapter 2 presents the basic device concept and operational principle of the GB-HET. The fabrication process and current-voltage characteristics of our first GB-HET prototype (GB-HET1) are demonstrated. The metal-oxide-graphene-silicon stacked structure is used to construct the device with mechanically exfoliated graphene. The ultrathin aluminum oxide layer serves as the tunnel barrier and the graphene-silicon Schottky barrier serves as the filter barrier. The Schottky contact between graphene and semiconductor will also be discussed.

Chapter 3 describes the fabrication and characterization of the GB-HET devices (GB-HET2 and GB-HET3) with a collector-up metal-oxide-graphene-oxide-silicon configuration and the high-k dielectric material as the filter barrier. Thermal silicon dioxide is adopted for better
tunnel oxide quality. Large area chemical-vapor-deposition (CVD) graphene is used to improve the process yield and compatibility with modern VLSI technology.

Chapter 4 studies the influence of the materials and device parameters on the overall device dc performance. Several types of devices (i.e., GB-HET4, GB-HET5 and GB-HET6) are fabricated and characterized. GB-HETs with optimized device parameters exhibit much improved dc performance. In addition, the energy loss mechanisms in the dielectric layers and the electron reflection at the interfaces within GB-HETs are discussed.

Finally, we conclude the dissertation and propose suggested future works in terms of process, modeling and materials that the current GB-HET structures can be enhanced in order to achieve RF operation.
Chapter 2

GB-HET with Schottky-Barrier as the Filter Barrier

2-1. Introduction: Graphene-Base Hot-Electron Transistor

Although the traditional HETs have shown great potential in RF applications, including short transit time in the base, large output resistance, and negative differential resistance feature for high frequency application, there are still obstacles to overcome. For example, in the case of the metal-base HET, the current gain of the transistor was low, as the MFP of hot electrons in metals is short. In addition, a pinhole-free thin metal is difficult to fabricate. The base is an isolation screen between the input and output and is required to supply an appropriate potential difference to the emitter and to the collector. If pinholes are formed in the base film, a direct injection of electrons into the semiconductor will occur via pinholes. These electrons will make the transfer ratio $\alpha$ seem large, but the device loses the isolation between the input and output. Furthermore, a thinner base region with a lower doping concentration is favorable for reducing scattering in the base region and thus improving the current gain, but it will increase the series resistance in base and degrade the overall device RF performance.
Figure 2-1. Energy band diagram of a GB-HET. It consists of an emitter-base-collector and two energy barriers that separate the three regions. One barrier is thin to facilitate tunneling and the other one is thick to prevent leakage current. Electrons are injected from the emitter to the base via the tunnel barrier, and they are collected at the collector after being selected by the filter barrier.

To overcome these obstacles, the concept of using graphene as the base region for hot-electron transistors (GB-HET) has been proposed by Mehr et al.[28], followed by Kong et al.[29]. In a GB-HET, graphene is used as the base region of a HET as shown in Figure 2-1. A GB-HET consists of an emitter-base-collector and two energy barriers that separate these three regions. Graphene is a superior material for the base region of the HET benefiting from these unique
properties of graphene: Although the thickness of graphene is only one atomic layer of carbon atom (~ 0.35 nm [30]), the crystal structure of graphene is very stable and robust because of the nature of the sp2 bonds. The ultra-thin base region minimizes the base transit time, and thus gives GB-HET great potential for RF applications. Both Mehr and Kong’s group have predicted that the operational frequency of GB-HETs can reach the terahertz regime. Furthermore, the operational principle of a HET is different from that of a MOSFET. A bandgap is not required to achieve high current on/off ratio for HETs. Therefore, the zero bandgap and semi-metallic property of graphene is not a disadvantage for GB-HETs, but rather favorable for lowering the series resistance in the base region. GB-HETs has also great potential for high-speed digital logic applications.

The figures of merits to characterize the performance of a GB-HET include the common-base current gain, $\alpha$, the current on-off ratio, $I_{on}/I_{off}$, and the cutoff frequency, $f_T$. $\alpha$, defined as $I_C/I_E$, is also called the transfer ratio from emitter to collector and it quantifies the fraction of the injected carriers that reaches the collector after suffering from various scattering and reflections in the base and at the interfaces. $I_{on}/I_{off}$ reflects the output current difference between the two distinguished states of a GB-HET when a control signal changes. It determines whether a GB-HET is suitable for logic applications. Finally, the cutoff frequency that represents the high-frequency performance of a GB-HET can be expressed as $f_T = \frac{1}{2\pi C_{TOT}} g_m$, where $g_m$ is the transconductance and $C_{TOT}$ is the total capacitance of the transistor including the emitter-base capacitor, base-collector capacitor and the quantum capacitor of graphene.

2-2. Fabrication of GB-HET1
2-2-1. Device Structure

The schematic structure of our first GB-HET prototype (GB-HET1) is illustrated in Figure 2-2. Ti/Au, graphene, and silicon are used as the emitter, base and collector, respectively. Aluminum oxide serves as the tunnel barrier and the graphene-silicon Schottky barrier (SB) serves as the filter barrier.

Figure 2-2. Schematic device structure of GB-HET1. It consists of a metal-oxide-graphene-silicon structure. Aluminum oxide is used as the tunnel barrier and the graphene-silicon Schottky barrier is used as the filter barrier. The purple arrows indicate the direction of hot electron flow.

2-2-2. Making Graphene Visible on Si

The graphene flake is prepared by mechanical exfoliation, which is a stable, widely used method to obtain high quality samples by researchers all over the world [1]. Peeling small mesas
of Kish natural graphite is repeated many times until thin films of graphite are found uniformly distributed on a Scotch tape. The tape is pressed against the substrate pre-patterned with cross markers and 200 × 200 µm electrode pads and then peeled off. Thin films of graphite will adhere onto the substrate with random dimensions, thicknesses and positions.

Those thin films can be characterized via an optical microscope with one’s own eyes by observing the difference in contrast between the graphene and substrate. The material and thickness of the substrate are critical parameters and have to be engineered to satisfy the optical resonant conditions based on a multilayer reflection model. Thickness of 90 nm and 300 nm SiO₂ on Si are the most commonly used substrates for studying graphene because they provide the highest contrast between the graphene and the SiO₂/Si substrate within the wavelength range of visible light, which makes the graphene easily visible via an optical microscope [31].

GB-HET1 has the metal-oxide-graphene-silicon structure and thus requires graphene being put on top of silicon, however, the contrast is extremely low if graphene sits on a bare silicon substrate [31]. To overcome this problem, we place graphene on top of a silicon-on-insulator (SOI) substrate. The multilayer reflection model can be also applied to the graphene-SOI stack to simulate the optical constant as a function of the film thicknesses. The optimized thicknesses for the surface Si layer and the buried SiO₂ layer are 70 nm and 140 nm, respectively. In addition, an optical microscope with a variable interference filter of FWHM = 10 nm is also required so that the thin graphene flakes are easily visible (see Figure 2-3) [32].
Figure 2-3. Optical images of graphene on SOI with different wavelengths of illumination. The thicknesses for the surface Si layer and the buried SiO₂ layer are 70 nm and 140 nm, respectively. Graphene has the largest contrast with the underlying substrate at wavelengths of 605 nm. [32]

Once thin films of graphene are found, the positions of the flakes will be labeled with reference to the pre-patterned markers for further processing. Then Raman spectroscopy is used to confirm the number of layers. The typical Raman spectrum for single-layer-graphene (SLG) on SOI [Figure 2-4 (a)] has a high intensity 2D band at around 2700cm⁻¹. The 2D peak stands for the double resonant defect band and serves as a sensitive characterization feature for identifying the number of layers. Since the double resonant process involves phonon-electron interaction, in the SLG case [Figure 2-4 (a)], the 2D peak has only one phonon involved resulting in a single Raman frequency. However, in the bi-layer graphene case [Figure 2-4 (b)], there are four possible routes
that satisfy the double resonant conditions, resulting in four phonon frequencies stating four phonons. The graphene films are usually categorized according to the number of layers before further processing.

![Image of Raman spectroscopy](image)

Figure 2-4. (a) Raman spectroscopy of SLG on SOI substrate and 300 nm SiO₂ control substrate. The spectroscopy of SLG depending on the polarity of Si surface. (b) Raman spectroscopy of BLG on SOI and SiO₂ substrate. The 2D band can be fitted with four Lorentzian functions. The Raman was taken at a condition of 600 second acquisition time with less than 2 mW laser power. The Raman intensity for Si substrates are enhanced by a factor as indicated on each spectrum.
2-2-3. Process flow

The complete process flow is described as follows:

a. Collector contact. The fabrication starts with putting a collector contact metal onto an SOI substrate with the optimized Si and SiO₂ thicknesses. A 50-nm Al / 50-nm Pt contact to the surface Si layer of the SOI substrate is defined by photo lithography and is deposited by e-beam evaporation. The Pt layer is used for protection against the HF etching process in the next step [see Figure 2-5 (a)].

b. Graphene transfer. The pre-patterned SOI substrate is treated with diluted HF to remove the native oxide, immediately followed by exfoliating graphene onto the substrate. The mechanical exfoliation and identification of graphene on SOI is performed as discussed in Section 2-2-2 [see Figure 2-5 (b)].

c. Base contact. The patterning of the base contact is performed by e-beam lithography. This step includes three sub-steps: spin-coating resist, exposure, and development.

A configuration of the bi-layer Polymethyl methacrylate (PMMA 495 and PMMA 950) is used as the E-beam resist, which is a versatile polymeric material well suited for many imaging and non-imaging microelectronic applications. The E-beam exposure is done in a modified SEM with an NPGS E-beam writing control part. A developer with MIBK:IPA (1:3) is used in the development.

An uncut or “reversed-T” sidewall profile after development is achieved and is desirable for the lift-off process. A 10 nm Ti / 100 nm Au is deposited by e-beam evaporation, which is a commonly used metal combination for Ohmic contact onto carbon-based devices such as carbon
nanotubes and graphene [33]. Then, the metal in the unexposed region is lifted-off in an acetone bath [see Figure 2-5 (c)].

d. Tunnel oxide deposition. Several kinds of metal oxide can be used as the tunneling barrier on top of graphene, of which MgO and Al2O3 are the two most commonly used materials. Single crystal MgO can be deposited by molecular beam epitaxy (MBE), and Al2O3 could be deposited by first evaporating a thin layer of aluminum followed by oxidization into Al2O3 [34, 35]. In our device, a 1.2 nm thick Al is deposited on top of graphene by e-beam evaporation at room temperature, and then naturally oxidized into Al2O3 in the ambient condition. The volume ratio of Al2O3 to Al is 1.7 [36], therefore the total thickness of this thin layer of the oxidized Al layer is expected to be around 2 nm [see Figure 2-5 (d)].

e. Emitter contact deposition. A 10 nm Ti / 100 nm Au is deposited by e-beam evaporation as the emitter of the GB-HET. The process is the same as in Step 3 [see Figure 2-5 (e)].

f. Insulating layer deposition. An insulating layer is required to isolate the electrodes and pads from the conductive silicon substrate. Two layers of oxide are used for the insulation. The first layer is 30 nm Al2O3 that is deposited by atomic-layer-deposition (ALD). The second oxide is 150 nm SiO2 that is deposited by plasma-enhanced-chemical-vapor-deposition (PECVD). The purpose of the layer of Al2O3 is to protect graphene against the plasma power during the PECVD process. Due to graphene being hydrophobic, a seed layer, which will allow for the bonding of Al2O3, has to be deposited before the ALD process. The evaporated tunneling oxide in Step 4 is able to act as a seed layer for the ALD process and hence no extra step is needed. PECVD of SiO2 follows and it is a widely used process for insulation and passivation in silicon technology [see Figure 2-5 (f) and (g)].
g. Via hole etching. A third e-beam process is used to pattern via holes. A thicker e-beam resist, MMA EL9, is used as the etching mask in this step. MMA EL9 is spin-coated at 5000 RPM to reach a thickness of around 550 nm. A dry etching by advanced-oxide-etcher (AOE) is used to remove the insulating layer. The selectivity between PECVD SiO$_2$ and MMA is about 1:1, and the selectivity between Al$_2$O$_3$ and MMA is about 5:1. Therefore, 550nm MMA is definitely thick enough to protect the patterns and insulating layer underneath [see Figure 2-5 (h)].

i. Electrode and pad deposition. A fourth e-beam lithography is used for the patterning and Ti/Au is used for the pads; the same as in Step 3 [see Figure 2-5 (i)].

Finally, the fabrication is completed and an optical microscopy picture of the completed device is shown in Figure 2-6.
d. Tunnel oxide deposition

e. Emitter contact

f. Al₂O₃ deposition
Figure 2-5. Schematic of the process flow of GB-HET1. (a) Collector contact deposition. (b) Graphene transfer. (c) Base contact deposition. (d) Tunnel oxide deposition. (e) Emitter contact deposition. (f) ALD Al₂O₃ deposition. (g) PECVD SiO₂ deposition. (h) Via hole etching. (i) Electrode and pad deposition.
2-3. Electrical Characteristics of GB-HET1

2-3-1. Characterization of the Graphene-Silicon Schottky Contact

GB-HET1 can be treated as two coupled diodes. One is the metal-oxide-graphene (emitter-base) tunneling diode, which serves as the tunnel oxide that provides hot electron injection. The properties of the metal-oxide-graphene have been studied extensively in the author’s previous works [37, 38]. The other is the graphene-silicon (base-collector) Schottky diode, which serves as the filter barrier in the HET. The Schottky barrier (SB) height determines the amount of energy that hot electrons need to overcome in order to arrive at the collector. Therefore, it is very valuable to experimentally obtain the SB height between graphene and silicon.
Figure 2-7. Schematic of the experimental setup for measuring the graphene-silicon Schottky barrier height. The I-V characteristics between graphene and silicon at various temperatures were taken to extract the Schottky barrier properties.

We used the experimental setup shown in Figure 2-7 to measure the I-V characteristics of the graphene-silicon contact at various temperatures from 300 K to 335 K. The I-V characteristics illustrate a strong dependence on the temperature as shown in Figure 2-8.
Figure 2-8. I-V characteristics of the graphene-silicon Schottky contact at various temperatures (from 300 to 335K in a 5 K step). The red arrow indicates the direction of increasing temperature (T).

Figure 2-9. Plot of \( \ln(I_{\text{sat}} / T^2) \) vs. \( 1/T \) at \( V_{BC} = 1.5 \, V \). The extracted Schottky barrier height between graphene and silicon for this device is \( \sim 0.19 \, \text{eV} \) according to the thermionic emission model.

The Schottky diode equation [39] is given by:

\[
I = A A^* T^2 \exp \left( \frac{-q\phi_b}{k_BT} \right) \left[ \exp \left( \frac{qV_{\text{bias}}}{\eta k_BT} \right) - 1 \right]
\]

where \( A \) is the area of the Schottky junction, \( A^* \) is the effective Richardson constant, \( q \) is the elementary charge, \( k_B \) is the Boltzmann constant, \( \phi_b \) is the SB height, and \( T \) is the temperature.

According to the above equation, the diode current becomes insensitive to \( V_{\text{bias}} \) in the reverse bias...
saturation regime as \( \exp\left(\frac{qV_{\text{bias}}}{\eta k_B T}\right) \ll 1 \) so that \( I_{\text{sat}} \propto T^2 \exp\left(-\frac{q\varphi_b}{k_B T}\right) \). Hence, the graphene-silicon SB height \( \varphi_b \) can be extracted from the plot of \( \ln(I_{\text{sat}} / T^2) \) versus \( 1/T \) (Figure 2-9). The extracted graphene-silicon SB height is \( \sim 0.19 \) eV, which is in good agreement with other experimental results [39] and thus confirms the formation of SB between graphene and silicon.

### 2-3-2. I-V Characteristics of GB-HET1

To characterize the device performance, we investigated the input and transfer I-V characteristics of GB-HET1 with the common-base configuration, where the base was grounded (see Figure 2-10). The input characteristics are specified by the dependence of the input current \( (I_E) \) on the input voltage bias \( (V_{BE}) \), while the transfer characteristics are governed by the dependence of the output current \( (I_C) \) on the input voltage bias \( (V_{BE}) \).

![Schematic of the common-base experimental setup for measuring the I-V characteristics of GB-HET1](image)

Figure 2-10. Schematic of the common-base experimental setup for measuring the I-V characteristics of GB-HET1. The base terminal is grounded and a voltage bias is applied to the emitter and the collector, respectively.
The transfer I-V characteristics in a GB-HET (I\textsubscript{C} vs. V\textsubscript{BE}) are very similar to the transfer characteristics in a FET (I\textsubscript{DS} vs. V\textsubscript{GS}). These characteristics reflect the ability of controlling the output current (I\textsubscript{C}) by the control voltage signal (V\textsubscript{BE}) in a transistor. The transfer characteristics measured in GB-HET1 are plotted in Figure 2-11. Two distinguishable states (on-state and off-state) in I\textsubscript{C} are observed, depending upon the magnitude of the input bias V\textsubscript{BE}. The operational principle is illustrated in Figure 2-12. In the case of the off-state [see Figure 2-12 (a)], since V\textsubscript{BE} is small, the hot carriers’ kinetic energy perpendicular to the interface is insufficient to overcome the filter barrier. Hence, most of the hot carriers will bounce back and remain in the base, leading to a small I\textsubscript{C}. In the case of the on-state [see Figure 2-12 (b)], V\textsubscript{BE} is large enough so that the kinetic energy of the hot carriers can overcome the filtering barrier. Therefore, a substantial fraction of the hot carriers can travel over the filtering barrier, and reach the collector, resulting in an increase of I\textsubscript{C}.

Figure 2-11. Transfer I-V characteristics (I\textsubscript{C} vs. V\textsubscript{BE}) at various V\textsubscript{CB} for GB-HET1 in the (a) linear scale and (b) logarithmic scale. Two distinguishable states (on-state and off-state) in I\textsubscript{C} are observed, depending upon the magnitude of the input bias V\textsubscript{BE}. High on-off ratios of the output
current $I_C$ is achieved. The on-off ratio decreases when larger collector voltage is applied because of the increased leakage current from the reverse-bias graphene-silicon Schottky junction.  

![Energy band diagram of the GB-HET1 in the (a) off-state and (b) on-state.](image)

Figure 2-12. Energy band diagram of the GB-HET1 in the (a) off-state and (b) on-state. Electrons are injected from the emitter to the base via tunneling. The injected hot electrons do not have sufficient energy to overcome the filter barrier when $V_{BE}$ is small. As $V_{BE}$ increases, hot electrons gain larger energy from the emitter and thus they are more likely to overcome the filter barrier and contribute to $I_C$.

High on-off ratios of the output current $I_C$ has been achieved in this device as shown in the logarithm plot of $I_C$ in Figure 2-11 (b). The current on-off ratios for $I_C$ are above 100 at all $V_{CB}$ biases with the largest one above $10^5$ when $V_{CB} = 0$ V. The on-off ratio decreases when larger collector voltage is applied because of the increased leakage current from the reverse-bias graphene-silicon Schottky junction. Based on the operation principle discussed above, the high current on-off ratios are expected because the current on-off ratio in GB-HETs primarily depends on the hot-electron energy and transmission probabilities through the filter barrier rather than the
bandgap of graphene as in GFETs. These results confirm that an energy bandgap in the base material is not required to realize a high current on-off ratio in HETs. Hence, the zero bandgap and semi-metallic property of graphene is not a disadvantage for GB-HETs, but rather favorable for lowering the series resistance in the base region.

Figure 2-13. (a) Output characteristics ($I_C$ vs. $V_{CB}$) at various $V_{BE}$ from 0 V to 1 V with 0.2 V a step. A current saturation is observed in high $V_{CB}$ regime because the filter barrier height is not sensitive to $V_{CB}$. (b) Energy band diagram of GB-HET1 under different $V_{CB}$ ($V_{CB1} < V_{CB2}$). The Schottky barrier height between graphene and silicon is mainly determined by the electron affinity.
of the two materials. Since the electron affinity is the intrinsic property of a material and is not affected by $V_{CB}$, the filter barrier height is insensitive to $V_{CB}$.

We also investigated the output characteristics of GB-HET1. The output characteristics are specified by the dependence of the output current ($I_C$) on the output voltage ($V_{CB}$) at various $V_{BE}$. They are very similar to the $I_D$ vs. $V_{DS}$ family curves for a FET. Figure 2-13 (a) shows the output characteristics of GB-HET1 under the common-base configuration. The device displays a noticeable saturation regime at multiple $V_{BE}$ biases, and the current saturation persists up to $V_{CB} \sim 3$ V. The current saturation is attributed to the weak dependence of the filter barrier height on $V_{CB}$ [see Figure 2-13 (b)]. As discussed previously, two factors determine whether a hot electron can contribute to $I_C$. One factor is hot electron energy and the other is the filter barrier height. The hot electron energy is controlled by $V_{BE}$ bias and the filter barrier height, which is the graphene-silicon Schottky barrier height, is mainly determined by the electron affinity of the two materials. As we know, the electron affinity is the intrinsic property of a material and is not affected by $V_{CB}$. Hence, the filter barrier height is insensitive to $V_{CB}$. Consequently, $I_C$ is mainly controlled by $V_{BE}$ but not significantly affected by $V_{CB}$ and a current saturation is observed in the $I_C$-$V_{CB}$ family curves.

In addition to the current saturation, a faster increase of $I_C$ than that in the saturation region is observed in the output characteristics, when $V_{CB}$ is very close to 3 V and $V_{BE}$ is at 0.8 V and 1.0 V. This faster increase of $I_C$ at high bias region is attributed to the reverse-bias graphene-silicon Schottky junction leakage current at high bias. The graphene-silicon Schottky barrier is reverse biased when a positive $V_{CB}$ is applied. The reverse-bias leakage current are typically from four sources: thermionic emission of electrons over the barrier, tunneling of electrons through the barrier, generation in the depletion region on the silicon side, and barrier lowering due to image
force [40]. For graphene-silicon Schottky barrier, there is a fourth reason. That is the barrier lowering due to the Fermi level shift in graphene. The details of the Fermi level shift in graphene will be discussed in Chapter 4. If $V_{CB}$ continues to increase, the depletion region will eventually break down.

2-3-3. Current Gain of GB-HET1

An important figure of merit to benchmark the performance of GB-HETs is the common-base current gain, $\alpha$, defined as $I_C/I_E$. $\alpha$ is also called the transfer ratio from emitter to collector and it quantifies the fraction of the injected carriers that reaches the collector after suffering from various scattering and reflections in the base and at the interfaces. To examine the carrier transport behavior, we extract $\alpha$ from the transfer and the input I-V characteristics and plot them as a function of $V_{BE}$ in Figure 2-14. It is not surprising to see that $\alpha$ increases as $V_{BE}$ increases when the transistor stays in the on-state. As the energy of injected hot electrons increases with $V_{BE}$, a larger fraction of hot electrons will have sufficient energy to overcome the filter barrier and arrive at the collector.
Figure 2-14. The common-base current gain, $\alpha$, as a function of $V_{BE}$ for GB-HET1. $\alpha$ increases with increasing $V_{BE}$ bias, because a larger portion of injected electrons are able to overcome the filter barrier when they gain higher energy from the emitter. The maximum $\alpha$ for GB-HET1 is $\sim0.03\%$.

The maximum value of $\alpha$ in GB-HET1 is $\sim3 \times 10^{-4}$, which is relatively low compared to state-of-the-art HETs [24, 27]. The undesirable channels in the ultrathin aluminum oxide tunnel barrier is possibly the main reason for the low $\alpha$. The tunnel barrier in GB-HET1 is formed by firstly evaporating a thin layer of aluminum and then oxidizing the aluminum into aluminum oxide. Pin-holes are usually unavoidable in this process [41]. In addition, low-energy extended electron states exist in the very thin and disordered oxide [42]. These two undesirable channels allow low-energy electrons to enter the base region from the emitter. Those low-energy electrons are unlikely to contribute to the collector current since they do not have sufficient energy to overcome the filter barrier (see Figure 2-15) As a result, the transfer ratio from emitter to collector is significantly degraded by these low-energy channels. In order to improve $\alpha$, a high-quality tunnel barrier is required to suppress those low-energy channels.
Figure 2-15. Energy band diagram of GB-HET1 with undesirable current channels, including pin-holes and low-energy extended states in ultrathin aluminum oxide. Low-energy electrons can enter the base region through those channels without contributing to the collector current.

2-4. Summary

We fabricated and characterized the graphene-base hot-electron transistor with aluminum oxide as the tunnel barrier and graphene-silicon Schottky barrier as the filter barrier. Benefiting from the non-FET operational principle, an energy bandgap in graphene is not required to achieve high on-off ratio and current saturation in GB-HET. We successfully observed two distinguishable states (on-state and off-state) of the collector current as the input voltage $V_{BE}$ increased. The maximum current on-off ratio reached up to $\sim 10^5$ in GB-HET1. In addition, current saturation was observed in the output characteristics of GB-HET1. These excellent device characteristics reveal the advantages of GB-HETs over GFETs for digital logic applications. Unfortunately, the value of $\alpha$ (the common-base current gain or the transfer ratio from emitter to collector) is very low because
of the difficulty of fabricating ultrathin high-quality tunnel oxide on top of graphene and the undesirable low-energy extended states in very thin and disordered oxide. A revised device structure with high-quality tunnel oxide is needed to improve $\alpha$. 

Chapter 3

GB-HET with High-k Dielectric as the Filter Barrier

We successfully demonstrated our first prototype of GB-HET in Chapter 2. High current on-off ratios and current saturation behavior were observed, which showed the advantages of using graphene as the base region of a hot-electron transistor. At the end of Chapter 2, we analyzed the possible reasons that caused the low $\alpha$ value in GB-HET1, and we concluded that a revised device structure with high-quality tunnel oxide was necessary in order to improve $\alpha$. In this chapter, we will illustrate the fabrication and I-V characteristics of the improved GB-HET structures.

3-1. Device Structure of GB-HET2

Based on the analysis in Chapter 2, we redesigned the GB-HET structure with different materials in order to realize higher $\alpha$. A schematic diagram of the new device structure (GB-HET2) is shown in Figure 3-1 (a) with the corresponding energy band diagram shown in Figure 3-2 (b).
First, in order to avoid the formation of pin-holes and low-energy extended states in the ultrathin aluminum oxide tunnel barrier, we replaced the oxidized aluminum layer by the thermally oxidized silicon dioxide layer as the tunnel barrier. Thermal SiO$_2$ is known to be a high-quality dielectric and is widely used as the tunnel barrier for nonvolatile memory applications [43]. Second, the metallic emitter was replaced by a degenerately-doped silicon substrate ($n \approx 1 \times 10^{19}$ cm$^{-3}$). The addition of an energy bandgap in the emitter (i.e. n$^+$-Si) suppresses electrons at the valence band edge from tunneling into the graphene base, because these electrons are subject to a much higher energy barrier than those degenerated at the conduction band edge. Therefore, the energy distribution of hot electrons being injected into the base is more monochromatic, and this will result in a larger percentage of electrons being able to travel over the filtering barrier. Third, as the CVD graphene technology becomes more developed [44-46], CVD graphene is used to replace exfoliated graphene to improve the yield and to offer large-scale integration of GB-HETs. Although the mobility of CVD graphene is lower than that of exfoliated graphene, the low mobility might not be critical in the base transit time of the GB-HETs, because the electrons traverse along the vertical direction perpendicular to the 2-D plane of the graphene sheet. Finally, high-k dielectrics such as Al$_2$O$_3$ and HfO$_2$ grown by ALD serve as the filter barrier since it is impossible to grow crystalline silicon on top of graphene so far. The Al$_2$O$_3$ and HfO$_2$ have been widely used as high quality top-gate dielectric materials on graphene with low leakage current [12, 47, 48].
3-2. Process flow of GB-HET2

The fabrication starts with growing a 3-nm-thick thermal SiO$_2$ on top of a degenerately-doped Si substrate ($n \sim 1 \times 10^{19} \text{ cm}^{-3}$). The graphene is grown on copper foil by using a chemical vapor deposition (CVD) method [46, 49] and then it is transferred onto the surface of the SiO$_2$/Si substrate using a poly(methyl methacrylate) (PMMA) transfer method [50]. The PMMA layer was removed with an acetone bath followed by H$_2$/Ar forming gas annealing at 350 °C for 1 hour. Subsequently, the base contact (20-nm-thick Cr/100-nm-thick Au) is patterned by photolithography and deposited onto the graphene. The graphene outside the active region is then etched by oxygen plasma to isolate each device. A 1-nm-thick Ti seed layer is evaporated on top of graphene and naturally oxidized in air, followed by atomic layer deposition (ALD) of a 14-nm-thick HfO$_2$ as the filter barrier. The collector (100-nm-thick Al/5-nm-thick Pt) are patterned and
deposited on top of the filter barrier. The Si-SiO2-graphene-HfO2-metal heterojunction structure is formed underneath the collector contact [see Figure 3-2 (a) – (f)].

The insulating layer for electrical isolation of pads and electrodes are fabricated by using a similar method as described in Chapter 2 for GB-HET1. A 30 nm Al2O3 layer is deposited by ALD followed by a 150 nm PECVD SiO2 layer. Contact holes are etched by dry etching through the two layers and reach the contacts. Two contacts holes are placed on each metal contact in order to verify that the insulating layers are completed etched away. Finally, Ti/Au electrodes and pads are deposited by e-beam evaporation [see Figure 3-2 (g) – (i)]. An optical microscope image of the completed device is shown in Figure 3-3.
Figure 3-2. Schematic diagram of the process flow to fabricate GB-HET2. It includes: (a) Thermal oxidation of silicon. (b) Transfer graphene. (c) Pattern graphene. (d) Base contact deposition. (e) High-k dielectric deposition. (f) Collector contact deposition. (g) Isolation layer deposition. (h) Via hole etching. (i) Electrode and pad deposition.
Figure 3-3. Optical microscope image of the completed device GB-HET2. Redundant electrodes are used to make sure the via hole etching are completed.

**3-3. Electrical Characteristics of GB-HET2**

**3-3-1. Input I-V Characteristics of GB-HET2**

The electrical characterization of GB-HET2 was carried out in the same common-base configuration, as shown in Figure 3-4. We first investigated the input characteristics ($I_E$ vs $V_{BE}$ at various $V_{CB}$) as shown in Figure 3-5. They represent the tunneling properties of electrons through the thin SiO$_2$ tunnel barrier. The SiO$_2$-graphene conduction band discontinuity $\chi_C$ can be directly measured by the internal photo-emission method. We have successfully extracted $\chi_C$ to be $\sim$3.6 eV from a Si-graphene-SiO$_2$ structure by the internal photo-emission method [51]. As the SiO$_2$ tunnel barrier is thin, the $V_{BE}$ bias applied across the tunnel barrier is smaller than $\chi_C$. Hence, the tunneling current is dominated by direct tunneling instead of Fowler-Nordheim tunneling.
Figure 3-4. Schematic diagram of the common-base configuration for the electrical characterization of GB-HET2. The base terminal is grounded. Voltage bias is applied on the emitter and collector, respectively.

The tunneling current density for the direct tunneling can be expressed as follows [52]:

\[
J_D = \frac{AF_{ox}^2}{1 - \left(\frac{\phi_s - qV_{ox}}{\phi_s}\right)^{1/2}} \exp \left[-B \frac{\phi_s^{3/2} - (\phi_s - qV_{ox})^{3/2}}{\phi_s^{3/2}}\right] \\
\times \left[1 - \exp \left[-\frac{3}{2} B \frac{\phi_s^{1/2} - (\phi_s - qV_{ox})^{1/2}}{\phi_s^{3/2}} E_{FS}\right]\right]
\]

The parameters \(A\) and \(B\) depend on the tunnel barrier height \(\phi_s\) and the effective mass of the tunneling electron \(m_{ox}^*\):

\[
A = \frac{q^3}{16\pi^2 h\phi_s}
\]
The expression for the direct tunneling current density can be simplified in our case since the n++ silicon substrate used in the emitter of our devices has a very strong degenerate accumulation layer. The direct tunneling current density becomes:

\[ J_D = \frac{AF_{ox}^2}{1 - \left( \frac{\phi_s - q V_{ox}}{\phi_s} \right)^{1/2}} \exp \left[ -\frac{B \phi_{s}^{3/2} - (\phi_s - q V_{ox})^{3/2}}{F_{ox} \phi_s^{3/2}} \right] \]

Although the above expression has been simplified, it is still difficult to fit it with experimental data because of the difficulty to obtain accurate values of parameters A and B from the experiments and the thickness variation of the tunnel barrier within the entire device area. However, the magnitude of the current density shown in Figure 3-5 still have a fairly good agreement with other reports for the tunnel barriers with thickness close to 3 nm [52, 53].
Figure 3-5. Input characteristics ($I_E$ vs. $V_{BE}$ at various $V_{CB}$). The tunneling current shows very weak dependence on $V_{CB}$, which means a good isolation between the input and output terminal of the device.

In addition, we also notice that $I_E$ has a very weak dependence on $V_{CB}$ in Figure 3.4. The curves are almost identical at different $V_{CB}$. This reflects a good isolation between the input and output terminals of our device.

3-3-2. Transfer I-V Characteristics of GB-HET2

Next, we measured the transfer characteristics ($I_C$ vs $V_{BE}$ at different $V_{CB}$) by using the same setup shown in Figure 3-4. The results are shown in Figure 3-6. The magnitude of $I_C$ increases with $V_{CB}$, which can be attributed to the base-collector leakage current. However, we did not observe a significant increase of $I_C$ as $V_{BE}$ increases, which is quite different from the transfer characteristics of GB-HET1. According to the operational principle of GB-HET, the hot-electron energy and filter barrier height decide the magnitude of $I_C$ and hence the on- and off-state of a GB-HET. The filter barrier height in GB-HET2 is the graphene-HfO$_2$ conduction band offset, which is $\sim$ 2.0 eV according to the work function and electron affinity of graphene and HfO$_2$. We should be able to see that the device is turned on when $V_{BE}$ is above $\sim$ 2 V. Indeed, a slight increase of $I_C$ is observed when $V_{BE}$ is above 2 V as highlighted in Figure 3-5. This suggests that there are some injected electrons being collected in the collector, however, the percentage is low because of some unexpected energy-loss mechanisms. It also gives us a hint that we may be able to observe a large $I_C$ if we continue to increase $V_{BE}$. 

49
Figure 3-6. Transfer characteristics ($I_C$ vs. $V_{BE}$ at various $V_{CB}$) for GB-HET2. The magnitude of $I_C$ increases as $V_{CB}$ increases, which can be attributed to the base-collector leakage current. The highlighted region shows a slight increase of $I_C$ with $V_{BE}$, which suggests that there are some injected electrons being collected. It also gives us a hint that we may be able to observe a large $I_C$ if we continue to increase $V_{BE}$.

Unfortunately, as we increased $V_{BE}$ to above 3 V, the electric field across the 3 nm thick SiO$_2$ also exceeded 10 MV/cm. The emitter current suddenly jumped by three orders of magnitude to the compliance of the measurement system when $V_{BE}$ reached ~3.3 V (see Figure 3-7). Dielectric breakdown occurred in the tunnel oxide. After the breakdown, current leaked to the base from the emitter without tunneling through the SiO$_2$ layer. Although the current density increased dramatically, those electrons did not have sufficient energy to overcome the filter barrier. Therefore, $I_C$ stayed in the noise level ($\sim 10^{-13}$ A) of the measurement system after the breakdown occurred, as shown in Figure 3-7.
Figure 3-7. Input and transfer characteristics when a large $V_{BE}$ is applied. Dielectric breakdown occurs as shown in the circled region, since the electric field in the tunnel oxide is above 10 MV/cm.

3-4. Device Structure of GB-HET3

The brute force way of solving the breakdown problem is to increase the thickness of the SiO$_2$ layer so that the tunnel oxide can survive under higher voltage biases. In addition, since the tunneling current density drops dramatically as the tunnel barrier thickness increases, a large device area is needed to make sure that the tunneling current is higher than the lowest sensitivity of the measurement instrument. Based on these two points, the device structure is revised and shown in Figure 3-7. Compared with GB-HET2, the new device (GB-HET3) has a 7 nm SiO$_2$ tunnel barrier and a 20 nm Al$_2$O$_3$ filter barrier. The active region of the device is also increased.
from $1 \times 10^3 \ \mu m^2$ in GB-HET2 to $3.2 \times 10^5 \ \mu m^2$ in GB-HET3. The process flow of GB-HET3 is very similar to GB-HET2 with only a few changes on the layout design.

Figure 3-8. (a) Schematic device structure of GB-HET3. Compared with GB-HET2, the SiO$_2$ tunnel barrier thickness is increased to 7 nm so that the tunnel oxide can survive under higher voltage biases. (b) Energy band diagram of GB-HET3. Electrons can gain higher energy from the emitter as the maximum $V_{BE}$ bias increases, therefore, they have a higher probability being
collected. (c) Optical microscope image of GB-HET3. The active region area is increased to $3.2 \times 10^5 \, \mu m^2$. A larger device area is required as the thicker tunnel barrier thickness significantly decreases the tunneling current density.

3-5. Electrical Characteristics of GB-HET3

3-5-1. Input Characteristics of GB-HET3

We performed a similar study on the I-V characteristics of GB-HET3 by using the common-base configuration shown in Figure 3-4. As the SiO$_2$ layer thickness is increased, Fowler-Nordheim tunneling (FNT) is expected in GB-HET3 when $V_{BE}$ is larger than the conduction band offset between graphene and SiO$_2$ (~3.3 eV, measured by using the internal photoemission method in our recent work [54]). Differing from direct tunneling, the FNT current equation is given by [55]:

$$J_{FN} = A F_{ox}^2 \exp \left[ - \frac{B}{F_{ox}} \right]$$

where $F_{ox}$ is the electrical field strength in the oxide layer, and $m_0$ is the free-electron mass. $A$ and $B$ depend on the tunnel-barrier height $\phi_s$ and the effective mass of the tunneling electron $m_{ox}$:

$$A = \frac{q^3 m_0}{16 \pi^2 \hbar m_{ox} \phi_s}$$

$$B = \frac{4}{3} \left( \frac{2 m_{ox}}{q \hbar} \right)^{1/2} \phi_s^{3/2}$$
According to the above equations, a straight line is expected in the Fowler-Nordheim (FN) plot (i.e., \( \ln(J / F_{ox}^2) \) versus \( 1 / F_{ox} \)) if the current is dominated by FNT and the electron tunneling effective mass in the tunnel oxide can be extracted from the slope of the linear fitting. The input characteristics (\( I_E - V_{BE} \)) of GB-HET3 are shown in Figure 3-9 (a). We notice a very weak dependence of \( I_E \) on \( V_{CB} \), assuring good isolation between the emitter and collector electrodes. We also plot the data in the form of a FN plot as shown in Figure 3-9 (b). \( \ln(J / F_{ox}^2) \) is on a straight line in the high-field regime, and the electron tunneling effective mass \( m_{ox} \) is extracted to be \( \sim 0.26 \ m_0 \) from the linear fitting in the high-field regime. The extracted value of \( m_{ox} \) is consistent with other reported experimental results [52].

Figure 3-9. (a) Input characteristics of GB-HET2 at various \( V_{CB} \). (b) Fowler-Nordheim plot of the emitter current. A linear fitting can be obtained in the high-field regime. The extracted electron effective mass is \( 0.26 \ m_0 \).

3-5-2. Transfer Characteristics of GB-HET3
Following the input characteristics, we studied the transfer characteristics ($I_C$ vs. $V_{BE}$) of GB-HET3. As we mentioned earlier in this chapter, we did not observe GB-HET2 being turned on when $V_{BE}$ was up to $\sim 3\, V$. After the tunnel oxide thickness was increased to 7 nm in GB-HET3, the tunnel oxide could sustain a higher $V_{BE}$ bias. Indeed, as shown in Figure 3-10, the maximum $V_{BE}$ bias reaches up to 5.5 $V$ without dielectric breakdown. A current on-off ratio of more than 300 for the collector current is observed as $V_{BE}$ is swept from 0 $V$ to 5.5 $V$. This high current on-off ratio is attributed to the operational principle of GB-HET, where the on- and off-states primarily depend on the transmission probabilities through the filter barrier rather than the bandgap of the channel material as in FETs.

![Figure 3-10](image)

**Figure 3-10.** Input characteristics ($I_E$ vs. $V_{BE}$) and transfer characteristics ($I_C$ vs. $V_{BE}$) of GB-HET3. A current on-off ratio of larger than 300 is observed as the $V_{BE}$ increase from 0 to 5.5 $V$. 

55
As explained in Figure 3-11, when $V_{BE}$ is applied to the emitter, hot electrons with high kinetic energy are injected from the emitter to the base (i.e., graphene) by tunneling through the SiO$_2$ layer. The injected hot electrons will traverse the base region. When $V_{BE}$ is small, the kinetic energy of most hot electrons is insufficient to overcome the filter barrier. The transmission probability through the filter barrier for those hot electrons is low. Hence, these electrons will be bounced back, remain in the base and eventually be collected by the base contact without contributing to the collector current $I_C$. This is the off-state as shown in the red region of Figure 3-10. As $V_{BE}$ increases, the kinetic energy of hot electrons increases. When the hot electron energy is high enough to overcome the filter barrier, a substantial fraction of the hot electrons can travel over the filter barrier, and reach the collector, resulting in an increase of $I_C$. This is the on-state as shown in the blue region of Figure 3-10. The high current on-off ratio in GB-HET3 confirms again that an energy bandgap in graphene is not required to realize a high on-off ratio in GB-HETs. Therefore, the zero bandgap and semi-metallic property of graphene is not a disadvantage for GB-HETs, but rather favorable for lowering the series resistance in the base region.
Figure 3-11. Energy band diagram of GB-HET3 to illustrate the operational principle of the device. The on- and off- states primarily depend on the transmission probabilities through the filter barrier rather than the bandgap of the channel material as in FETs.

3-5-3. Output Characteristics of GB-HET3

We also investigate the common-base output characteristics of GB-HET3 as shown in Figure 3-12 (a). The output characteristics are specified by the dependence of the output current ($I_C$) on the output voltage ($V_{CB}$) at a set of $V_{BE}$. This set of characteristics are similar to the $I_D$ vs. $V_{DS}$ family curves in FETs. A saturation of $I_C$ is observed in GB-HET3 as $V_{CB}$ increases for each $V_{BE}$. The weak dependence of $I_C$ on $V_{CB}$ is corroborated by the transfer characteristics at various $V_{CB}$ as shown in Figure 3-12 (b). From both of the figures, $I_C$ is mainly controlled by the input voltage $V_{BE}$ and is not sensitive to the output voltage $V_{CB}$, which indicates a high output impedance for the device (i.e., small Early effect).
Figure 3-12. (a) Output characteristics ($I_C$ vs. $V_{CB}$) of GB-HET3 at various $V_{BE}$. $I_C$ saturates as $V_{CB}$ increases for each $V_{BE}$. (b) Transfer characteristics of GB-HET3 at various $V_{CB}$. The results are consistent with the output characteristics. $I_C$ shows weak dependence on $V_{CB}$ and is mainly controlled by the input voltage $V_{BE}$.

This saturation behavior on $I_C$ can be attributed to the weak dependence of the filter barrier height on $V_{CB}$ as illustrated in Figure 3-13. According to the operational principle of GB-HET, $I_C$ is mainly determined by the energy of the hot electron and the filter barrier height. When a larger $V_{CB}$ bias is applied between base and collector, the potential drop and electric field across the
$\text{Al}_2\text{O}_3$ filter barrier increases. However, the conduction band offset between graphene and $\text{Al}_2\text{O}_3$ is mainly determined by the work function of graphene and the electron affinity of $\text{Al}_2\text{O}_3$. Both of them are not a function of $V_{\text{CB}}$. Thus, the filter barrier height is not very sensitive to $V_{\text{CB}}$ except for a slight decrease (typically $<0.2$ eV in our devices) due to the quantum capacitance of graphene, which will be discussed in Chapter 4. The energy of the injected electron is controlled solely by $V_{\text{BE}}$, while the filter barrier height is not significantly influenced by $V_{\text{CB}}$. As a result, the collector current is mainly controlled by $V_{\text{BE}}$ rather than $V_{\text{CB}}$ and current saturation is observed for each $V_{\text{BE}}$ bias in the output characteristics.

Figure 3-13. Energy band diagram of GB-HET3 under different $V_{\text{CB}}$ biases: $V_{\text{CB}1} < V_{\text{CB}2}$. A larger $V_{\text{CB}}$ increase the electric field inside the oxide, but the band offset between graphene and $\text{Al}_2\text{O}_3$ is mainly determined by the work function of graphene and the electron affinity of $\text{Al}_2\text{O}_3$ and it is not sensitive to $V_{\text{CB}}$. 

59
3-5-4. Current Gain of GB-HET3

We extracted the common-base current gain $\alpha$ from the above input and transfer characteristics. Figure 3-14 shows $\alpha$ as a function of $V_{BE}$ in the on-state of GB-HET3. We notice that $\alpha$ increases as $V_{BE}$ increases, which is very similar to what we observed in GB-HET2. Since the electron energy increases with $V_{BE}$, a larger portion of injected hot-electrons is able to overcome the filter barrier and contributes to $I_C$. The maximum value of $\alpha$ is $\sim 0.13\%$, which is much higher than $0.03\%$ in GB-HET2. Although these results suggest that the changes we made on the device structure and material choice indeed improve the performance of the GB-HET, $\alpha$ is still far below unity.

![Figure 3-14. The common-base current gain $\alpha$ as a function of $V_{BE}$ in the on-state of GB-HET3. $\alpha$ slightly increases as $V_{BE}$ increases since the energy of hot-electrons increases with $V_{BE}$.

$V_{CB} = 0.5\ V$

$\alpha (10^{-3})$

$V_{BE} (V)$

4.8 4.9 5.0 5.1 5.2 5.3 5.4 5.5

1.6 1.4 1.2 1.0 0.8

60
3-6. Summary

We fabricated two types of GB-HETs with high-k dielectrics as the filter barrier. The GB-HET having a 3 nm tunnel barrier (GB-HET2) could not be switched on because the tunnel oxide was not thick enough to sustain a high enough $V_{BE}$ bias to overcome the filter barrier. The normal transistor behavior was successfully demonstrated in the GB-HET having a 7 nm tunnel barrier (GB-HET3). Moreover, a current on-off ratio above 300 was achieved in the transfer characteristics of GB-HET3 and a current saturation in the output characteristics was observed in GB-HET3. These results presented the successful operation of the GB-HET with high-k dielectric as the filter and further confirmed that no energy bandgap in graphene was required to attain high current on-off ratio and current saturation. Hence, GB-HET is a very promising candidate for utilizing graphene’s unique properties in RF electronics. Finally, the extracted current gain in GB-HET3 is much higher than that in GB-HET2. Although it is still much smaller than unity, we will study and optimize the parameters that affect $\alpha$ in the next chapter.
Chapter 4

Optimization of the Device Parameters

We demonstrated and investigated the GB-HET with a Schottky barrier as the filter barrier and the GB-HET with high-k dielectric as the filter barrier in the last two chapters. High current on-off ratio and collector current saturation were achieved in the I-V characteristics for both device structures. However, the current gain $\alpha$ is still far below unity. In this chapter, we study the device parameters that affect $\alpha$ and optimize them for better performance.

There are two important factors that determine whether the injected electrons can contribute to $I_C$ and hence affect $\alpha$ in a GB-HET. One is the energy of hot electrons and the other is the filter barrier height. Low-energy electrons that enter the base region through undesirable channels in the tunnel oxide do not have sufficient energy to travel over the filter barrier to reach the collector. Thus, increasing the energy of hot electrons and suppressing low-energy electrons can increase $\alpha$. We have already seen that $\alpha$ is raised from 0.03% to 0.13% by changing the tunnel oxide from naturally oxidized $\text{Al}_2\text{O}_3$ to $\text{SiO}_2$ in the last two chapters. In addition, the filter barrier
height determines the required energy for the hot electrons to reach the collector. A lower filter barrier can increase the transmission possibility of electrons through the filter barrier and hence raise $\alpha$. [28, 29, 56]

In addition, theoretical studies suggest that the scattering and reflection in the dielectrics (i.e. the tunneling oxide and the filtering oxide) can significantly lower the electron kinetic energy. These energy loss mechanisms may be the ultimate limitation for further improvement of the device performance with the current choice of materials.

4-1. Optimization of the Tunnel Barrier

Based on the above analysis, in order to raise the energy of the injected electrons energy even more, a larger $V_{BE}$ bias was required to be applied on the SiO$_2$ tunnel barrier. Therefore, we further increased the thickness of the SiO$_2$ layer from 7 nm to 25 nm and fabricated GB-HET4 as shown in Figure 4-1. The device structure and fabrication process were the same as GB-HET3 except for the SiO$_2$ thickness.
Figure 4-1. (a) Schematic diagram of the GB-HET4. The thickness of the SiO$_2$ layer is increased from 7 nm to 25 nm to sustain a larger $V_{BE}$ bias across the tunnel oxide. Electrons can gain higher energy from the emitter with larger $V_{BE}$ bias. (b) The corresponding energy band diagram for GB-HET4.

The input I-V characteristics are very similar to GB-HET3 as shown in Figure 4-2 (a). Since $qV_{BE}$ will be greater than the graphene-silicon band offset (~3.3 eV), Fowler-Nordheim tunneling is also expected in GB-HET4. Hence, we are able to show a linear dependence of $\ln(I/F_{ox}^2)$ on $1/F_{ox}$ as in Figure 4-2 (b). The tunneling effective mass of 0.36 $m_0$ is extracted from the high-field regime of the Fowler-Nordheim plot.

Figure 4-2. (a) Input I-V characteristics ($I_E$ vs. $V_{BE}$) of GB-HET4 at different $V_{CB}$ biases. (b) Fowler-Nordheim plot of the tunneling current through the 25 nm SiO$_2$ tunnel barrier. The slope of the linear fitting at the high field regime reveals the effective mass of 0.36 $m_0$ for electrons tunneling through the SiO$_2$ layer.
The transfer I-V characteristics of GB-HET4 at various $V_{BE}$ are shown in Figure 4-3. Compared with GB-HET3, a higher $V_{BE}$ is required ($\sim 16$ V) to observe the increase of $I_C$ in GB-HET4 because of the thicker SiO$_2$ tunnel barrier. The current on-off ratio in this device is around 40, which is smaller than the on-off ratio in GB-HET3, nevertheless it is still at least one order magnitude higher than traditional GFETs. The current on-off ratio in a GB-HET is mainly limited by the magnitude of the on-state current, instead of the off-state current as in GFETs. The maximum on-state current is limited by the dielectric breakdown of the tunnel oxide.

Figure 4-3. Transfer I-V characteristics of GB-HET4 at various $V_{CB}$ biases. A larger $V_{BE}$ bias is needed to observe the increase of $I_C$ since the thickness of the SiO$_2$ tunnel barrier is increased. The current on-off ratio is $\sim 40$ for GB-HET4, which is mainly limited by the on-state current.

In addition, $\alpha$ is extracted from the I-V characteristics of GB-HET4 and plotted in Figure 4-4. Since the thickness of the SiO$_2$ tunnel barrier is increased from 7 nm to 25 nm, a larger $V_{BE}$ can be applied to the emitter without breaking down the dielectric. The extracted $\alpha$ in the on-state
of GB-HET4 (from $V_{BE} = 17$ V to $V_{BE} = 20$ V) is around 0.25% - 0.75%, which is a few times larger than $\alpha$ in GB-HET3 (0.13%). However, $\alpha$ reveals a decreasing trend as $V_{BE}$ increases, which is unexpected. As will be discussed later in this chapter, this phenomenon can be attributed to the acoustic phonon scattering mechanisms in the SiO$_2$ and Al$_2$O$_3$ dielectric barriers.

Figure 4-4. $I_C$ and $I_E$ as a function of $V_{BE}$ from 13 V to 20 V for GB-HET4. The common-base current gain $\alpha$ is calculated by dividing $I_C$ by $I_E$. The value of $\alpha$ is larger than what we obtained in GB-HET3. Unexpectedly, $\alpha$ exhibits a decreasing trend as $V_{BE}$ increases, which is related to acoustic phonon scattering in the SiO$_2$ and Al$_2$O$_3$ dielectric layers.

4-2. Optimization of the Filter Barrier

In addition to the energy of the injected hot electrons, the filter barrier height also play an important role in determining $\alpha$ of a GB-HET. To study the influence of the filter barrier on $\alpha$, we substitute the Al$_2$O$_3$ filter barrier layer with HfO$_2$ while maintaining the same thickness (20 nm).
in GB-HET5. The input and transfer I-V characteristics of GB-HET5 are shown in Figure 4-5. Because the tunnel barrier is identical in GB-HET4 and GB-HET5, IC starts to increase at a similar $V_{BE} (\sim 16 \, V)$ in both devices. More importantly, the extracted $\alpha$ rises up to $\sim 10\%$ when $V_{BE}$ is 18 V (see the blue dots in Figure 4-5). This is the largest $\alpha$ value that we have achieved among all of our GB-HET device structures so far.

Figure 4-5. IC and IE as a function of $V_{BE}$ from 13 V to 20 V for GB-HET5. The common-base current gain $\alpha$ is calculated by dividing IC by IE. The value of $\alpha$ is larger than what we obtained in GB-HET4. The improvement of $\alpha$ can be attributed to the lowered filter barrier height when replacing Al$_2$O$_3$ with HfO$_2$ for the filter barrier. $\alpha$ exhibits a decreasing trend as $V_{BE}$ increases, which is similar to GB-HET4.

This improvement of $\alpha$ originates from a lower filter barrier height in GB-HET5 than in GB-HET4. The lower filter barrier height in GB-HET5 can be attributed to two reasons, as illustrated in Figure 4-6. First, the band offset between the Dirac point of graphene and the
conduction band edge of the HfO$_2$ (~2.0 eV) is lower than that of Al$_2$O$_3$ (~3.3 eV), which is determined by the work function of graphene and the electron affinity of the dielectrics.[57, 58] Second, when the same $V_{CB}$ is applied, the Fermi level shift in graphene induced by the electrostatic potential $\phi$ across the filtering barrier is larger in GB-HET5 than GB-HET4 because HfO$_2$ has a larger dielectric constant than Al$_2$O$_3$. This shift reduces the energy difference between the Fermi level of graphene and the conduction band edge of the dielectrics, resulting in a smaller filtering barrier height. To estimate this Fermi level shift in graphene for both GB-HET4 and GB-HET5, we use the equation [59]

$$V_{CB} = \frac{E_{FG}}{e} + \phi$$

with $E_{FG} / e = h|V_F| \sqrt{\pi n} / e$ being determined by the quantum capacitance of the graphene, where $E_{FG}$ is the graphene Fermi level, $h$ is the reduced Planck constant, $V_F$ is the Fermi velocity of graphene, and $n$ is the carrier concentration in graphene; $\phi = n e / C_F$ being determined by the geometrical capacitance $C_F = \varepsilon_0 \varepsilon_{ox} / t_{ox}$ of the filtering barrier, where $\varepsilon_{ox}$ is the dielectric constant of the filtering barrier and $t_{ox}$ is the thickness of the filtering barrier. Since HfO$_2$ has a larger dielectric constant $\varepsilon_{ox}$ than Al$_2$O$_3$ [60], the Fermi level shift in graphene is larger in GB-HET5 (~0.18 eV) compared to GB-HET4 (~0.12 eV). The two reasons discussed above both result in a lower filter barrier height in GB-HET5. Therefore, a larger $\alpha$ is observed in GB-HET5.
Figure 4-6. Schematic energy band diagrams to illustrate the different filter barrier heights between GB-HET4 and GB-HET5. Using HfO$_2$ as the filter barrier for GB-HET5 reduces the barrier height between the Fermi level of graphene and the conduction band edge of the oxide.

4-3. Scattering and Reflection Mechanisms in the Dielectrics

Although we have achieved a significant increase of $\alpha$ from 0.03% to 10% by optimizing the device materials, the largest $\alpha$ in our devices is still much smaller than that in state-of-the-art hot-electron transistors and the unsatisfying $\alpha$ may limit the practical applications of GB-HETs. According to the operational principle of GB-HETs, the energy of the hot electrons and the filter barrier height determine whether the electron can contribute to $I_C$. We have increased the maximum $V_{BE}$ bias from 1 V in GB-HET1 to 20 V in GB-HET5, which should be much higher than the filter barrier height that we used in the devices. However, there is still a large portion of injected hot electrons that do not pass through the filter barrier and thus cannot contribute to $I_C$. In
addition, we observed that $\alpha$ decreased as $V_{BE}$ increased in GB-HET4 and GB-HET5. This means the transmission probability through the filter barrier is smaller when electrons have higher energy in these two types of GB-HETs. The low $\alpha$ and the decreasing trend of $\alpha$ as a function of $V_{BE}$ suggest that there are other energy loss mechanisms and reflection of electrons inside the device and these mechanisms play a very important role in determining $\alpha$.

The major energy loss and electron reflection mechanisms are illustrated in Figure 4-7. They include phonon scattering in the SiO$_2$ tunnel barrier, carrier-carrier scattering in graphene, reflection at the graphene-Al$_2$O$_3$ interface, phonon scattering in the Al$_2$O$_3$ filter barrier, and reflection at the Al$_2$O$_3$-metal interface.

![Figure 4-7. Major scattering and reflection mechanisms in GB-HETs. They cause energy loss and back scattering of hot electrons.](image)
When electrons are injected from the emitter to the base via F-N tunneling, they enter the conduction band of the SiO₂ layer first before reaching the SiO₂-graphene interface. Researchers have studied the high-field transport in SiO₂ by vacuum emission technique [61]. As shown in Figure 4-8 that the energy distributions of the electrons coming out from the SiO₂ were peaked at low-energy region (~2 eV above the conduction band edge of the SiO₂ layer). The peak moved up slightly with increasing electric-field and the electron energy distribution was broadened at higher fields. These results were explained well by considering longitudinal optical (LO) phonon scattering and acoustic phonon scattering in the SiO₂ layer. LO phonon scattering dominates the low-field behavior, while acoustic phonon scattering become dominating at higher fields. [62-64] Therefore, as we increase V_{BE} from 1 V to 20 V in GB-HETs, the hot-electron energy increases much less than what we expect from elastic tunneling. Most of electrons have energy below 2-3 eV above the conduction band edge of SiO₂ when they escape from SiO₂ and enter the graphene base. The phonon scattering in the SiO₂ limits the hot-electron energy that we can obtain by increasing the tunneling oxide thickness and the V_{BE} bias.
Figure 4-8. Electron energy distributions at different electric-field obtained from the vacuum emission experiment. These data were obtained from a sample with 50 nm SiO$_2$ and 25 nm Al [61]. The distributions are peaked at 2 eV. The peak only slightly increases and the electron energy distribution broadens at higher electric-fields. The results suggest that most of electrons have energy much less than what we expect from elastic tunneling when they escape from SiO$_2$ and enter the graphene base. Therefore, the phonon scattering in SiO$_2$ limits the hot-electron energy that we can obtain by increasing the tunneling oxide thickness and the $V_{BE}$ bias.

The carrier-carrier scattering (i.e., Coulombic) is the fastest energy relaxation mechanism in graphene with a time constant of 35 - 100 fs [65]. Assuming the hot-electron energy is 5 eV above the Fermi level of graphene and a free-electron model, the velocity of electron in graphene is $1.3 \times 10^6$ m/s. The thickness of graphene is only 0.34 nm [66], hence the time that it takes for an electron to traverse the base region in the direction normal to the interfaces is only ~0.26 fs, which is much smaller than the time constant of the carrier-carrier scattering. Therefore, hot electrons are unlikely to suffer from the carrier-carrier scattering as long as they travel in the direction normal to the interfaces through the base. On the other hand, if hot electrons are blocked by the filter barrier or back-scattered due to the acoustic phonon interactions, they will stay in the base and relax their energy very fast by carrier-carrier scattering.

When hot electrons travel through the base region, they arrive at the filter barrier. The transmission probability of hot electrons through the filter barrier consists of three components: the transmission probability for the graphene-oxide interface $\tau_{GO}$, the transmission probability in the oxide $T_{ox}$, and the transmission probability for the oxide-metal interface $\tau_{OM}$. The transmission probability for the graphene-oxide interface $\tau_{GO}$ is dominated by the k-space states limitation
because of the mismatch of the k-space states between the oxide side and the graphene side. It can be represented by the projection in the interface plane of the constant energy surface of the oxide onto that of the graphene. The transmission probability for the oxide-metal interface $\tau_{OM}$ is determined in a similar fashion. The transmission probability in the oxide $T_{OX}$ is dominated by LO phonon scattering and acoustic phonon scattering.

Researchers have studied the transport and transmission probability through thin metal-oxide-semiconductor structures by using the ballistic electron emission microscopy (BEEM) technique [67-70]. As shown in Figure 4-9 (a), the energy band configuration of BEEM is very similar to that of a hot-electron transistor, in which the emitter is replaced by a scanning tunneling microscope (STM) tip. The energy dependence of the transmission probability through such a thin metal-oxide-semiconductor structure can be investigated by varying the tip bias and measuring the tunneling current $I_T$ and the collector current $I_C$. As shown in Figure 4-9 (b), the transmission probability drops significantly as $V_T$ increases. This decreasing transmission probability with increasing $V_T$ was well explained by considering the phonon scattering in the oxide and the k-space state limitation at the metal-oxide interfaces. Acoustic phonon scattering was found the main mechanism that caused the low transmission probability at higher electron energy because of backscattering. An electron transport model based on Monte Carlo integration of the Boltzmann transport equation using a simplified band structure of the oxide and semiempirical electron-phonon scattering rates was used to simulate the transmission probability and the simulation results matched the BEEM experiment data very well [67, 68]. The observed behavior of the transmission probability with $V_T$ in BEEM experiment is consistent with our decreasing current gain $\alpha$ with $V_{BE}$ in GB-HET4 and GB-HET5.
Figure 4-9. (a) Schematic energy band diagram of the BEEM experiments. The energy band configuration of BEEM is very similar to that of a hot-electron transistor, in which the emitter is replaced by an STM tip. The energy dependence of the transmission probability through such a thin metal-oxide-semiconductor structure can be investigated by varying the tip bias and measuring the tunneling current $I_T$ and the collector current $I_C$. (b) Collector current and transmission probability through SiO$_2$ as a function of the tip bias $V_T$ for a Pt-SiO$_2$-Si sample from reference [67]. The transmission probability drops significantly as $V_T$ increases, which can be well explained by considering the acoustic phonon scattering in the oxide and the k-space state limitation at the metal-oxide interfaces.

Furthermore, BEEM was also used to study the transport through Al$_2$O$_3$ [69, 70]. Compared with SiO$_2$, the transmission probability through Al$_2$O$_3$ is much smaller because of more disorder scattering for Al$_2$O$_3$. The magnitude of the transmission probability through Al$_2$O$_3$ was ~ 0.1%, which was very close to the $\alpha$ value obtained in our samples with Al$_2$O$_3$ as the filter barrier.
All of above suggest that the unsatisfying $\alpha$ and its decreasing trend with increasing $V_{BE}$ is related to the phonon-scattering in the oxide and reflection at the graphene-oxide interface.

4-4. Optimization of the Device Geometry

It is worth mentioning that the GB-HETs with high-k dielectric material as the filter barrier have a “collector-up” design in order to achieve a low collector-base capacitance for eventually a high frequency response [71]. However, as shown in Figure 4-10 (a), the collector area is smaller than the emitter area in these devices, therefore only the electrons located at the smaller region underneath the collector can contribute to the collector current. The area ratio of the collector to the emitter is only $\sim 11\%$ for GB-HET3, GB-HET4, and GB-HET5, which could dramatically reduce $\alpha$. In order to solve this problem, the GB-HET device structure was revised to have current confinement structure inside the emitter to block undesirable current paths as shown in Figure 4-10 (b) (GB-HET6). An extra SiO$_2$ layer fabricated by local oxidation of silicon (LOCOS) technique was used in the current confinement structure and it assured that the injected current from the emitter only occurs right underneath the collector. The rest of the device parameters are the same as in GB-HET5.
Figure 4-10. (a) Schematic device structure for GB-HET3-5. As the collector area is smaller than the emitter area, only a portion of the injected hot electrons that are right underneath the collector can contribute to the collector current and the rest of the hot electrons only go to the base contact. (b) Improved structure (GB-HET6) with current confinement. The emitter active area is smaller than the collector area. The extra SiO2 layer confines the emitter current to flow only underneath the collector region.

The input and transfer I-V characteristics of the GB-HET6 are shown in Figure 4-11 (a). A significant increase of $I_C$ is observed when $V_{BE}$ is above 29 V. Unfortunately, the base-collector leakage current ($\sim 2$ nA) is much larger than the previous devices because of the change of the deposition facilities. Therefore, we only measure the transfer I-V characteristics at $V_{CB} = 0$ to minimize the leakage current. The current gain $\alpha$ is extracted after subtracting the leakage current from the collector current. We can see that the current gain moves up to $\sim 60\%$. We are conservative when looking at this result because the base-collector leakage current could provide extra channels for electrons to enter the collector without going over the filter barrier. Although the measured gain is high, the transistor loses its output performance. A more optimized fabrication process is needed to fully utilize the current confinement idea to raise the current gain.
Figure 4-11. (a) Input and transfer I-V characteristics for GB-HET6. A significant increase of $I_C$ was observed when $V_{BE}$ is above 29 V. The leakage current from base to collector is around 2 nA. (b) The current gain as a function of $V_{BE}$ for GB-HET6. Because of the base-collector leakage current, the current gain is calculated after subtracting the leakage current from the collector current. The current gain moves up to ~60%, however, the base-collector leakage current could provide extra channels for electrons to enter the collector without going over the filter barrier.

**4-5. Summary**

We studied the device parameters that may affect the current gain of GB-HET by changing the tunnel barrier thickness, the filter barrier material and the emitter/collector area ratio. By increasing the tunneling barrier thickness, a larger $V_{BE}$ bias can be applied across the tunnel oxide, therefore electrons can gain higher energy from the emitter. By replacing Al$_2$O$_3$ with HfO$_2$ as the filtering barrier material, the filter barrier height is lowered by 1.36 eV. The reduced filter barrier height allows a larger portion of hot-electrons to be collected. Benefiting from these parameter
optimization, the common-base current gain $\alpha$ is improved from 0.13% to 10% in spite of the smaller collector/emitter area ratio (~11%). A current confinement structure is implemented in the device structure to further improve the common-base current gain by increasing the collector/emitter area ratio. I-V characteristics indicate that the current gain moves up to ~60% in the device with the current confinement structure. However, the improvement is still arguable because of the base-collector leakage current in the device.

In addition, studies showed that the phonon scattering in the oxide and reflection at the oxide interfaces give rise to additional energy loss and change of direction for the hot electrons. When hot electrons are injected into the graphene base, their kinetic energy can be much less than what we expect from the elastic tunneling condition because of the phonon scattering in the tunneling oxide. Furthermore, the phonon scattering in the filter barrier and reflections at the graphene-oxide interfaces suppress the transmission probability of electrons through the filter barrier as $V_{BE}$ increases. These mechanisms have adverse impact on the current gain of GB-HETs and may limit the ultimate performance of GB-HETs with the current choice of materials. Novel material and technology that can have less phonon scattering and provide smoother interface transition are highly desirable.
Chapter 5

Conclusion and Future Works

5-1. Conclusion

The work presented in this dissertation focuses on the demonstration and development of the graphene-base hot-electron transistor (GB-HET). It combines the unique properties of graphene, including its single atomic thickness and zero bandgap, into the hot-electron transistor device structure in order to solve the low on-off ratio issue for traditional graphene field-effect transistor (GFET) and has great potential for RF applications. The fabrication, characterization and optimization of several types of GB-HETs have been discussed in this dissertation. Our results are highlighted in the following.

First, GB-HET1 with graphene-silicon Schottky barrier as the filter barrier was successfully fabricated and characterized. We successfully observed two distinguishable states (on- and off- state) of the collector current as the input voltage $V_{BE}$ increased. The maximum
current on-off ratio reaches \(\sim 10^5\). These results confirm that the operational principle of GB-HET does not require an energy bandgap in graphene in order to achieve high current on-off ratio in the transistor. In addition, current saturation is observed in the output characteristics of the transistor because of the weak dependence of the filter barrier height on the \(V_{CB}\) bias. The common-base current gain \(\alpha\) is extracted to be 0.03%. The low \(\alpha\) is attributed to the pinholes and low-energy extended states in the ultrathin aluminum oxide tunnel barrier.

Second, we revised the device structure and fabricated GB-HET2 and GB-HET3 with thermal SiO\(_2\) replacing native the aluminum oxide as the tunnel barrier and ALD grown high-k dielectric as the filter barrier. The thickness of the tunnel barrier in GB-HET2 (3 nm) is not thick enough to sustain a high enough \(V_{BE}\) bias for hot electrons to overcome the filter barrier. The transistor behavior was successfully demonstrated in the GB-HET3 when the thickness of the tunnel barrier was increased to 7 nm. The I-V characteristics of GB-HET3 also show a large current on-off ratio (\(\sim 300\)) and a current saturation behavior. Those results present the successful operation of the GB-HET with high-k dielectric as the filter barrier and further confirm that no energy bandgap in graphene is required to attain high current on-off ratio and current saturation. The current gain moves up to 0.13% from 0.03% as the result of the higher-quality tunnel barrier.

Third, we studied the device parameters that may affect the current gain of GB-HET. Three more GB-HETs were fabricated and characterized to investigate the influence of the tunnel oxide thickness (GB-HET4), the filter barrier height (GB-HET5), and the emitter/collector area ratio (GB-HET6) on the current gain. In spite of the smaller collector/emitter area ratio (\(\sim 11\%\)), a moderate value of \(\alpha\) (\(\sim 10\%\)) is achieved in our device by increasing the tunnel barrier thickness to 25 nm and decreasing the filter barrier height with HfO\(_2\) as the filter barrier. Current confinement design was introduced into GB-HET6 to help concentrate the emitter current into the area right
underneath the collector. Phonon scattering in the oxide and reflection at the oxide interfaces were studied and used to phenomenologically explain the unsatisfying $\alpha$ and its decreasing trend with increasing $V_{BE}$.

5-2. Suggested Future Works

From the work that has been done so far, the research on GB-HET is still on its early stage. There are still some issues in device modeling, process, experimental methods, materials, and fundamental physics. These issues prevent the implementation of GB-HET into practical applications:

First, a large scale CVD graphene growth and transfer technology has been used for the devices. However, this process is not mature enough for mass production yet. Poly(methyl methacrylate) (PMMA) used in the transfer process leaves residues on the graphene surface, resulting in low yield. Although the PMMA residues can be partially cleaned by various methods such as acetone, annealing and most recently acetic acid [72, 73], the results are still unsatisfying. Therefore, the optimization in graphene growth and transfer process is required to further enhance the GB-HET yield and performance.

Second, since the filter barrier is very critical to the current gain of GB-HET, novel materials with excellent properties would greatly improve the device performance. An ideal filter barrier material should have a relative low band offset with graphene ($<1$ eV) to reduce the operational voltage, while the band offset cannot be too low, otherwise the leakage current due to electron thermal energy will degrade the output performance of the GB-HET. In addition, an ideal filter barrier material should be compatible with graphene and have less k-space state mismatch
with graphene in order to minimize the interface reflection. The state-of-the-art hot-electron transistors utilize the graded compound semiconductor such as InAlGaAs to reduce interface scattering. Recently, van der Waals materials such as MoS$_2$ (semiconductor)[74] and h-BN (insulator)[75] have drawn more and more attention from researchers and scientists because of their versatile electronic properties and compatibility with graphene. They may be good candidates for the tunnel and filter barrier material in GB-HETs and bring GB-HETs closer to practical applications.

Last but not least, theoretical understanding and accurate physical models for the electron transport through graphene in the vertical direction and the transmission probability through the dielectrics are still lacking. A better understanding of the electron transport through graphene in the vertical direction may require new theories for this intriguing 2-dimensional system. According to the uncertainty principle, since the time it takes for electrons to travel through graphene is very short, the energy states of those electrons may be largely broadened once they enter the graphene. Therefore, the semi-classical ballistic transport model for conventional hot-electron transistors may not be valid in GB-HET. In addition, vacuum emission spectroscopy and ballistic electron emission microscopy are very good tools to study these physics. Electron energy distribution of the tunnel barrier and the transmission probability through the filter barrier for GB-HET can be obtained from these tools and help us have a better understanding on the transport physics in GB-HETs.
References


