Practical Challenges of Processing III-Nitride/Graphene/SiC Devices

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Abstract

Practical challenges associated with processing III-nitride/graphene/SiC devices are investigated. The III-nitride/graphene/SiC device structure has potential for implementation as a high frequency, high power hot electron transistor, where the III-nitride layer is the emitter, graphene is the base, and SiC is the collector. Formation of III-nitride emitter on epitaxial graphene is enabled by XeF_2 functionalization of the graphene, followed by atomic layer epitaxy (ALE) growth. The XeF_2 functionalization creates out-of-plane C-F bonds to serve as nucleation sites for III-nitride growth. ALE enables epitaxial growth of AlN, AlGaN, and GaN at temperatures low enough to utilize the C-F bonds. Continuous III-nitride films are capable of serving as a thermionic or tunnel emitter. Rectifying base-emitter heterojunctions (graphene-AlN) show potential for high efficiency, low leakage hot electron transistor operation.

INTRODUCTION

III-nitride/graphene/SiC devices can function as a hot electron transistor, potentially enabling high efficiency power switching, high frequency power converters, and terahertz microwave devices applicable to a wide range of military and commercial radar applications, electronic warfare, and communication systems. Although graphene has been traditionally researched as a channel material for field effect transistors [1], graphene can also be used as a vertical device topology. Implementing a wide bandgap collector material, such as SiC in a hot electron transistor increases the breakdown voltage and the Johnson's figure of merit of the device [2]. Demonstrations of graphene/SiC heterojunctions have indicated that high ON-current and low leakage, rectifying junctions are obtainable [3, 4].

With graphene as the base layer, the base resistance can be 10x lower than a semiconductor base, facilitating a high maximum oscillator frequency (f_{max}). Also, the base (graphene) thickness can be extremely thin, increasing the transistor cut-off frequency (f_T). To inject electrons across the graphene base into the SiC collector, the semiconductor material for the thermionic emitter must have a larger bandgap than SiC (3.2 eV). Therefore, III-nitride semiconductors are appealing to create a thermionic emitter. Alternatively, AlN could serve as tunneling junction for a tunnel emitter device. Processing hot electron transistor where the emitter is a III-nitride semiconductor, the base is graphene, and a SiC collector is extremely challenging. A key-processing step for realization of the hot electron transistor is growth of III-nitride semiconductors, such as AlN, AlGaN, and GaN, directly on graphene. Previously, epitaxial growth of the III-nitride/graphene heterostructure has been realized [5], a key enabling technology for graphene hot electron transistors.

DEVICE FABRICATION

Figure 1 illustrates a schematic cross-section of the III-nitride/graphene/SiC device. Fabrication of 16 x 16 mm^2 III-nitride/graphene/SiC devices began with 5 µm of epitaxial growth of n- SiC (n = 4 x 10^{15} cm^{-3}) on 4-degree offcut n+ SiC substrate for the collector layer.

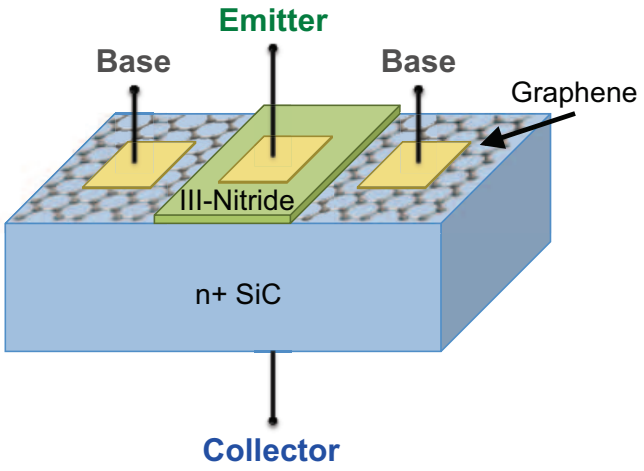

Figure 1. Schematic diagram of a III-nitride/graphene/SiC vertical transport hot electron transistor.

Next, sublimation of the SiC into graphene [6] was performed in an Aixtron/Epigress VP508 hot-wall chemical vapor deposition reactor. Approximately 4-5 monolayers of epitaxial graphene (EG) were formed on the surface of the SiC for the base layer, confirmed by X-ray photoelectron spectroscopy (XPS).

Processing the devices begins by pattering zero level alignment marks etched into the SiC using SF6/O_2 plasma. The base (graphene) mesas were etched using an O_2 reactive ion etch (RIE), eliminating graphene outside of the device active region. Then, the graphene was exposed to XeF_2 to create out-of-plane C-F bonds to allow for adhesion of atomic layer deposition (ALD) Al_2O_3 deposited in an Ultratech/Cambridge NanoTech Savannah system. The ALD Al_2O_3 serves as an interlayer dielectric to isolate the bond pads from the active area of the device. Next, the ALD Al_2O_3 was etched in buffed oxide etchant (BOE) to open a contact window down to the graphene to serve as the base contact. Then, the base metal (Ti/Al) is deposited by electron-beam metal evaporation and patterned by lift-off. Next, etching in BOE opens the emitter contact window exposing the graphene. Then, the sample is exposed to XeF_2 to functionalize the graphene in preparation for formation of the III-nitride emitter. Next, in a customized Ultratech/Cambridge Nanotech Fiji system, III-nitride films were grown by atomic layer epitaxy (ALE) on the surface. Finally, the emitter metal (Al) was evaporated and patterned by lift off.

Results and Discussion

The critical step to fabricating III-nitride/graphene/SiC devices is growth of III-nitride films on graphene. A pristine graphene sheet, such as grown epitaxially on a SiC surface, will have sp^2 bonding, with few dangling bonds on the surface. Epitaxial growth is typically nucleated at dangling surface bonds, thus it is problematic to grow semiconductor epitaxial layers directly on a graphene surface. Exposing the graphene surface to XeF_2 allows for creation of sp^3 nucleation sites on the top graphene surface allowing for epitaxial III-nitride growth. Growth of an AlN epitaxial layer by ALE on a graphene surface by first creating sp^3 nucleation sites using XeF_2 exposure shows uniform coverage by atomic force microscopy (AFM) as seen in Figure 2. Large area growth of four layers of graphene on the entire SiC wafer allows sp^3 bonds to be created on the top graphene sheet, that will serve as nucleation sites, while preserving the pristine sp^2-bonded nature of the underlying graphene sheets. The X-ray diffraction (XRD) full width half max (FWHM) of the (0002) and (0004) peaks are comparable to AlN films grown on SiC and sapphire XPS results. For example, rocking curves of ALE grown films on graphene show GaN(0002) and GaN(0004) to be 544 and 461 arcsec [5].

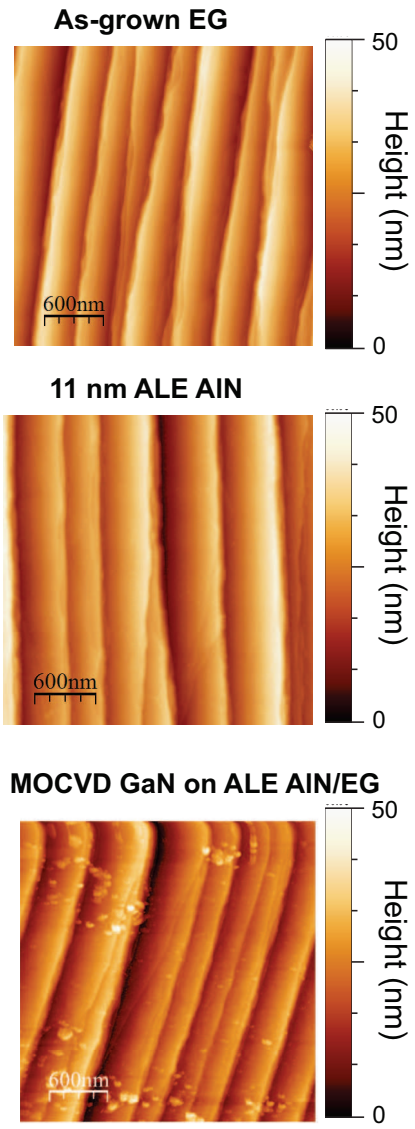

Figure 2. AFM images of As-grown EG surface, after growth of 11 nm of ALE AlN, then after growth of MOCVD GaN on the ALE AlN/EG [5].

A tunnel emitter structure was grown on EG by ALE with an initial base layer of 3 nm of 280 °C AlN to utilize the C-F bonds created by the XeF_2 at low temperature. Then, 1.5 nm of 400 °C AlN was grown to provide an improved quality AlN layer. Then, 2 nm of 400 °C GaN was grown to cap the layer structure to prevent oxidation of the AlN. XPS was performed on the ALE stack using a Thermo Scientific K-Alpha system with the instrument operating at a background pressure of 10-7 torr. High-resolution XPS spectra of Al 2p and N 1s peaks are shown in Figure 3. Fitting Al 3d and N 1s peaks indicates the presence of Al-O N species besides Al-N. Ga Auger peak is due to ~1 nm GaN cap layer. Thicker III-nitride layers can then be grown by metal organic chemical vapor deposition (MOCVD).

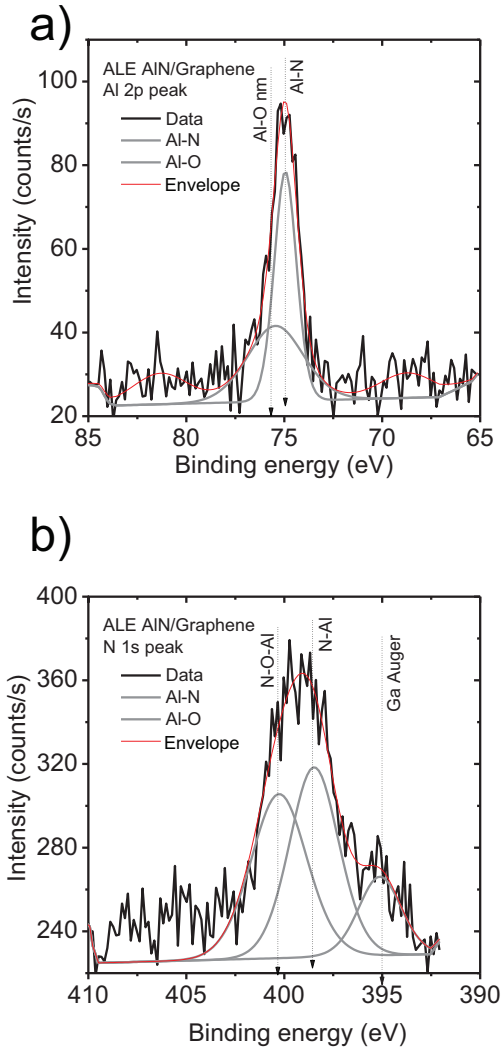

Figure 3. High resolution XPS spectra of Al 2p and N 1s peaks are shown in Fig. Fitting In 3d and N 1s peaks indicates the presence of Al-O besides Al-N. Ga Auger peak is due to ~1 nm GaN cap layer

The base-emitter (graphene-III-nitride) heterojunction is shown to be rectifying as shown in current-voltage (I-V) characteristics in Figure 4a. In Figure 4b, the base-collector (graphene-SiC) heterojunction exhibits increased leakage in the off state due to the high doping of the n+-SiC collector layer. This undesirable leakage can be overcome by implementing a lowly dope n-type epitaxial SiC layer allowing for the hot electron transistor to modulate to the off state.

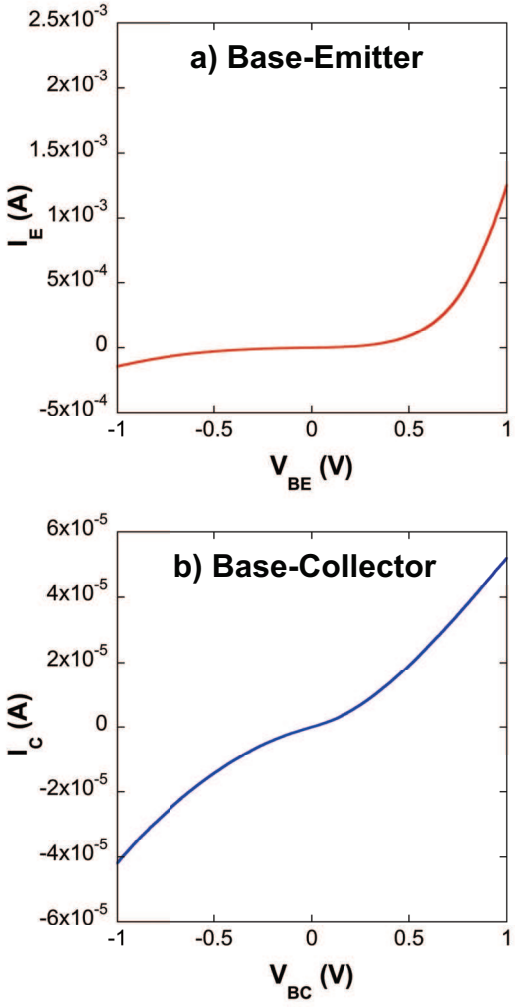

Figure 4. I-V characteristics for a) base-emitter (graphene-III-nitride) and b) base-collector (graphene-SiC).

The three-terminal measurement of the III-nitride/graphene/SiC structure (Figure 5) shows injection of electrons from the emitter to collector. The base voltage modulates the turn on voltage of the emitter to collector current and shows promising results for future hot electron transistors enabled by III-nitride/graphene/SiC heterostructures. However, the large base-collector leakage current prevents the transistor from turning completely off.

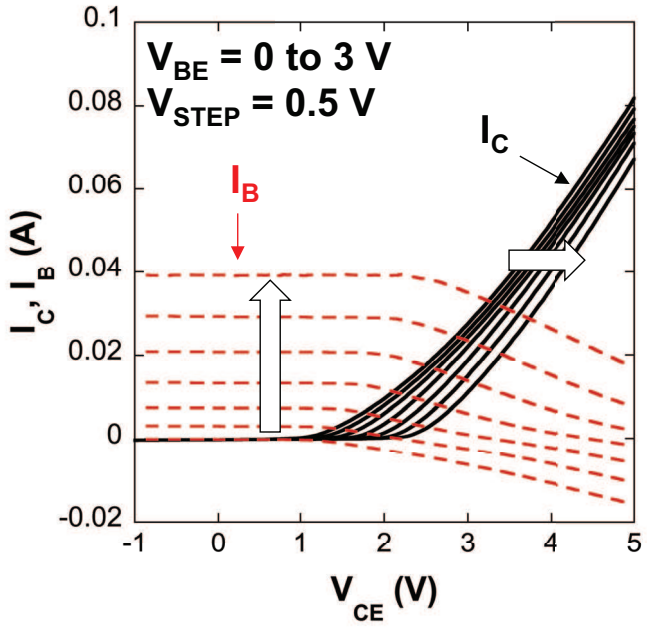

Figure 5. Three terminal measurement of the III-nitride/graphene/SiC device.

The large base current (I_B) observed increasing with increasing base-emitter voltage (V_{BE}) is due to the poor base-emitter junction, since the graphene was grown on n^+ SiC. A low doped SiC drift region would support lower base-collector leakage current.

Conclusions

A device consisting of III-nitride/graphene/SiC shows potential for a hot electron transistor capable of operating at high frequency with a high breakdown voltage. Practical challenges associated with the fabrication of these devices include formation of the III-nitride films on pristine epitaxial graphene. Functionalization of the graphene surface by XeF_2 creates C-F bonds enabling nucleation sites for III-nitride growth by atomic layer epitaxy. Both the base-emitter and base-collector demonstrate rectifying characteristics, yet the lack of a low-doped collector region created excessive collector leakage preventing the structure from turning completely off.

Acknowledgements

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Acronyms

AFM: Atomic force microscopy
ALD: Atomic layer deposition
ALE: Atomic layer epitaxy
BOE: Buffered oxide etchant
EG: Epitaxial graphene
HET: Hot electron transistor
RIE: Reactive ion etch
XRD: X-ray diffraction
XPS: X-ray photoelectron spectroscopy