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Electronic Structure of Ultra-wide Bandgap Semiconductor Surfaces and Interfaces

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EXECUTIVE SUMMARY

In this program, experimental capabilities were developed that can directly probe the interface region in ultra-wide bandgap (UWBG) heterostructures and thereby provide fundamental information about the interface electronic properties (e.g., barrier height, band offset) that are critical to electronic device performance. These capabilities are based on a new custom light source that can be tuned across an extremely broad spectral range (NIR to DUV), thereby enabling the use of internal photoemission and other threshold photoexcitation techniques to probe the interface, surface, and bulk electronic structure in UWBG materials. By using these techniques in combination with a surface analysis system that provides complementary chemical and lattice structure information, systematic studies can be used to gain a better understanding of epitaxial UWBG materials and device structures under development. Ultimately, this research can provide a scientific foundation to guide the design and fabrication of high-power electronic device technology based on next-generation UWBG materials that is of critical importance to the Navy.

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Final Report: Electronic Structure of Ultra-wide Bandgap Semiconductor Surfaces and Interfaces (Work Unit: 1L60)

1. INTRODUCTION

1.1 Background and Motivation

Ultra-wide bandgap (UWBG) materials have tremendous potential to provide the higher-power, higher-temperature, and superior RF performance needed for next-generation Navy systems. To advance this future capability, NRL is pioneering the molecular beam epitaxial (MBE) growth of new UWBG materials for device fabrication, including AlN, Ga_2O_3, and c-BN (with bandgaps of 6.2, 4.9, and 6.4 eV, respectively). However, the electronic properties of these materials are relatively unexplored due to the extreme nature of their band structure and the difficulty in growing the materials epitaxially. The electronic properties at interfaces in UWBG heterostructures are especially important since UWBG device characteristics will be dominated by electronic properties such as the barrier height at a metal interface, band offsets at a semiconductor interface, and traps and defect states in the interface region (Fig. 1a). As such, it is imperative to gain greater insight into the material properties and dynamical processes that govern interface formation in UWBG material systems.

While interfaces are conceptually simple, they are actually very challenging to model, and all the more so in newly-emerging UWBG structures. This is due to the fact that the interface electronic structure is dependent on the surface and bulk properties of the two materials in contact. However, most of these surface and bulk properties are not fundamental constants of the material and must be measured. The interface properties are also difficult to model since interface formation is a dynamical process that depends on atomic-scale interactions driven by the specific formation conditions. As a result, it is important to study the surface and interface properties under carefully controlled conditions.

Even with such control, these studies are challenging. In fact, only a few previous studies of the surface electronic structure have been performed on UWBG materials such as AlN. Such surface studies are typically performed in ultrahigh vacuum (UHV) systems using photon and electron spectroscopy. However, these surface-sensitive techniques can only probe about 2 nm below the surface due to the short inelastic mean free path of the emitted electrons, and therefore they are not able to access deeper-lying interface regions. Instead, the interface properties of semiconductor devices are typically characterized indirectly by fitting electrical measurements to an idealized analytical model to calculate barrier heights and other key transport parameters, but these techniques break down for UWBG materials and devices.

Recently, internal photoemission (IPE) spectroscopy has emerged as a powerful method to directly probe and evaluate the interface electronic structure in semiconductor and oxide structures. In such IPE

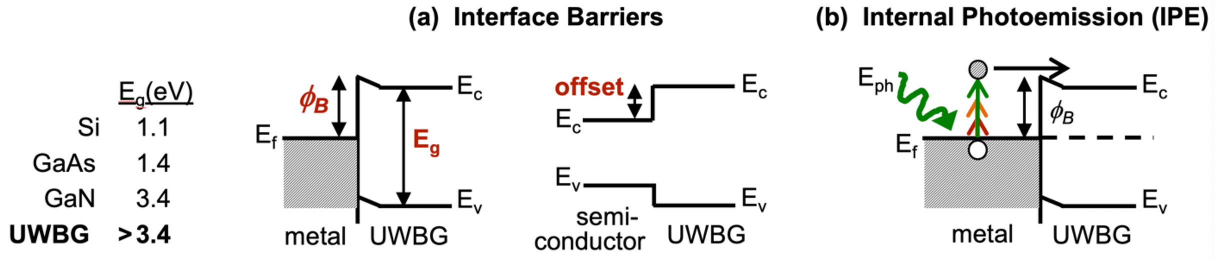

Fig. 1 — (a) Energy band diagrams of UWBG material interfaces with metal and semiconductor. (b) Schematic of IPE technique in which the threshold photon energy provides a direct measurement of the barrier height (ϕ_B) or band offset.

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measurements, a photon beam (from a tunable light source) is directed at the surface of a heterostructure, and the photon energy is systematically increased until photoelectrons are injected over the interface barrier and a photocurrent is detected (Fig. 1b). Hence, the threshold photon energy provides a direct measure of the interface barrier height, while analysis of the photocurrent spectra at higher photon energy can provide additional transport information in the near-interface region. Additionally, threshold photoconductivity (PC) measurements can be used to determine the bandgap and probe for defect states.

Broadband light sources are now available that extend far into the UV, thereby making the IPE technique well suited for UWBG material structures. However, the measurements must be done in vacuum to avoid the negative impacts of ozone production at high photon energy. As a result, it is advantageous to combine the IPE technique with UHV surface analysis to evaluate both the surface and interface properties. Importantly, NRL has surface analysis facilities along with state-of-the-art MBE facilities for the growth and characterization of novel UWBG materials. With these capabilities, NRL is uniquely positioned to undertake this challenging but important research to characterize the surface and interface electronic properties of UWBG materials and thereby provide a scientific foundation for the development of next-generation electronic devices.

1.2 Technical Goals

The scientific objective of this research program is to gain a better understanding of the electronic structure at surfaces and interfaces of newly-emerging UWBG materials and heterostructures through the use of threshold photoexcitation techniques. Through systematic and controlled studies, insight can be gained into how the growth conditions and material properties affect the interface structure and transport properties. This knowledge can then guide the optimized growth of epitaxial UWBG semiconductors and lead to more accurate device design and performance modeling. Ultimately, the realization of high-performance UWBG materials will enable the development of advanced electronic devices with higher power output, higher temperature operation, and superior RF and mm-wave performance for future Navy radar, EW, and communications systems.

2. TECHNICAL APPROACH

2.1 Materials Growth

UWBG films and heterostructures are grown by MBE using growth facilities in NRL Code 6852 (e.g., AlN (WU 1L59), Ga_2O_3 (WU 1J04), and c-BN (WUs 1V16, 2A67). In particular, the UWBG films and test structures (with refractory metal or metal nitride contact layers) can be designed for compatibility with the measurement technique and modeling approach. Because the growth parameters can strongly influence the film and interface properties, the material growth and characterization efforts are coordinated so as to allow for a systematic study of tailored materials under controlled conditions. Through this approach, the electronic properties of the material can be correlated to the specific growth conditions and thereby provide critical feedback to the growers. The initial studies are focused on AlN-based structures to gain an understanding of the interface characteristics that are critical to the performance of device structures currently under development. Meanwhile, the interface and surface properties of newly-emerging Ga_2O_3 and c-BN materials can be characterized when appropriate test structures are available for study.

2.2 Experiments

Threshold photocurrent spectroscopy (IPE, PC, photoyield) is used to directly characterize the electronic properties of the UWBG materials. However, this measurement approach requires a tunable photon source that can cover the full energy range in UWBG device structures, i.e., as high as 6 - 7 eV for bandgaps and as low as sub-eV for interface barriers. In this program, recently-developed laser-driven light source (LDLS) technology (from Energetiq Technology) is exploited that provides high-brightness output across the NIR-VIS-DUV spectrum (i.e., 0.6 - 7.3 eV). The LDLS is then coupled to a customized computer-driven monochromator (from Horiba Instruments) that can precisely tune the photon energy as needed to characterize electronic features within the surface, bulk, and interface regions (Fig. 2). When working in the UV regime, however, the negative impacts of ozone production must be avoided. To do so, the light system is fully purged with nitrogen gas and measurements are taken in a vacuum chamber.

The threshold spectroscopic studies are performed in a UHV chamber that houses a range of surface analysis techniques including Auger electron spectroscopy (AES) and x-ray photoemission spectroscopy (XPS) for in-situ chemical analysis and low energy electron diffraction (LEED) for lattice structural analysis. With this experimental set up, the interface and surface properties can be evaluated in a very controlled environment. In particular, the studies can evaluate the influence of temperature and surface treatment on the surface and interface properties so as to gain insight into the dynamics that govern the resulting electronic structure.

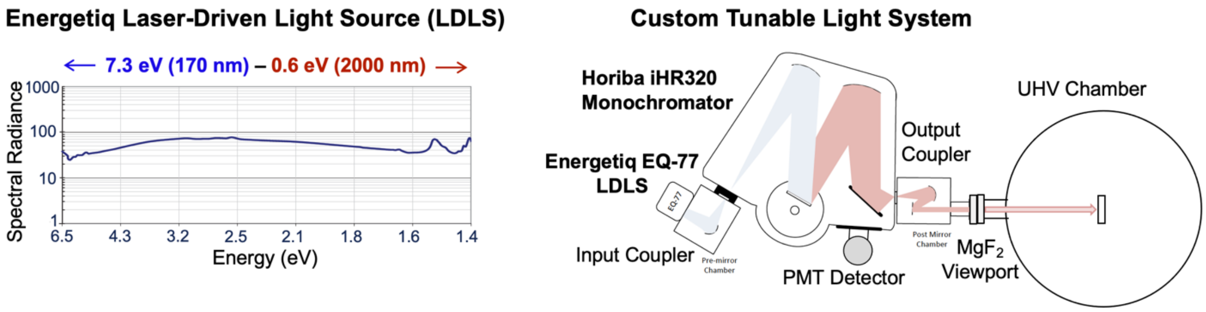

Fig. 2 — Custom tunable light system consisting of LDLS with broad spectral output and precision monochromator customized for high UV throughput. The light system is attached to a UHV chamber for measurements in the UV regime.

2.3 Measurements

2.3.1 Surface and Bulk Properties

The surface chemical composition and lattice structure are determined using AES/XPS and LEED, respectively. In addition, photoyield measurements and photo-assisted secondary electron emission spectroscopy can be used to characterize the surface electronic structure (ionization energy, electron affinity, and Fermi level) while PC measurements are used to determine the bulk electronic structure (bandgap, gap states) of UWBG films and heterostructures. Further analysis of the photoyield spectra can provide information about surface states and band bending that may influence interface formation. By correlating the electronic, chemical, and structural properties to each other and to the specific growth conditions, surface models can be established for the UWBG materials.

2.3.2 Interface Electronic Structure

IPE is used to directly measure the barrier height or band offset at relevant interfaces, while analysis of the photoyield spectra can provide information about possible near-interface states that impact the transport efficiency. The measurements are taken over a range of temperatures to characterize the thermodynamic changes in the electronic properties, which are critical to the performance of high-power devices. By correlating the interface properties to the surface and bulk properties of the films, as well as to the growth parameters, interface models can be established for the UWBG heterostructures.

As a first step, IPE measurements can be correlated with the material and growth parameters to identify common trends and determine the factors that influence the barrier height. As a next step, the photoyield spectra can be analyzed using existing IPE models in the literature to interpret energy-dependent features in the curves. Through such modeling, information can be deduced about the electronic properties in the near-interface region (which may differ from the bulk) and gain insight into the mechanisms that limit electron transport across the interface.

3. EXPERIMENTAL SYSTEM

3.1 Tunable Broadband Light System

The tunable broadband light system was designed and procured following extensive discussions with Energetiq and Horiba, who agreed to collaborate on the custom order. Upon delivery, the light system was installed (Fig. 3) by a Horiba engineer, and basic training was provided. However, it was later discovered that the DUV photonic output did not meet the stated specifications. Eventually, it was determined that the pressure / flow rate of the nitrogen purge gas must be higher than specified to avoid even minute amounts of ozone generation that decrease the UV/DUV photonic output.

The spectral output of the light source was then evaluated using the integrated photomultiplier tube (PMT) detector and Horiba-provided software. Due to the one-of-a-kind design of the light system, a significant effort was required to become proficient in its use. Specifically, the various mechanical components (e.g., slits, apertures, and gratings) and optical components (mirrors, filters) were adjusted in a systematic manner to confirm proper behavior and to document their effects on the output power and beam properties.

The output spectral power at the target position was measured as a function of photon wavelength using external photodiode sensors (from ThorLabs). Because of the wide spectral range of the light source, two sensors were required to cover the low and high wavelength range (i.e., 200-1100 nm and 700-1800 nm, respectively). The calibration measurements are critical for accurate analysis of the measured photocurrent spectra, and they require precise synchronization between the power meter and the monochromator control. Similarly, the automated acquisition of photocurrent spectra from UWBG test structures must be synchronized with the monochromator. To achieve such synchronization, calibration and data acquisition programs were written using LabVIEW software. Because of the extensive range of variable parameters, the programs required extensive testing and modification before they were bug free.

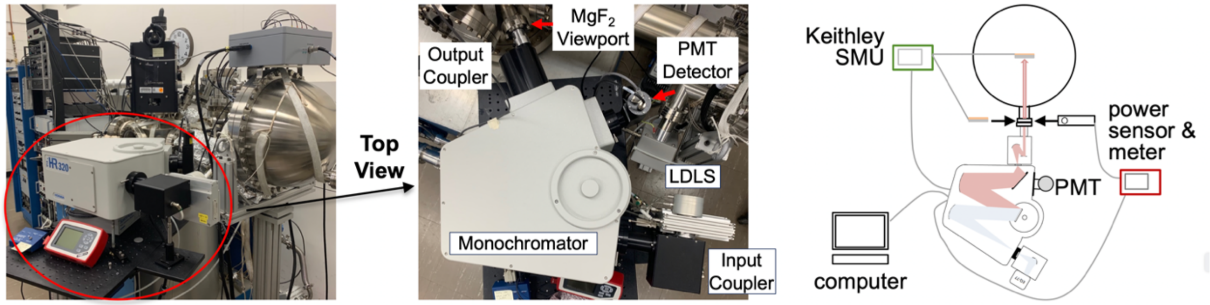

Fig. 3 — Custom tunable light system after installation; and illustration of measurement configurations, where sample can be positioned inside or outside of vacuum chamber.

It should be noted that, while this custom light system is very versatile and can be used in a wide range of studies, it is a prototype design and falls outside of the standard applications that are supported by Horiba. As such, a significant effort was required by NRL to verify and optimize the mechanical and optical configurations. During the initial evaluations using the PMT and photodiode sensors, several issues were discovered that were eventually resolved, including:

1. Spectral shifts and intensity changes were observed in PMT measurements taken over the course of a day. Upon analysis of detailed spectral scans, it was concluded that the spectral changes are a consequence of the closed monochromator slits (i.e., ~10 micron wide) required to avoid PMT saturation. Unfortunately, this means that the PMT detector cannot be used as planned to monitor the stability of the LDLS without the insertion of a neutral density filter into the PMT housing (which requires an on-site service visit by a Horiba technician).
2. Large variations in the output power were observed in photodiode measurements taken on different days. Fortunately, a systematic study demonstrated that the spectral output power was sufficiently stable throughout a given day so as to meet the stability specifications of the LDLS. However, the day-to-day spectral variation appears to correspond to changes in atmospheric conditions, especially humidity (in spite of being within acceptable humidity specs). To limit the absorption of water in the light system, the background nitrogen flow rate was increased during non-use periods.

Prior to taking photocurrent measurements from UWBG samples, a series of calibration measurements was taken using the two power sensors. For the measurements, a mounting assembly was constructed to reproducibly position the two sensors in the same position in front of the monochromator exit plane. To cover the full wavelength range (200-1800 nm), a series of spectral scans were taken using the appropriate filter and grating for each wavelength range. The scans were then repeated for varying slit and aperture widths to determine the optimum parameters for maximum throughput and resolution.

3.2 UHV Characterization System

3.2.1 UHV Chamber

An existing UHV analysis chamber was modified to house instrumentation needed for the threshold photocurrent measurements as well as for characterization of the chemical and lattice structural properties of the UWBG surfaces (Fig. 4). Specifically, a specialty MgF_2 viewport was mounted on the UHV chamber to permit the efficient transmission of the monochromatized light (especially UV/DUV photons) into the chamber. Additionally, a high-resolution hemispherical energy analyzer from ScientaOmicron was mounted on the chamber for taking XPS and other photoemission measurements from the sample surface, and an x-ray source was procured to enable the XPS capabilities. In addition, a LEED/AES energy analyzer from ScientaOmicron was mounted for evaluating both the chemical composition and lattice structure at the same sample spot. Finally, a sputter ion gun was installed for surface cleaning studies.

Because of the newly added instrumentation, each of which has a fixed working distance, a new sample manipulator was configured to permit the necessary sample positioning. Specifically, a long-travel XYZ-manipulator stage with 4” bore was mounted directly on the top port of the chamber. On top of this stage, a multi-port flange was mounted for connecting electrical and thermocouple feedthroughs used for sample bias, heating, and temperature measurement. In the center of the flange, a precision rotary feedthrough was mounted for positioning the sample stage in front of the various instrumentation about the chamber. With this design, the sample stage can be easily inserted and removed from the chamber by lifting the relatively light multi-port flange, while the heavy XYZ-manipulator remains fixed on the chamber.

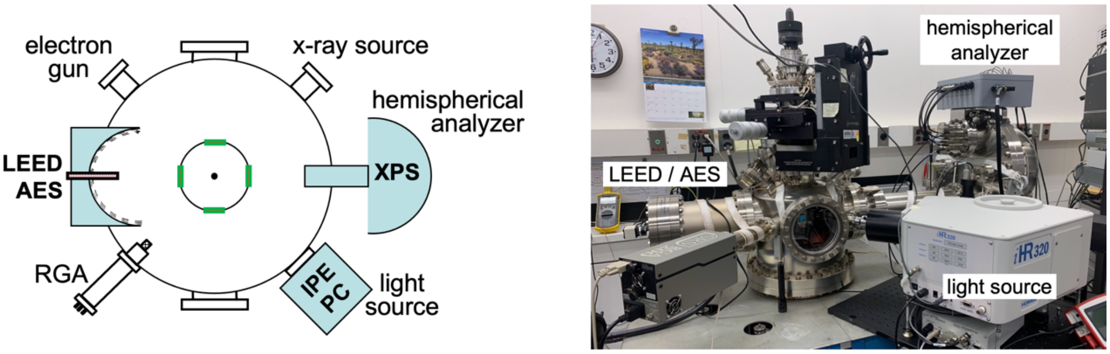

Fig. 4 — (a) Top-view schematic and (b) photo of UHV characterization chamber

3.2.2 *Sample Stage*

IPE measurements are challenging since a bias must be placed across an electrically isolated sample in the forward and/or reverse direction. In addition, it is necessary to heat the sample and measure the sample temperature. To satisfy these requirements, it was necessary to design and build a new sample stage to provide the electrical biasing, heating, and measurement capabilities needed to study the interface, surface, and bulk properties of a broad range of UWBG material films and structures under development (Fig. 5). To make these measurements possible, sample holders were machined using an adjustable slot design to accommodate a wide range of sample sizes for the different UWBG materials being grown. In addition, the holders were designed to provide electrical isolation of the front and back sides as needed for sample biasing. More generally, the stage was designed to allow for:

- Three samples of varying size from 5x5 mm^2 to 18x18 mm^2
- Isolated front-side and back-side contacts for forward/reverse biasing (in IPE measurements)
- Heater filaments and thermocouple leads for sample heating (in temperature-dependent measurements)
- A phosphor screen for analyzing the size/shape of the output light beam at the sample position
- A Faraday cup for evaluating the beam size/current from the LEED/AES electron gun

The construction of the new sample manipulator stage was challenging for several reasons. First, the wide range of sample sizes and experimental configurations used in the studies required a novel design for a universal sample mount and compatible lead assemblies that could be used for all samples and measurement techniques. Due to procurement limitations (during the pandemic), the sample mounts and

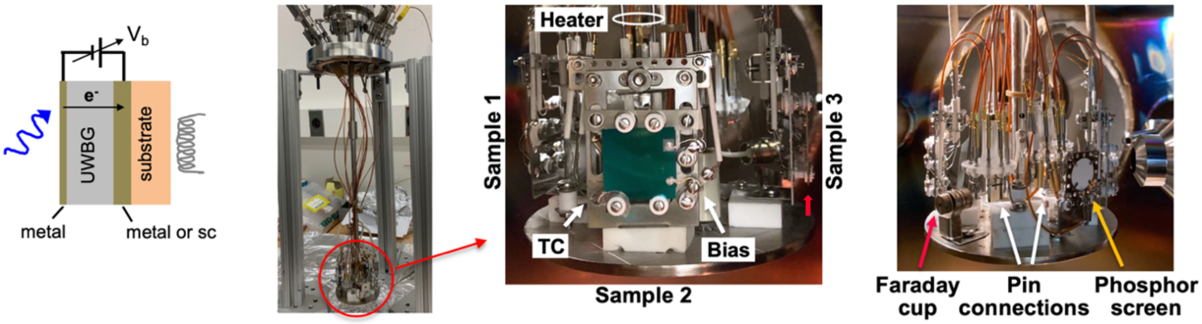

Fig. 5 — Schematic of sample holder with required biasing for IPE measurements; and photos of constructed sample manipulator and stage with sample holders that provide such biasing capabilities.

lead assemblies were designed in-house using a set of modular electron-gun assembly parts that were available from previous programs. After several design iterations and model assemblies, sample mounts were machined in-house that were compatible with the commercially-available modular parts, thereby allowing for greater flexibility to modify and optimize the design as needed. Secondly, the numerous components (e.g., mounts, leads, and connectors) were constrained to fit onto a 3.5”-diameter base plate positioned approximately 16” below the top mounting flange (using a long rod), with fifteen lead wires extending from feedthroughs on the top flange to the base plate. Because of these physical constraints, a very compact design was required that could still provide easy access to all components. While the design and construction required a significant effort, the universal mount and lead assemblies allow multiple samples to be quickly inserted and removed from the stage in a reliable and reproducible manner. In addition, a modified sample holder and a modular mount assembly (with alignment capabilities and BNC connections) were constructed for IPE measurements taken outside of the UHV chamber when non-UV light can be used.

4. MEASUREMENTS AND RESULTS

The manipulator stage was loaded into the chamber with three samples that included two different NbN/AlN/NbN/SiC device structures and a GaN sample. Electrical contacts were made on all three samples by bonding gold (Au) wire using UHV-compatible high-temperature silver paste. For the NbN/AlN/NbN/SiC samples, two wires were bonded to NbN metal at the surface and at the buried layer (exposed by etching) for IPE measurements; and for the GaN sample, two wires were bonded to front-side indium contacts for PC measurements. The wires were then connected mechanically to contacts on the sample holders. To enable sample heating, coiled W filaments were formed using 9 mil W wire, and the filaments were positioned closely behind the samples. A Cr/Al thermocouple pair was positioned at the front corner of each sample and was held in place by a mica washer to ensure good contact with the surface. After inserting the manipulator stage into the UHV chamber, the system required extensive time to pump down due to outgassing produced by the numerous Kapton-coated wires and other mechanical and electrical components in the sample stage assembly. Prior to bake out, a custom transfer cart was designed and built to move the tunable light system away from the chamber (and to properly re-position and align the light source after re-installation). The vacuum system was then baked extensively and eventually reached a base pressure of ~3-4 x 10^{-10} Torr.

Following bakeout, the various components on the manipulator stage were tested. First, the resistance between the GaN surface contacts remained reasonably high (~ 2 MΩ), but the resistance between the NbN contacts decreased significantly after the extended bakeout. The pre-bake resistance had already been less than optimal ($R < 1$ MΩ) for both NbN/AlN/NbN/SiC samples, but the resistance after bakeout was 2.4 kΩ at one sample and 200 Ω at the other. This was unfortunate since it is important to have very low leakage current for IPE and PC measurements. The filament heaters were tested next, and they produced sample heating up to T ~ 200-300 °C through radiative heating alone. Higher sample temperatures are possible using electron-beam heating, but this could not be performed with insulating SiC substrates.

4.1 Bandgap Measurements of GaN Film

In order to verify the accuracy of the threshold photocurrent technique, PC measurements were used to determine the bandgap of the conductive (Si doped) GaN sample (Fig. 6). During optical illumination, a bias was applied across the front-side contacts so as to sweep the photogenerated electrons and holes to opposite sides. The photogenerated current was then measured for a range of bias voltages (0.5-1.5 V) and slit/aperture widths using a Keithley 2611B SourceMeasure unit (SMU). As the photon energy was scanned (starting at sub-gap energy), a sharp rise in photocurrent was repeatedly detected at ~3.4 eV (consistent with the known GaN bandgap). While a background signal of ~ 0.1-1 microamp was present due to the

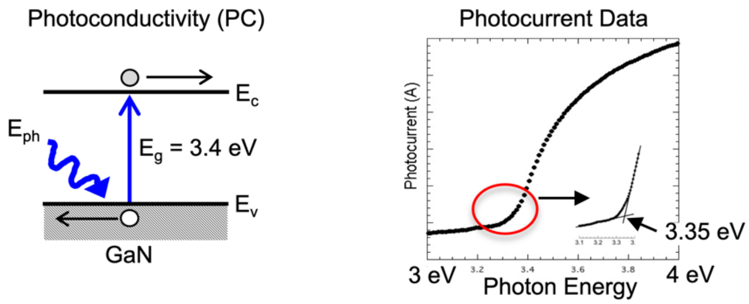

Fig. 6 — Determination of GaN bandgap from photoconductivity measurements

resistance between the surface contacts, the rise in photocurrent signal was sufficiently higher. As such, the measurements verified the threshold photocurrent technique using the tunable light system.

4.2 Interface Studies of NbN/AlN/NbN/SiC Heterostructure

For the first interface studies, IPE measurements were taken from the NbN/AlN/NbN/SiC sample with R = 2.4 kΩ (Fig. 7). This AlN tunnel structure consisted of a 200 nm thick AlN layer sandwiched between two NbN layers, which are metallic. For the initial measurements, an interface barrier height of 1.0-1.3 eV (or 950-1200 nm) was assumed based on reports in the literature, and a series of spectral scans were taken for varying wavelength range and grating / filter selection. However, neither the 550-nm filter (with range 600-1100 nm) nor the 1-micron filter (with range 1100-2000 nm) provided continuous coverage across this range of interest, and therefore multiple scans were taken using each filter. During optical illumination, a bias was applied across the NbN contacts so as to sweep the photoexcited electrons across the AlN film into the NbN buried layer. The photogenerated current was then measured for a range of bias voltages (V_b = 0.01-0.1 V) and slit/aperture widths using the Keithley 2611B SMU. Unfortunately, a rise in photocurrent was not detected in the IPE measurements, and thus the interface barrier height was not measured.

One problem may be the large background signal present in the measured spectra. On some days, a background current of ~ 4-38 microamp was present (depending on bias voltage), which was consistent with the contact resistance. However, on other days, the background current was as high as 750 microamp. It is suspected that an intermittent source of noise is present in the lab, and this needs to be investigated. However, a more fundamental challenge for the photocurrent measurements will be to improve the electrical contacts in order to reduce leakage current and improve the sensitivity of the measurements.

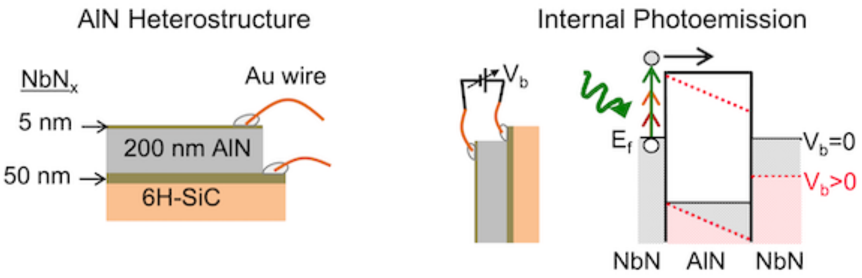

Fig. 7 — Schematic of AlN heterostructure used in IPE measurements; and energy band diagram of NbN/AlN/NbN heterostructure with and without a bias voltage applied across the heterostructure.

4.3 Surface Studies of NbN Films

Early in the program, a parallel surface analysis study was performed in a different UHV analysis system while waiting for delivery of the light source. Specifically, transition metal nitride (TMN) films grown by MBE in Code 6852 were characterized by XPS after exposure to atmosphere. The goal of this study was to determine whether the resulting oxide layer can be removed by annealing or sputtering in vacuum without damaging the film. This is a critical issue since TMNs, such as NbN_x and Ta_2N, have the potential to enable advanced electron heterostructures and devices, but the surface must be controlled prior to epitaxial growth of subsequent semiconductor layers. To investigate this issue, a 20-nm thick NbN_x film (grown on a SiC substrate) was annealed from 100°C to 950°C in 50°C increments up 600°C and in 25°C increments subsequently. After annealing at each temperature, high-resolution XPS measurements were taken to determine the relative concentration of O, Nb, and N (as well as Si and C) within the ~2-nm-thick measurement region (Fig. 8a). Prior to heating, the relative oxygen concentration was ~37%, but the surface oxygen was gradually removed during heating to 600°C. However, a measurable concentration of bound oxygen (~5%-10%) persisted after subsequent annealing to higher temperatures. In fact, the relative concentrations of O, Nb, and N remained stable from 600°C to 750°C, but the film began to decompose above 750°C before the oxygen was fully removed. A similar annealing study was also performed in a partial nitrogen pressure but this approach was less effective at removing oxygen than in UHV conditions.

To examine whether the residual oxygen concentration was due in part to oxygen diffusion into the bulk, a flash annealing study was performed so as to limit the heating time. In this case, the sample temperature was rapidly increased to 600°C in just over 5 minutes, and the surface oxygen was observed to desorb rapidly (Fig. 8b). In fact, the oxygen concentration reached a steady value of <10% in about 15 minutes, while it had taken several hours of annealing at 600°C to reach a similar concentration. As such, the flash annealing approach is preferable since it may prevent prolonged thermal diffusion of oxygen into the bulk. However, it did not fully remove the oxygen layer formed at the NbN_x surface, and it has yet to be determined whether higher flashing temperatures would be effective. As an alternate approach, an argon sputtering study was performed at room temperature in order to avoid heating. In this study, the surface oxygen was removed after 1.5 hours of low-energy (500 eV) ion sputtering, but a substantial oxygen concentration of ~20% remained even with continued sputtering (Fig. 8c). In fact, further sputtering removed uniform amounts of the epitaxial NbN_x film along with the oxygen such that the relative concentrations of O, Nb, and N remained constant. It therefore appears that the native oxide layer is bound rather tightly to the NbN, and thus a different approach will be needed to remove it completely. The results of this study were included in an invited journal article by team member Scott Katzer.

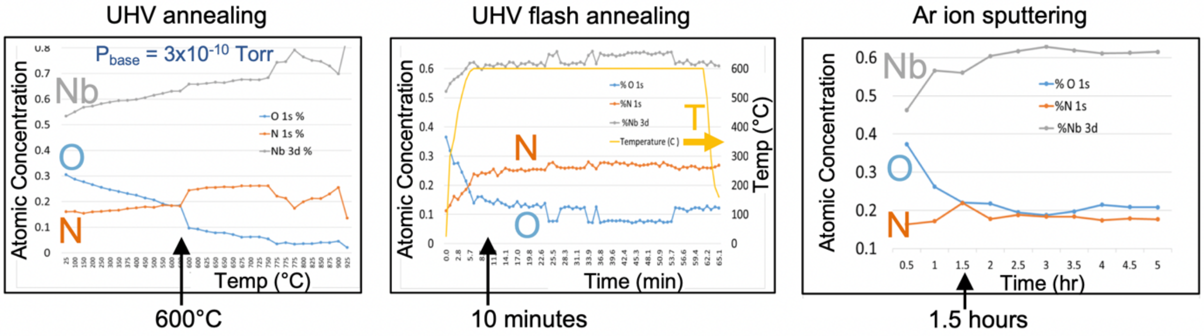

Fig. 8 — XPS spectra taken from NbN_x film as a function of (a) annealing temperature, (b) flash annealing time, and (c) Ar ion sputtering time.

Conclusions

While the experimental system has been successfully set up, configured, and validated for IPE and PC measurements, there are several issues that have hampered the studies. First, there have been problems with the UHV chamber pressure due to issues with the aging ion pump that developed following unplanned power outages. Specifically, the pumping speed decreased, and there were sometimes large pressure fluctuations that caused the base pressure to change from day to day. To reduce the demands on the ion pump and to improve the chamber pressure, a new pumping tee was placed on the chamber with a turbo pump positioned on one end and a non-evaporable getter (NEG) pump (procured, to be delivered) on the other end. Once installed, the NEG pump will help reduce the high partial pressure of H in the ion pump and maintain a low and stable chamber pressure. After many months of pumping on the chamber with only the turbo pump (backed by a new ACP-15 pump), the ion pump is now being used as well and the pressure has become more stable (in low-to-mid 10^{-10} Torr range). With the additional NEG pump, UHV conditions should be maintained and surface analysis will be possible in the chamber

Secondly, the electrical contacts at the sample need to be improved to reduce leakage current that impedes the sensitive IPE measurements. Future samples must be designed to provide better-defined contact areas along with higher-quality contacts at these locations. Furthermore, sample substrates should be used that allow for e-beam heating to achieve higher sample temperatures. This can be accomplished by using semiconducting substrates (if possible) or by depositing a thin metal layer on the back surface for electrical contact. Furthermore, some of the UWBG samples to be investigated may be insulating themselves and may become electrically charged during illumination by x-rays and UV photons. As such, an unmounted electron flood gun was ordered that permits off-axis positioning required in our chamber, and it will provide charge neutralization for XPS/UPS measurements and other electron spectroscopy studies.

Although this program has ended, the characterization facility developed during the program represents an important experimental resource for Code 6850 that can be used in future NRL programs. In particular, the custom light source is a unique experimental tool that can be tuned across an extremely broad spectral range (NIR to DUV) in order to probe the interface, surface, and bulk electronic structure in UWBG materials. More generally, the experimental analysis system enables measurements of the electronic, chemical, and lattice structural properties of electronic materials, and these characterization capabilities can be used to develop a better understanding of epitaxial UWBG materials with great potential for advanced electronic device technology. Looking forward, many next-generation electronic devices will exploit novel heterojunctions of different functional oxide and nitride materials, including UWBG materials, for a range of device applications. However, the device capabilities and performance will depend strongly on the interface electronic structure. Therefore, future research efforts using IPE and PC measurements can provide a scientific basis for these new epitaxial materials and device concepts.

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