MBE
Room Silver Creek - Session MBE-1WeM
Superconductor/Semiconductor Interfaces

Moderator: Christopher Schuck, University of Delaware

8:15am **MBE-1WeM1 Towards Topological Qubits with MBE-grown Heterostructures*, Michael Manfra,*** Purdue University **INVITED**

Decoherence through sensitivity to local perturbations is a key impediment to many current generation qubit technologies. The topological properties of emergent non-local degrees of freedom in condensed matter systems are conjectured to protect quantum states from environmental noise. Numerous material systems are now under investigation to explore topological properties, several of which are amenable to fabrication into complex heterostructures using molecular beam epitaxy techniques. In this talk I will review our efforts to exploit the power of MBE to build systems capable of hosting topological qubits.

The best controlled topological phase is the quantum Hall effect in AlGaAs/GaAs heterostructures. Here the notion of dissipationless edge modes and Abelian and non-Abelian braiding statistics were first theoretically developed and can be systematically studied in experiments. Recent innovations in heterostructure design (see Fig. 1) have allowed for exploration of these properties in small electronic Fabry-Perot interferometers. I will discuss MBE's crucial role enabling these experiments.

Hybrid heterostructures of s-wave superconductors with semiconductors possessing strong spin-orbit coupling are conjectured to behave as topological superconductors and host Majorana zero modes. Using a multi-chamber MBE we have developed Al/InAs heterostructures that display experimental signatures consistent with Majorana zero modes. I will describe some of the opportunities and challenges for epitaxy presented by this approach.

Figure 1: new heterostructure design facilitates operation of interferometers in the fractional quantum Hall regime.

+ Author for correspondence: mmanfra@purdue.edu

8:45am **MBE-1WeM3 Aluminum Metallization of III-V Semiconductors for the Study of Proximity Superconductivity*, Wendy Sarney***, *S. Svensson, A. Leff,* CCDC Army Research Laboratory*; J. Yuan, W. Mayer, K. Wickramasinghe, J. Shabani,* New York University

Reactivity issues and the required mitigating growth conditions encumber molecular beam epitaxy of precise superconductor/semiconductor interfaces. In this work we study metallurgical transitions between Al and various III-As(Sb) binary and ternary semiconductors. To minimize reactivity, we deposit Al at slow growth rates onto cold (less than 0 °C) substrates. Since the interface's crystallinity affects the electronic/optical properties, i.e. Schottky barrier heights [1], etc., we conduct extensive structural characterization studies with transmission electron microscopy (examples shown in Figure 1). The close proximity of the superconductor may negatively affect the neighboring semiconductor [2], compelling the use of very thin intermediate layers. Certain intermediate layers have a secondary desirous effect of preventing the Al metal layer from interacting with the underlying semiconductor [3], and may control electrostatic potentials and local carrier densities.

Our primary semiconductor of interest is InAsSb. Over recent years, we demonstrated unstrained, unrelaxed InAsSb grown on virtual substrates and metamorphic buffer layers [4] - [5]. For compositions near 50%, InAsSb exhibits a very strong g-factor [6]. In hybrid InAsSb-Al structures, we observed superconducting proximity effect in InAsSb films where the product of supercurrent and normal resistance reaches the Al superconducting gap, as expected from theory. In this paper, we discuss the tradeoffs between different Al deposition conditions and the selection and optimization of intermediate layers.

[1] R. Tung, et al, Appl. Phys Rev **1**, 011304 (2014).

[2] W. Cole, et al, Phys. Rev. B **92**,174511 (2015).

[3] W.L. Sarney, et al, J Vac Sci & Technol B **36**, 062903 (2018).

[4] G. Belenky, et al, Proc. SPIE 8012, 80120W (2011).

[5] W.L. Sarney, et al, J. Vac. Sci. Technol. B **30**, 02B109 (2012).

[6] M. Hatefipour, et al, Bulletin of the American Physical Society, (2019).

+ Author for correspondence:wendy.l.sarney.civ@mail.mil

9:00am **MBE-1WeM4 Epitaxy and Characterization of Superconducting Aluminum Films on InAs Quantum Well Heterostructures*, Tiantian Wang*,** Purdue University

The epitaxial coupling of superconductors and high spin-orbit coupled semiconductors has recently been of growing interest for topological quantum computation applications [1]. Reducing disorder at the superconductor-semiconductor interface and in the superconducting layer is of main importance to improve device performance [2]. In this study, we focus on the in-situ molecular beam epitaxial deposition of Al superconducting layers on top of high spin-orbit coupled InAs planar heterostructures [3, 4].

The structural properties of the Al epitaxial layer will be reported relying on transmission electron microscopy (TEM). The determination of the predominant Al growth orientation, of the presence of grains and their properties and the characterization of the defects present in the Al layer are important parameters that we will present.

Figure 1 reports high resolution TEM data associated to Al-InAs hybrid planar hetero-structures with different strain profile in the quantum well. A clear impact of the strain on the Al growth orientation is observable in Figure 1(b) with the transition of the Al growth orientation from (111) to (110). The impact of Al growth temperature will also be analyzed.

Figure 1. The layer stack of two types of Al-InAs quantum well heterostructures (a) and the high-resolution TEM images of the aluminum layer in the two structures (b). The red lines represent one Al unit cell, indicating that the growth orientation is (111) for structure I and (110) for structure II. The zone axis is along InGaAs.

[1] P. Krogstrup et al., Nature Materials. 14(4):400406, 2015

[2] W. Chang et al., Nature Nanotechnology 10(3):232236, 2015

[3] F. Nichele et al., Phys. Rev. Lett. 119.136803, 2017

[4] A. Hatke et al., Appl. Phys. Lett. 111.142106, 2017

+ Author for correspondence: wang2444@purdue.edu [mailto:wang2444@purdue.edu]

9:15am **MBE-1WeM5 Transport Properties of Superconductor-Ferromagnetic- Semiconductor Heterostructures*, Kaushini Wickramasinghe***, *J. Yuan, K. Sardashti, M. Dartiailh, W. Mayer,* New York University*; M. Jiang, L. Anh, M. Tanaka, S. Ohya,* University of Tokyo, Japan*; V. Manucharyan,* University of Maryland*; J. Shabani,* New York University

The rising interest in superconducting quantum computation has led to the exploration of topological superconductors. One of the schemes to achieve a topological superconductor is to use hybrid superconductor-semiconductor structures [1]. We are studying MBE grown InAs surface 2DEGs coupled with Al as a potential candidate. In addition to the good epitaxial contacts, spin texture of the induced current governs the nature of superconductivity. Using dilute magnetic semiconductors $In_xMn_{1-x}As$, we can filter the triplet states over the singlets. The Al-InAs heterostructures have been characterized and studied using Josephson junctions. We also report on structural analysis of MBE epitaxy of Al-InMnAs-InAs and corresponding magnetic and electronic measurements.

[1] Jason Alicea. Rep. Prog. Phys. **75**, 076501 (2012)

+ Author for correspondence: jshabani@nyu.edu

9:30am **MBE-1WeM6 LATE NEWS: Van der Waals Epitaxy of High Quality AlN towards Deep Ultraviolet Light Emitting Diodes on Monolayer Graphene*, Ping Wang***, *A. Pandey, E.T. Reid, J. Gim, W.J. Shin, D.A. Laleyan, D. Zhang, Y. Sun, Z. Zhong, R. Hovden,* University of Michigan

Van der Waals epitaxy of III-nitrides on two-dimensional (2D) materials has attracted significant attention, as it promises significantly reduced dislocation densities compared to conventional heteroepitaxy on lattice mismatched substrates.[1] The resulting epilayers can also be readily exfoliated and transferred to arbitrary substrates for subsequent device processing and integration.[2] To date, however, controlled nucleation of adatoms on the sp2-hybridized 2D surfaces has remained difficult, due to the extremely low surface energy, which limits the formation of large-area single-crystalline epilayers.

Here, we have investigated the epitaxy and characterization of AlN and AlGaN-based heterostructures on monolayer graphene by using plasma-assisted molecular beam epitaxy (MBE). Commercial one monolayer graphene was transferred on sapphire and AlN template substrates to explore the effects of crystallographic information underneath graphene on the epitaxial relationship. The initial adatoms stacking manner and nucleation orientation can follow the epitaxial registry of the AlN template beneath graphene, whereas it is more challenging for graphene covered sapphire to maintain the epitaxial relationship. Without using any pretreatment and buffer layer, we have demonstrated that single-crystalline AlN can be achieved on monolayer graphene covered AlN template (Figure 1). Such AlN has comparable crystal quality and band edge emission with the commercial AlN template. We have further investigated the epitaxy and fabrication of AlGaN-based deep ultraviolet light emitting diodes (DUV-LED) on monolayer graphene. The as-fabricated devices exhibit excellent current-voltage characteristics and strong electroluminescence emission at ~260 nm with a maximum external quantum efficiency (EQE) of ~4%. The device performance is comparable to identical structures grown directly on commercial AlN template.

9:45am **MBE-1WeM7 LATE NEWS: Determination of Background Doping Type in Type-II Superlattice using Capacitance-Voltage Technique with Double Mesa Structure***, **Seunghyun Lee**, D.R. Fink, S.H. Kodati, V. Dahiya, T.J. Ronningen,* The Ohio State University*; M. Winslow, C.H. Grein,* University of Illinois at Chicago*; A.H. Jones, J.C. Campbell,* University of Virginia*; J.F. Klem,* Sandia National Laboratories*; S. Krishna,* The Ohio State University

The background doping in superlattice absorber is one of the most important material parameters for the design and evaluation of infrared detectors. Due to the highly conductive substrates of these narrow-bandgap materials, it is difficult to conduct Hall measurements to verify the doping type of unintentionally doped materials [1]. This is especially true in Type -II superlattice (T2SL) InAs/AlSb where one of the constituents has a background doping that is n-type (InAs) and the other is background doped p-type (AlSb). Here, we demonstrate a novel technique that uses capacitance-voltage (C-V) measurements using a double mesa structure. Two p-i-n and n-i-p homojunction diodes were grown using 10 ML InAs/10ML AlSb were grown by molecular beam epitaxy. The top, intrinsic, and bottom layers are 300, 1000 and 500 nm thick, respectively. Double mesa devices were then fabricated using standard semiconductor fabrication processes. The first etch was a shallow etch that went past the top contact into the absorber layer. The second etch was a deeper etch that reach the bottom contact. CV measurements were undertaken on devices in which the radius of the deep etch was varied while the radius of the shallow etch was kept constant. The double mesa devices have two built-in junctions at the interfaces: the first is in the shallow mesa between the top contact, and intrinsic layer (1st junction), and the second in the deep mesa between the intrinsic layer and the bottom contact (2nd junction). For the PIN device, the device's capacitance will scale with the deep etch radius if the intrinsic layer is p-type. However, if the intrinsic doping is n-type the capacitance will not scale with the deep etch radius. Figure 1 shows capacitance as a function of deep etch radius. For p-i-n device, the capacitance scales with the deep etch radius, but for n-i-p device the capacitance is independent of the radius. This comparison clearly indicates that the doping type of this unintentionally doped InAs/AlSb T2SL is p-type (~ 3×10^{16} cm^{-3}). We plan to perform temperature studies on the doping type of the T2SL. These additional results will be discussed at the presentation.

Author Index

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