Quantum Materials and Technologies

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Principal Investigator(s): Huili Grace Xing, Debdeep Jena

User(s): John Wright, Zexuan Zhang, Jashan Singhal, Hyunjea Lee, Joseph Casamento

Affiliation(s): Materials Science and Engineering, Electrical and Computer Engineering; Cornell University

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Contact: djena@cornell.edu, grace.xing@cornell.edu, jgw92@cornell.edu, jac694@cornell.edu, zz523@cornell.edu, js3452@cornell.edu, hl2255@cornell.edu

Primary CNF Tools Used: Autostep 2000 i-line stepper, JEOL 6300, AJA sputter, Veeco AFM, PT-770 etcher, Oxford 81 etcher

Abstract:

The integration of new material properties into electronics devices creates new possibilities for device performance, architecture, and function. We therefore investigate the fabrication and applications of materials with exceptional properties, including superconductivity, ferromagnetism, ferroelectricity, and topologically non-trivial electronic states.

Summary of Research:

With a sizable bandgap higher than that of silicon, two-dimensional (2D) layered materials can be potential candidates for high voltage applications. One of 2D materials, WSe_2 is used for enhancement mode p-channel field effect transistors (FETs) for high voltage devices, being patterned by JEOL 6300 in CNF. Ambipolar transport in back-gate WSe_2 FETs is often reported in literature, which is a feature of junction-less transistors. However, the breakdown voltage of back-gate WSe_2 FETs with overlapping source and drain is found to be limited by the ambipolar transport. In the off-state of WSe_2 p-FETs, the voltage across the overlapping drain and gate creates an electron channel near the drain; electrons are then injected from the drain contact into the electron channel by tunneling and swept to the source by a lateral electric field across the channel, generating high off-state leakage currents. This ambipolar-limited breakdown is confirmed by depositing Al_2O_3, which introduces interface states near the conduction band edge of WSe_2, and the electron current is suppressed since the drain-gate voltage is not able to raise the Fermi-level into the conduction band. With the suppression of the ambipolar transport, WSe_2 p-FETs show improved breakdown voltages up to -100 V (Figure 1), corresponding to a critical electric field in WSe_2 higher than 200 kV/cm.

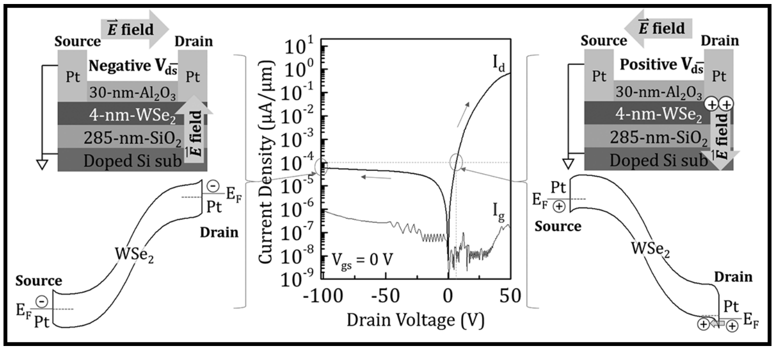

Figure 1: Off-state leakage currents and corresponding energy band diagram cartoons of the WSe_2 p-FET.

Epitaxial ferroelectric semiconductor devices have promise in applications of low power transistors and nonvolatile memories. Their realization has been largely hindered due to material development issues. Our goal was to utilize a novel epitaxial ferroelectric material system, $LuFeO_3$, integrated on GaN to achieve an epitaxial ferroelectric semiconductor field-effect transistor (FE-FET). With the utilization of CNF equipment such as the SC4500 odd hour electron beam evaporator, AG 610 rapid thermal annealer, AJA ion mill, Veeco Dimension Icon atomic force microscope, and GCA Autostep 200 DSW i-line wafer stepper, we have taken the steps toward achieving that goal.

$LuFeO_3$ is intended to act as a ferroelectric gate dielectric and a two-dimensional electron gas (2DEG) formed from a conduction band offset at the $Al_{0.25}Ga_{0.75}N$-GaN interface serves as the semiconductor electron channel.

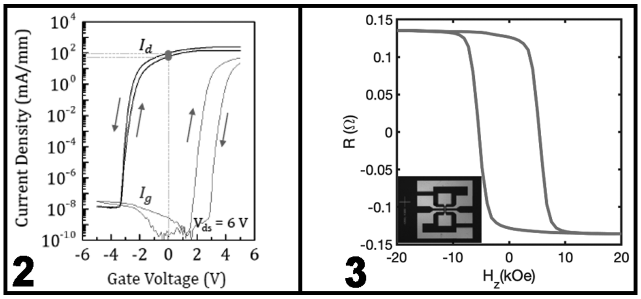

Figure 2, left: I_d-V_{gs} and I_d-V_d characteristics of the $LuFeO_3$-GaN Fe-FET device, showing 2DEG depletion and hysteretic behavior, as well as saturation. Figure 3, right: Hall resistance of Pt/Mn_4N Hall bar (Inset: photo of the measured device).

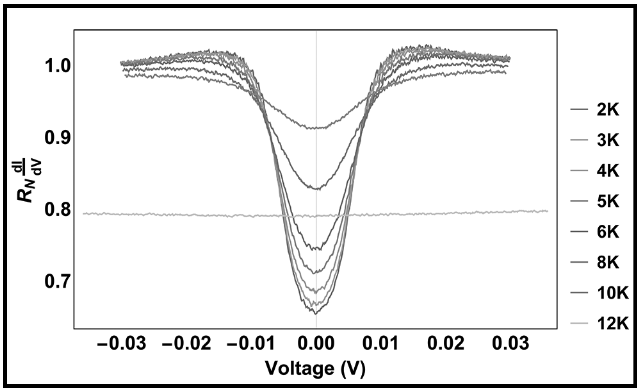

Figure 4: Differential conductance of a NbN/2DEG/NbN device fabricated using a nitrogen polar GaN/AlN quantum well. (See pages vi-vii for full color version.)

Drain current, gate voltage (I_d-V_{gs}) electrical data show a high on-off ratio (10^6) and depletion of the 2DEG in the negative bias regime with counterclockwise hysteretic behavior (Figure 2). These results show effective device patterning, etching, and electrical contact to the electron channel. This is a significant step toward a Fe-FET involving $LuFeO_3$-GaN based heterostructures.

Seamless integration of ferromagnet on semiconductor such as GaN is a promising route towards future energy efficient applications because it provides the unique opportunity to merge memory and logic components. To this end, we have focused on the epitaxial integration of various magnetic phases of MnxNy with wide bandgap semiconductors (GaN and SiC) [1]. Ferrimagnetic Mn_4N layers were grown using molecular beam epitaxy technique on different substrates including cubic MgO, $SrTiO_3$ and hexagonal GaN, SiC. Structural and magnetic characterization was done with the help of various CNF tools and they were found to differ significantly on different substrates [2]. Particularly, Mn_4N layers grown on MgO exhibits strong perpendicular magnetic anisotropy (PMA) and smooth surface.

For spintronic applications based on spin orbit torque (SOT), heavy metal Pt was sputtered on MBE grown Mn_4N and further patterned into test structures such as Hall bars through photolithography, ion mill and lift off process. An image of the patterned structure could be seen in inset of Figure 3.

Transport properties were measured on patterned devices where a square hysteresis loop in field dependent Hall resistances was observed (Figure 3). Such hysteresis loop is typical of a PMA magnetic thin film with high structural quality. At this stage, however, SOT switching of Pt/Mn_4N hasn't been demonstrated, possibly due to (1) poor interface quality between Pt and Mn_4N caused by air exposure or (2) insufficient spin injection considering the large strength of PMA in Mn_4N. Future steps would include optimizing Pt/Mn_4N structure along these directions.

Topological superconductivity can be engineered by utilizing topologically trivial S-wave superconductors to induce correlated electronic states in non-superconducting topological electronic systems, such as the quantum Hall state in high mobility two-dimensional electron gases (2DEG). To explore these phenomena we have grown epitaxial nitride superconductor/semiconductor heterostructures utilizing nitrogen polar GaN/AlN quantum wells with superconducting NbN contacts. The structure places the 2DEG in closer proximity to the surface then would be the case with the more conventional metal-polar nitride AlN/GaN quantum well, while also reducing the tunneling barrier between the superconducting top contact and the 2DEG. Once the structure is grown by MBE the NbN is selectively etched to create devices wherein the 2DEG in the GaN quantum well forms a conducting channel with NbN contacts.

Figure 4 shows the differential conductance of a NbN/2DEG/NbN device at temperatures around the superconducting transition temperature of the NbN film, which is approximately 12K. We see evidence that below 12K the 0V differential conductance is reduced, which is due to the opening of an energy gap at the fermi level in the NbN.

Further work will focus on placing the 2DEG in even closer proximity to the superconductor to increase the proximity induced correlated states, which will be evidenced by an increase in the 0V differential conductance.

References:

[1] S. Dhar, et al. Appl. Phys. Lett. 86, 112504 (2005).

[2] Z. Zhang, et al. AIP Advances 10, 015238 (2020).