Heterogeneous Heterostructures: A Path to Next Generation High Performance Compound Semiconductor Devices

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Abstract

Microwave and millimeter wave devices are key elements in modern defense and commercial wireless applications. Future defense and commercial sensor and communication systems require higher performance (e.g., higher data rates, higher sensitivity or dynamic range), lower SWAP (size, weight and power) and enhanced functionality per unit area to meet system requirements in increasingly congested electromagnetic (EM) environments. Existing high power and high-speed transistor technologies and their resulting circuits appear to be reaching their limits. However, just as GaN technology provided a leap ahead in capability over legacy Si and GaAs device technologies, new opportunities are emerging. Novel device structures in existing materials, new materials systems such as the ultra-wide bandgap (UWBG) semiconductors and advanced three-dimensional device-level heterogeneous integration techniques, all show promise to enable the next leap in RF electronic systems. This talk focuses on emerging materials and transistor technologies being explored under the DARPA Heterogeneous Heterostructures (H2) and related programs.

INTRODUCTION

Today's state of the art (SoA) microwave and millimeter wave power amplifiers have been made possible by the creation of lateral and vertical heterojunction semiconductor devices, such as high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs), respectively. To meet future mission requirements for longer range operation, wider bandwidth, and link robustness, power amplifiers with higher output power than can be achieved with today's SoA are needed. This in turn will demand radio frequency (RF) device structures that simultaneously exhibit higher charge density, higher breakdown field, good carrier transport properties, and high thermal conductivity. As shown in Figure 1, this combination of material properties does not exist today in any single material system.

Researchers have theorized that potentially game changing device structures can be formed by integrating dissimilar semiconductors to solve current device performance limitations, but have not succeeded in realizing these devices, primarily due to the poor interface quality between lattice mis-matched materials that degrades the electronic properties [1,2]. For example, the introduction of ultra-wide bandgap semiconductors (with their high breakdown field) into the drain of a GaAs, InP or GaN HEMT or the collector of a GaAs or InP HBT would enable much higher voltage and power density operation. However, if these structures are fabricated using conventional growth techniques such as MOCVD or MBE, the large lattice mismatch between the dissimilar materials results in a high density of defects (dislocations) which degrade the excellent GaAs, InP or GaN carrier transport properties [1,2].

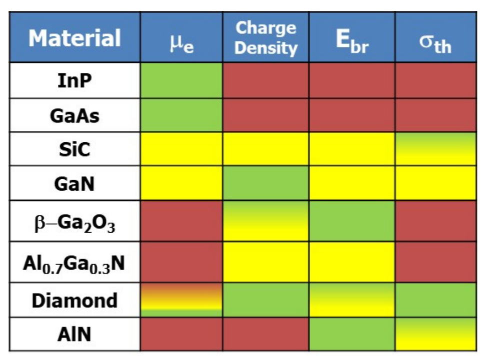
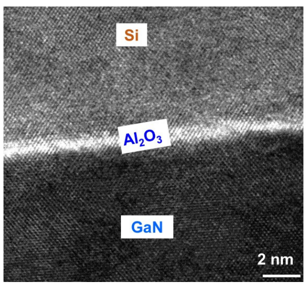


Fig. 1. Material properties for narrow bandgap (InP, GaAs), wide bandgap (GaN, SiC) and ultra-wide bandgap (β-Ga_2O_3, $Al_{0.7}Ga_{0.3}N$, diamond, AlN) semiconductors (μ_e is electron mobility, E_{br} is breakdown field and σ_{th} is thermal conductivity).

The DARPA Heterogeneous Heterostructures (H2) program is exploring potential new paths for realizing high-power density, microwave and millimeter wave devices by demonstrating heterogeneous heterojunctions. In particular, the H2 program is evaluating approaches to create low defect density interfaces between dissimilar (e.g., non-lattice matched) materials. These approaches will be used to create heterojunctions with low defect density and heterostructures that simultaneously exhibit high charge density, high breakdown field, good carrier transport properties, and high thermal conductivity to support the creation of RF transistors with a significant (10X) increase in power density compared with today's SoA.

As an example, recent developments have shown that electrically clean interfaces between dissimilar materials could be achieved by a technique called "grafting" [3]. As shown in Figure 2, grafting involves joining two different semiconductor layers with a uniform, thin, chemically active "glue layer," such as an oxide, nitride or semiconductor layer, to create a low defect density, stable junction. Grafting has recently been used to successfully create Si/GaAs diodes with a near ideal ideality factor of 1.07, indicating low defect density and minimal carrier recombination, and high Ion/Ioff ratio of 7.9×10^9. [3].



Source: University of Wisconsin [2]

Fig. 2. Cross sectional TEM of grafted, dissimilar semiconductor materials: Si to GaN using an Al_2O_3 "glue" layer.

Prior work under the DARPA Dynamic Range-enhanced Electronics and Materials (DREaM) program used grafting to bond diamond and GaAs substrates, creating the AlGaAs/GaAs/diamond layer structure shown in Figure 3 [4]. Although diamond has high thermal conductivity (>2000 W/m-K) and breakdown voltage (>10 MV/cm), there is considerable difficulty in obtaining n-type doping in this material. To overcome this challenge, a heterojunction was formed between n-type GaAs and p-type single crystal diamond to enable the fabrication of a p-n-p HBT. The grafted diamond/GaAs interface showed a high I_{on}/I_{off} ratio of 3.74×10^{10} at 5.2 V, providing quantitative evidence of low interface state density [4]. However, despite the fact that a device quality GaAs/diamond n–p junction was achieved, the HBT current gain was only about unity and further optimization (in particular, better alignment of the bands at the interface by tuning the electron affinity of the diamond surface that is grafted with GaAs) is required [4].

DISCUSSION

The H2 program is evaluating variations of the "grafting" technique for a wide variety of dissimilar materials to create a new set of candidate heterogeneous heterojunctions for the creation of vertical and lateral transport, high-power RF devices. In particular, performers are developing processes to create device-quality cBN-diamond, AlN-diamond, GaN-Ga_2O_3, GaAs-AlGaN and GaAs-ScAlN heterogeneous heterostructures to enable MODFETs, HEMTs and HBTs containing UWBG semiconductors. Figure 4 shows examples of lateral and vertical heterostructures that will be enabled by H2. Since the electronic properties of heterostructures are extremely sensitive to changes in heterojunction structure, chemical composition, and defectivity, understanding the impact of the interfacial or "glue" layer on the band bending of dissimilar materials is critical.

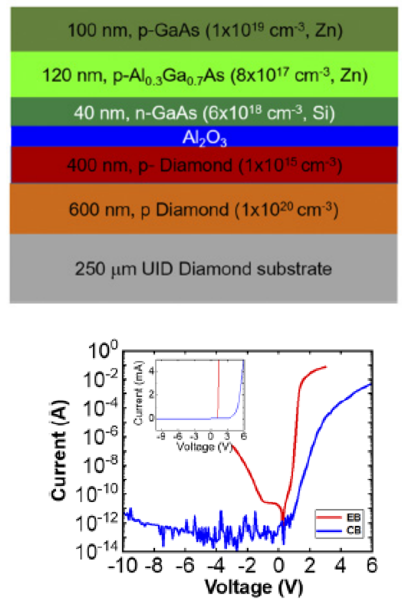
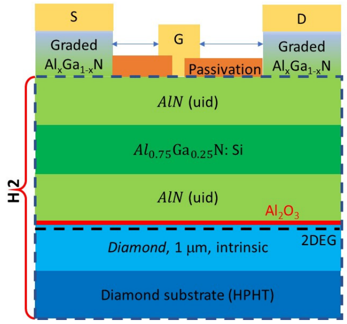


Fig. 3. Top: Schematic of AlGaAs/GaAs/diamond p-n-p HBT layer structure Bottom: Measured I–V curves of the p–n AlGaAs/GaAs emitter-base (E-B) and the p–n diamond-GaAs collector-base (C-B) junctions of the HBT [4]

The H2 metrics are show in Table 1. In Phase 1, which is currently underway, success will be measured by the demonstration of low defect density interfaces and the presence of high carrier density, for example a 2D electron or hole gas (for lateral devices), or near ideal p-n, p-p, or n-n junctions (for vertical devices) as required by the proposed high-power density device.

In Phase 2, performers will utilize the Phase 1 integration techniques in conjunction with physics-based modeling to design and demonstrate heterogeneous heterostructures that simultaneously support high breakdown field and high current density while maintaining good carrier transport properties. As shown in Table 1, performers are expected to demonstrate 10x SoA RF power density (simulated) and 100:1 carrier to heterojunction defect density by the end of Phase 2.



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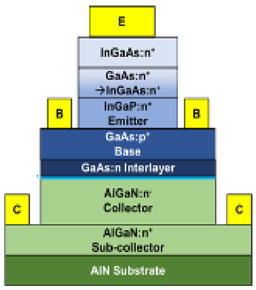

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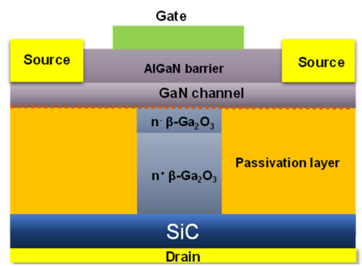
Fig. 4. Cross sections showing example H2 approaches: Diamond MODFET (Top) and GaAs HBT with UWBG collector (Bottom)

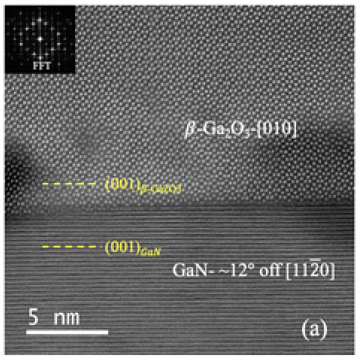
TABLE 1
H2 PROGRAM METRICS

<table>
<tr><th>H2</th><th>Phase 1</th><th>Phase 2</th></tr>
<tr><td>Frequency (GHz)</td><td colspan="2">Proposer Defined</td></tr>
<tr><td>RF Power Density (W/mm)</td><td>N/A</td><td>10x SoA (Simulated)</td></tr>
<tr><td>Junction Defect Density (/cm^2)</td><td>50x < Carrier Density</td><td>100x < Carrier Density</td></tr>
<tr><td>Carrier Density (/cm^2)*</td><td>1 x 10^{13}</td><td>3 x 10^{13}</td></tr>
<tr><td>Mobility (cm^2/V-s)*</td><td rowspan="4">N/A</td><td>850</td></tr>
<tr><td>V_{sat} (cm/s)*</td><td>2 x 10^7</td></tr>
<tr><td>Breakdown Field (V/cm)*</td><td>8 x 10^6</td></tr>
<tr><td>Thermal Conductivity (W/m-K)*</td><td>500</td></tr>
</table>

*Nominal values and should be refined by proposer based on proposer-defined device requirements and must be achieved simultaneously.

A related effort is being evaluated through a DARPA Young Faculty Award (YFA) project, which will fabricate a novel Wafer-Bonded Aperture VErtical Transistor, or BAVET. As shown in Figure 5, this device combines a conventional Ga-polar AlGaN-GaN HEMT structure with a Ga_2O_3 drain using substrate bonding. While Ga_2O_3 provides advantages such as a large bandgap (4.8 eV) and high breakdown field (~8 MV/cm), this material also has low mobility (180 cm^2/V-s), low thermal conductivity (10-30 W/m-K), and lacks p-type doping. However, GaN has a high electron mobility (2050 cm^2/V-s) and can be doped p-type. By integrating these semiconductors, the BAVET will achieve a projected breakdown voltage and power density greater than 120 V and 30 W/mm, respectively. Initial fabrication results for this device have successfully demonstrated atomic bonding of Ga_2O_3 and GaN substrates, as indicated in the STEM image in Figure 5 [5]. This result illustrates the feasibility of achieving a high-quality, void-free, electrically-active interface to enable the fabrication of a Ga_2O_3/GaN BAVET.





Source: University of Michigan

Fig. 5. Cross section of BAVET with Ga_2O_3 (top) and cross-sectional STEM of atomically bonded Ga_2O_3 and GaN (bottom) [5]

CONCLUSIONS

Initial results of the H2 and related programs show the promise of "grafting" and advanced integration techniques for the creation of next generation, high performance microwave and millimeter wave devices. These innovative device structures allow for a combination of dissimilar materials that cannot be achieved with conventional growth techniques. Realistic device simulations developed within the H2 program are expected to demonstrate a 10X increase in power density at microwave and millimeter-wave frequencies to enable wider spectral coverage, so that future radar, communications, and electronic warfare (EW) systems can deliver longer range operation and support more complex wideband waveforms with higher data rates.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
HEMT: High Electron Mobility Transistor
UWBG: Ultra-wide bandgap