Compound Semiconductor Technology for Modern RF Modules: Status and Future Directions

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Abstract — **The DARPA Microsystems Technology Office is developing revolutionary materials, devices, and integration techniques for meeting the RF integrated circuit performance requirements for advanced modern RF systems. The DARPA Nitride Electronic Next-Generation Technology (NEXT) program is developing high performance nitride transistors for high-speed RF, analog and mixed signal electronics. The DARPA Microscale Power Conversion (MPC) program is developing nitride-based technology to enable dynamic envelope-tracking power conversion embedded in RF radiating elements. The DARPA Diverse Accessible Heterogeneous Integration (DAHI) program is developing transistor-scale heterogeneous integration processes to intimately combine advanced compound semiconductor (CS) devices, as well as other emerging materials and devices, with high-density silicon CMOS technology. Taken together, these programs are addressing many of the critical challenges for next-generation RF modules and seek to revolutionize DoD capabilities in this area.** *

Modern RF systems are under consistent pressure to make use of the RF spectrum in increasingly sophisticated ways. RF spectrum congestion pushes systems to operate with increased interference while achieving frequency agility, spectral efficiency and simultaneously increased data rates. As mobile technology becomes ever more pervasive in both commercial and DoD applications, novel RF systems must work within increasingly limited power budgets on platforms that push to achieve reduced size and weight.

The compound semiconductor (CS) electronics industry is well-positioned to address these RF/mixed signal system challenges, due to the superior properties of CS materials. For example, high electron mobility and peak velocity of InP-based material systems have resulted in transistors with f_{max} above 1THz [1] as well as ultra-high-speed mixed-signal circuits (see, for example, [2]). The wide energy bandgap of GaN has enabled large voltage swings as well as high breakdown voltage RF power devices [3]. Excellent thermal conductivity of SiC also makes tens of kilowatt-level power switches possible [4]. Additionally, on-chip high-Q micro-electromechanical resonators and switches in various materials, such as AlN, have been demonstrated that potentially can be used for clock references and frequency selective filters [5].

While the superior properties of CS materials are attractive, the modest complexity of CS circuits relative to silicon circuits has limited their deployment in many applications. This is especially true for GaN, which offers an unparalleled combination of high breakdown field, band gap, and thermal conductivity, but with limited integration complexity to date. Overall, it is clear that no single material system excels in all metrics.

In order to address the challenges of next-generation RF system requirements, substantial innovation in compound semiconductor materials, devices, circuits, and integration technologies is required. The DARPA Microsystems Technology Office has invested in a number of programs which seek to provide this innovation. The DARPA Nitride Electronic Next-Generation Technology (NEXT) program [6] is developing high performance nitride transistors for high-speed RF, analog and mixed signal electronics, thus overcoming the Johnson figure of merit limit to achieving simultaneous high-speed operation and high breakdown voltage. The DARPA Microscale Power Conversion (MPC) program [7] is developing nitride-based technology to enable dynamic envelope-tracking power conversion embedded in RF radiating elements. The DARPA Diverse Accessible Heterogeneous Integration (DAHI) program [8] is developing transistor-scale heterogeneous integration processes to intimately combine advanced compound semiconductor (CS) devices, as well as other emerging materials and devices, with high-density silicon CMOS technology. This paper reviews the latest technical progress of these three DARPA programs.

II. DARPA NEXT PROGRAM

The DARPA NEXT program has made significant strides in enhancing the capabilities of GaN transistor technology to more fully realize GaN's potential for high speed-high breakdown devices, as indicated by its superior Johnson figure of merit [10]. NEXT has aggressively pushed the operating speed of GaN HEMTs by simultaneously minimizing carrier transit time, maximizing electron density, reducing access

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resistances, and optimizing parasitic capacitances with novel device structures [6]. The DARPA NEXT program goals, which have largely been met by program performers [8], focus on GaN enhancement-mode and depletion-mode HEMT performance, yield, uniformity, and reliability.

The current status of HEMT operating speed in the DARPA NEXT program is shown in Figure 2. Aggressive lateral and vertical device scaling has resulted in enhancement- and depletion-mode GaN HEMTs with dramatically improved unity-gain cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) as compared to the state-of-the-art prior to the program. Additionally, NEXT has aggressively improved device yield and circuit complexity, achieving a 501-stage ring oscillator using both enhancement-mode and depletion-mode HEMTs on a single substrate [6]. As shown in Figure 3, GaN has significant potential to produce world-record amplifier efficiencies at frequencies up to W-band.

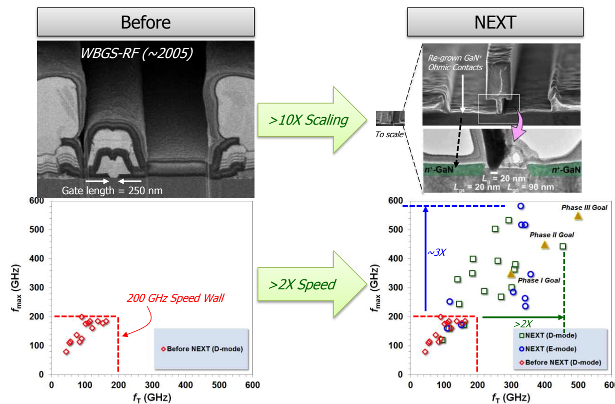

Figure 2. Micrograph and plot of f_{max} versus f_T for GaN HEMTs developed in the DARPA NEXT program. State-of-the-art GaN HEMTs developed before NEXT shown for comparison.

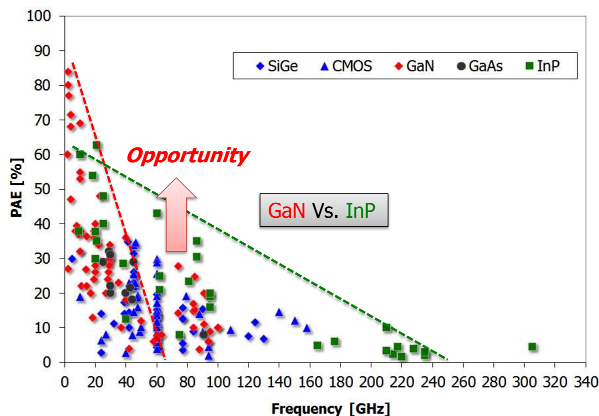

Figure 3. Plot of power-added efficiency versus output frequency for state-of-the-art power amplifiers by material.

III. DARPA MPC PROGRAM

The DARPA MPC program has focused on leveraging recent progress in GaN transistor technology to develop GaN MMIC-based RF power amplifiers which utilize envelope-tracking to achieve very high efficiency at X-band frequencies. The program envisions co-designing a MMIC power amplifier with a dynamic voltage power supply modulator consisting of a very fast GaN power switch [7].

MPC program participants have made substantial progress in advancing the state-of-the-art in envelope-tracking power supply technology. Program results show an efficiency increase from 20% to over 50% at 10GHz [7]. Figure 4, which plots efficiency versus envelope bandwidth, shows that the MPC program achieved a >450MHz RF envelope bandwidth with an efficiency of 40% or greater, more than an order of magnitude increase over the state of the art (20MHz).

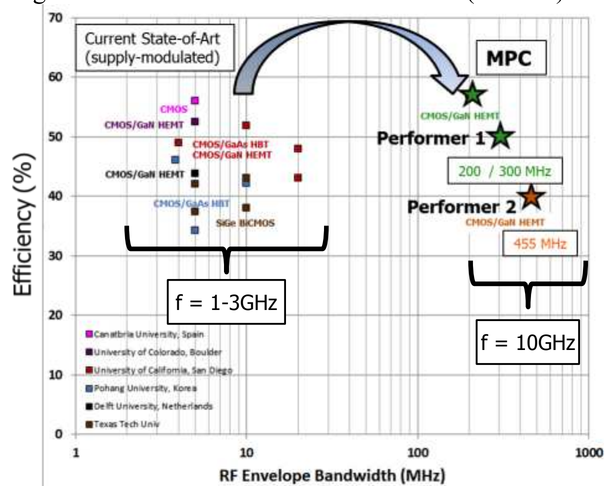

Figure 4. Plot of power-added efficiency versus RF envelope bandwidth for state-of-the-art envelope-tracking power amplifiers.

IV. DARPA DAHI PROGRAM

The preceding sections have highlighted many of the advantages of CS materials for RF modules. However, despite the advantages of CS materials, Si CMOS-based technologies have increasingly been employed in high-performance RF/mixed signal systems. These technologies have leveraged the enormous investments in digital CMOS device scaling and process development to achieve tremendous levels of complexity and integration, while also demonstrating far higher levels of yield and manufacturability than any CS technology. The integration density of Si-based technologies has enabled novel on-chip digital correction and linearization techniques (for example, [9]), producing excellent RF and mixed-signal circuit performance despite the limitations of silicon's material properties.

Such correction techniques have the potential to produce dramatic RF and mixed-signal performance improvements in CS electronics as well; however, CS technologies lack the integration density and yield to implement these circuit concepts. Given these trends, it is our view that the future of high-performance RF and mixed-signal electronics lies in the integration of CS materials with silicon technology in a way that will allow the advantages of the two technology types to be optimally combined.

Figure 5 illustrates the potential impact of heterogeneous integration in RF/mixed signal systems, using a representative transceiver as an example. Essentially all major components in a typical transceiver can potentially benefit from the reduced parasitics of heterogeneous integration, utilizing the benefits of high-performance CS materials with the control and calibration capabilities of Si CMOS.

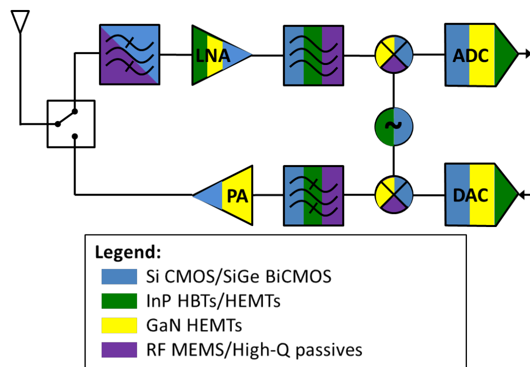

Figure 5. Diagram of a representative transceiver illustrating the preferred set of device technologies for optimal performance of each transceiver component.

To that end, the DARPA DAHI program is developing transistor-scale heterogeneous integration processes to **intimately** combine advanced compound semiconductor (CS) devices, as well as other emerging materials and devices, with high-density silicon CMOS technology. The ultimate goal of DAHI is to establish a manufacturable, accessible foundry technology for the monolithic heterogeneous co-integration of diverse (e.g., electronic, photonic, MEMS) devices, and complex silicon-enabled architectures, on a common substrate platform for defense and commercial users. This capability will not only have significant impacts on the performance of both military and commercial microsystems, but it also represents a new paradigm for the CS electronics community.

One element of DAHI, the Compound Semiconductor Materials on Silicon (COSMOS) thrust, has demonstrated three different approaches to achieving InP BiCMOS integrated circuit technology featuring InP HBTs and deep submicron Si CMOS [12][13][14] for RF and mixed signal circuits.

DAHI/COSMOS performers have demonstrated complex heterogeneously integrated mixed-signal circuit designs, including digital-to-analog converters (DACs) with unprecedented SFDR performance in the GHz output frequency regime [15] as well as revolutionary ultra-wide band ADCs with SINAD performance on par with the most advanced ADCs currently demonstrated. It is expected that the combination of InP HBTs heterogeneously integrated with an advanced CMOS node would enable dramatically improved SINAD at higher frequencies, far in excess of the current state-of-the-art. DAHI performers have also demonstrated the world's first GaN + CMOS RF amplifier using monolithic heterogeneous integration of GaN HEMTs with Si pMOS gate bias control [16].

The DAHI Foundry Technology thrust was initiated [17] to advance the diversity of heterogeneous devices and materials available in a silicon-based platform. This foundry includes a wider array of materials and devices (including, GaN and MEMS technologies) with complex silicon-enabled (e.g. CMOS) architectures and thermal management structures on a common silicon substrate platform. Recently, a DAHI multi-project wafer run was demonstrated [18] utilizing 0.25um InP HBTs and 0.2um GaN HEMTs heterogeneously integrated with 65nm Si CMOS (see Figures 6 and 7). This is the first known instance of heterogeneous integration of three device technologies at the transistor level. Initial characterization of process control monitors indicates high yield of heterogeneous interconnects among all technologies (characterization is still underway). This multi-project wafer included numerous designs which yielded, including a heterogeneous integrated Q-Band VCO-amplifier chain [19]. The InP VCO demonstrated 2GHz of tuning range at 35GHz while the GaN amplifier provides 15dB gain. Output power versus frequency for the VCO-amplifier chain is shown in Figure 8. Other circuits from the multi-project wafer run are currently under testing.

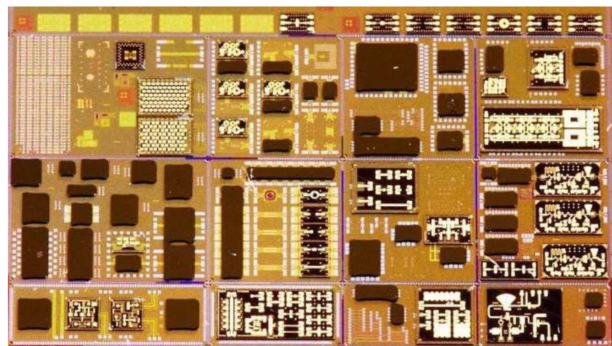

Figure 6. Micrograph of DAHI multi-project wafer fabricated reticle (from [18], used with permission).

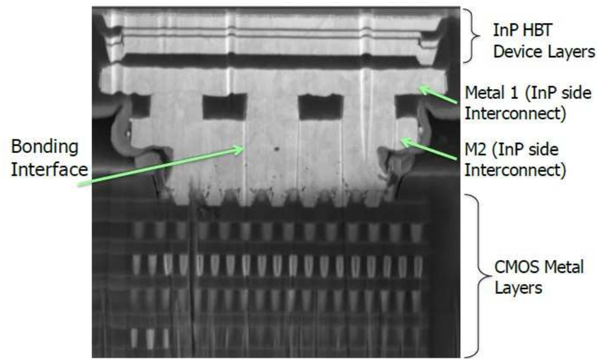

Figure 7. SEM FIB cross section of DAHI Foundry Technology heterogeneous interconnect (HIC) (from [18], used with permission).

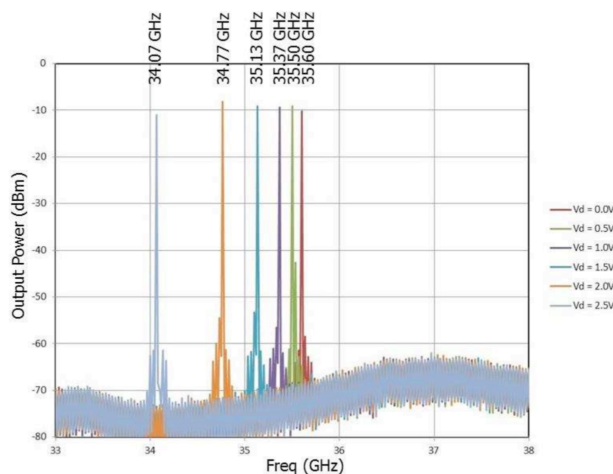

Figure 8. Heterogeneously integrated VCO-amplifier chain output for various input voltages (from [19], used with permission).

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