The DARPA Diverse Accessible Heterogeneous Integration (DAHI) Program: Convergence of Compound Semiconductor Devices and Silicon-Enabled Architectures

Daniel S. Green[1], Carl L. Dohrman[2], Tsu-Hsi Chang[2]

[1]U.S. Defense Advanced Research Projects Agency (DARPA), Arlington, VA 22203
[2]Booz Allen Hamilton, Inc., Arlington, VA 22203

The development of compound semiconductor (CS) electronics has been motivated by their many superior materials properties relative to silicon. 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].

At the same time, silicon CMOS-based technologies have achieved tremendous levels of complexity and integration, while also demonstrating higher levels of yield and manufacturability than any CS technology. Additionally, RF CMOS [6] and SiGe HBT [7] device speeds have continued to increase into the multi-100 GHz regime, albeit at the expense of breakdown voltage. These facts can be attributed to the aggressive device scaling and the advanced levels of back-end-of-the-line integration driven by Moore's Law over the past 50 years. In addition, on-chip digital correction and linearization techniques (for example, [8]), which leverage the integration density of Si-based technologies, have enabled excellent RF and mixed-signal circuit performance despite drawbacks of the material system. Such correction techniques have the potential to produce dramatic RF and mixed-signal performance improvements in III-V electronics as well; however, III-V 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 compound semiconductors with silicon technology in a way that will allow the advantages of the two technology types to be optimally combined.

Heterogeneous integration of compound semiconductors with silicon has been explored in past decades, but its main practical implementation today is through the use of multi-chip modules or similar assembly techniques. Multi-chip module techniques have been prevalent in various microwave/millimeter-wave RF systems, but performance for high-speed/bandwidth mixed-signal systems has been limited by I/O parasitic effects between chips in such modules and by device and interconnect variability issues. Many of the limitations (including I/O parasitics and phase mismatch) of multi-chip module approaches to heterogeneous integration are governed by the length of separation between CS and Si CMOS devices, and as such, the reduction of this separation is expected to yield dramatic improvements in performance of heterogeneous integrated circuits.

To that end, the U.S. Defense Advanced Research Projects Agency (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. 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. The DAHI transistor-level heterogeneous integration approach must overcome a number of difficult technical challenges associated with integration process technology (accurate device-level placement, robust heterogeneous interfaces, dense heterogeneous interconnects, thermal management), manufacturing (transfer of integration technology to state-of-the-art foundries, heterogeneous process yield enhancement, process design kit development, compatibility with computer-aided design tools), and design innovation (innovative circuit design methodologies and architectures for heterogeneous circuits). If this vision can be achieved with high yield and at reasonable cost, this revolutionary technology will allow circuits in which the optimum device is chosen for each specific function within integrated microsystems encompassing RF/mixed signal, photonics, and MEMS technology. 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 and photonics communities.

The DAHI program is composed of several thrusts which are developing the integration technologies, design innovations, and manufacturing technologies and expertise which will be required to realize the DAHI vision. 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 [9][10][11] for RF and mixed signal applications.

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. These DACs are utilizing a number of advanced calibration and self-healing techniques that are enabled by the heterogeneous integration of deep submicron Si CMOS with high-speed InP HBTs. Due to the required circuit complexity, these calibration and self-healing techniques would not be possible in a DAC implemented in a purely InP-based technology. However, the InP HBTs provide higher speed, higher breakdown voltage, and intrinsically better transistor matching than could be accomplished with a purely CMOS-based DAC. DAHI/COSMOS is presently developing advanced ADC designs with revolutionary mixed-signal performance in the InP BiCMOS technology. 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 [12].

Recently, a new DAHI Foundry Technology thrust was initiated [13] to advance the diversity of heterogeneous device and materials available in a silicon-based platform and make this technology available to the greater DoD and commercial microsystems design community through the establishment of an accessible, manufacturable foundry offering for device-level heterogeneous integration. This foundry will seek to include a wider array of materials and devices (including, for example, multiple electronics and MEMS technologies) with complex silicon-enabled (e.g. CMOS) architectures and thermal management structures on a common silicon substrate platform. The goal of the DAHI Foundry Technology thrust is to develop a mature, reliable heterogeneous integration technology, and to establish cost-effective access to sustainable DAHI foundry capabilities, that will enable microsystem designers to choose a range of available semiconductor technologies for transistors or circuit building blocks as needed in order to optimize performance of novel advanced microsystems.

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