Next Revolution in Compound Semiconductor Materials

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Abstract

The performance of compound semiconductor devices has reached practical limitations that requires new innovations beyond simple material and fabrication scaling. The next revolution will enable affordable, high-performance compound semiconductor technology. This will be achieved by theoretical simulations of emerging material systems, by engineering new material limits, and by leveraging silicon-like fabrication technology.

Introduction

Semiconductor technologies have evolved over the past seventy years with innovative approaches that have improved performance, size, weight, power, and cost for different applications. Such approaches have involved the engineering of electrons, holes, photons, and phonons across a wide variety of device architectures and operating environments. Silicon logic technology triumphed over GaAs logic technology in the 1990s, but GaAs HBT technology continues to dominate high-performance, power-efficient RF power amplifiers in today's cellular phones. This technology evolution has been fundamentally driven by intrinsic materials properties.

The most obvious technology example is bandgap engineering. The moderate 1.12 eV energy gap for silicon at 300 K supports high dopant concentrations, which has enabled various device types and electronic contacts. Compound semiconductors (CSs) have frequently been attractive alternatives because they are characterized by a larger energy gap (e.g., GaN, at 3.4 eV) or a smaller one (e.g., InAs, at 0.36 eV). In either case, the bandgap leads to desired materials characteristics, but also imposes additional challenges to appropriately engineer donors, acceptors, and surface states for good charge confinement and low contact resistance. In addition, many CS materials have direct energy bandgaps (compared to silicon's indirect energy bandgap), offering profound advantages with respect to high efficiency solid-state lasers and detectors.

In the first wave of the CS revolution (Figure 1), the U.S. government drove technology development to monolithically integrate CS devices on homogeneous substrates to enable solid state CS electronics [1]. Examples included GaAs-based MMICs for active electronically scanned arrays in the 1980s and InGaN-based light-emitting-diode (LED) to enable blue/green lasers in the 1990s. These innovations revolutionized defense systems and significantly impacted the commercial telecommunications and lighting industries.

The 2nd revolution in CS devices, also funded by the US government, was to move past homogenous to heterogenous device integration. Recognizing the semi-insulating electrical characteristics and superior thermal conductivity (e.g. compared to sapphire), SiC electronics investment began in the late 1970s by the Office of Naval Research (ONR). ONR quickly advanced SiC material synthesis and quality. Subsequent ONR investment in the 1990s demonstrated GaN-on-SiC electronics technology based on high performance GaN RF transistors on this SiC substrate. Beginning around 2000 and continuing over the next two decades, DARPA supported substrate quality advances as well as high power device development. This brought AlGaN/GaN HEMT-on-SiC technology to system adaptation in power electronics and RF electronics for both military systems and the commercial base station market. Similarly, DARPA's Antimonide Based Compound Semiconductors (ABCS) program developed μm-scale buffer layers to heterogeneously integrate dissimilar high performance AlSb/InAs channel (6.1 Å lattice family) on InP (5.8 Å) or GaAs (5.6 Å) substrates for low power, high frequency electronics circuits. Wide and narrow bandgap developments firmly established the feasibility of a heterogenous device in which the active material is grown on top of a substrate with similar lattice constant.

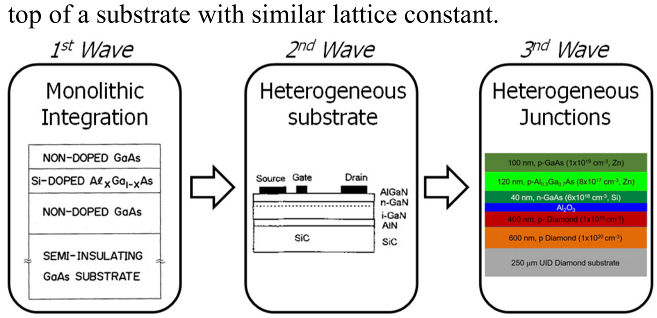

Figure 1: The three waves of the CS revolution

We suggest that the 3rd revolution in CS materials will involve heterogeneous junctions within devices at nanometer scale. The 3rd wave integration will realize abrupt junctions between high performance materials with dissimilar lattice constants within a device. Even more than the previous one, such a revolution would face daunting challenges of complexity, accessibility, and affordability, but would offer new materials characteristics with intrinsic and profound advantages. Although we will focus here on applications to electronics, many other areas that make use of CS materials (e.g., optical, quantum, magnetic devices) could similarly benefit from this revolution.

THE STATE OF THE ART

Because of its superior material characteristics, CS technology outperforms silicon technology in many applications, including radio-frequency (RF) electronics, high-power electronics (HPE), and optoelectronics. Table 1 highlights examples of fundamental material advantages enjoyed by CSs compared to silicon. Advantages with respect to energy band gap, carrier mobility, material breakdown field, or thermal conductivity provided the motivation of the 1st wave of CS technology revolution. In that wave, device performance was fundamental driven by material properties.

Table 1: Comparison of material properties for multiple compound semiconductors and Si CMOS.

Parameter	Motivation	Unit	Si	GaAs	ABCS	InP	GaN
Electron Mobility	Carrier velocity	10^3 cm^2/V·s	1.4	8.5	40	12	<1
V_{peak}	Transit time	10^7 cm/s	1	2	8	2.5	2.5
E_{BK}	Voltage swing	10^5 V/cm	5.7	6.4	0.4	4	40
E_g	Charge density	eV	1.12	1.42	0.35	0.74	3.4
κ	Heat removal	W/cm·K	1.3	0.5	0.27	0.05	2.9
Maturity	Circuit complexity		Excellent	Good	Limited	Ok	Limited

The 2nd wave involved the leverage of heterogenous substrates to further enhance the device performance. The transistors' parasitic components (e.g., intrinsic resistances and capacitances) also became much more important factors affecting device's performance. Similar to the famous Dennard scaling rule of silicon CMOS, CS devices had also been scaled to achieve high speed, power, and power efficiency. Figure 2 shows the trend of transistor speeds (f_T and f_{max}) for several SoA devices.

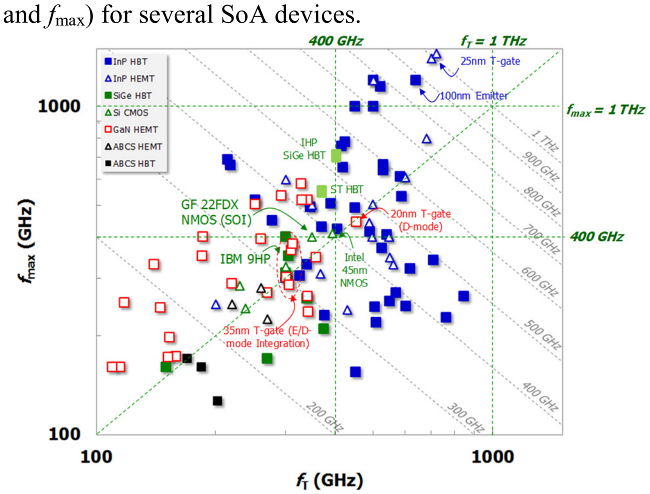

Figure 2: State-of the-art transistor speed for multiple compound semiconductors and Si CMOS.

Despite progress in CS material and device parasitic scaling, CS electronics have faced integration challenges that have limited their implementation in near-term needs, such as commercial 5G or beyond-5G systems or military wideband millimeter wave RF applications. For example, GaN-based MMICs can generate more RF output power than InP and silicon technologies around 100 GHz (as shown in Figure 3a) due to GaN's higher breakdown voltage supported by its larger energy band gap. However, the power efficiency of GaN MMICs is still relatively low compared to InP technology (Figure 3b) above millimeter wave because the GaN device access, contact, and channel resistances are intrinsically inferior to those of InP devices. To enable next-generation device performance, new integration approaches will be needed to further exploit intrinsic material advantages within a device – the 3rd wave revolution.

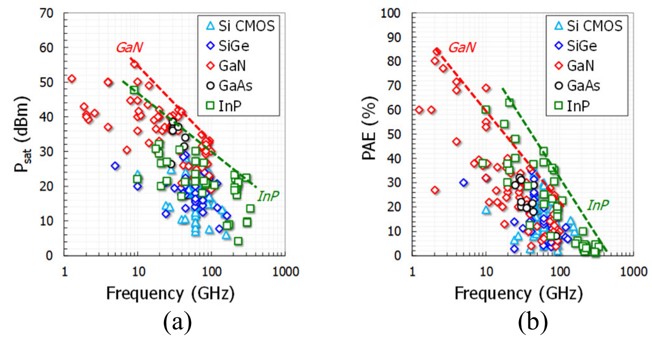

Figure 3: RF MMIC output power and Power Added Efficiency (PAE) for multiple compound semiconductors and Si CMOS.

CHALLENGES FOR THIRD-WAVE HETEROGENOUS JUNCTIONS

We propose the next wave of revolution will start with materials innovation with the combination of advanced fabrication techniques (similar to 1st and 2nd waves) with the emphasis on integrating dissimilar materials at junctions or interfaces within a device. Further, we suggest an end-to-end (from material selection, parasitics engineering, to device performance) theoretical research framework to identify and accelerate the innovations.

Table 2 lists some emerging ultra-wide bandgap (UWBG) semiconductor materials with great promise [1], which are likely to enable future electronics with device speed, power, and efficiency advantages. However, several daunting technical challenges will need to be overcome before these unique material properties can be fully exploited.

Understanding Materials Physics

Any emerging material systems, including UWBGs, are relatively new and incompletely studied. As a result, many hypotheses of material properties have not been fully assessed or proven by theoretical or experimental examination. Understanding fundamental limitations of a material system by theoretical simulation, prediction, and benchmarking is essential to decide whether further investment of device fabrication is warranted. For example, the thermal conductivity of β-Ga_2O_3 deserves additional fundamental research. The Boron Nitride (BN) material system also deserves more investigations into engineering its crystal structures, e.g. from c-BN (3D) to h-BN (2D), for different thermal and electrical properties. Future research should also focus on understanding the feasibility of low-temperature synthesis with high BN material quality.

Table 2: Properties of emerging UWBG materials

Parameter	Motivation	Unit	AlN	β-Ga_2O_3	Diamond	c-BN
Electron Mobility	Carrier velocity	10^3 $cm^2/V{\cdot}s$	0.43	0.15	4.5	0.83
V_{peak}	Transit time	10^7 cm/s	1.3	1.1	1.9	TBD
E_{BK}	Voltage swing	10^5 V/cm	154	103	175	150
E_g	Charge density	eV	6.0	4.9	5.5	6.4
κ	Heat removal	$W/cm{\cdot}K$	3.19	0.27	22.90	9.40

Approaching Materials Property Limits

Once the materials physics is understood, choosing appropriate material combinations for device design becomes possible. For instance, β-Ga_2O_3 has a large energy bandgap, which is attractive for power devices, but its thermal conductivity is currently low and theoretically it is only an n-type material. Due to these fundamental material properties, future innovations are needed to overcome these challenges and thus simultaneously realize a power device with an embedded thermal management strategy and low contact resistances to exploit the true potential of its large bandgap. In contrast, diamond has exceptional electrical and thermal characteristics, but the research community continues to struggle to identify doping techniques for electrical contacts as well as appropriate gate dielectric materials for stable operation. Such doping challenges are also common for other emerging UWBG material systems. Although preliminary device demonstrations are encouraging, to date the device performance is unfortunately limited by the electrical contact or channel access resistances.

Increasing Material Availability

After decades of research, both diamond and AlN have been identified as device materials that can potentially outperform GaN. However, the availability of these materials as native substrates at large size and high quality are necessary for research or production. Historically, the limiting factors determining the practicality of a semiconductor technology are the defect density and the size of the substrate. Si, GaAs, and SiC substrate technologies previously encountered similar scaling challenges. Without investment in material synthesis, purification, and large diameter wafer development, the innovation of new CS technology will be hampered.

APPROACHES FOR THE NEXT REVOLUTION

Fast discovery of new materials, advanced fabrication tool sets, and affordable computing resources have become more available today compared to decades ago. This argues for a strategy to quickly identify the technology opportunities, accelerate the innovation, and ensure the affordability of the 3rd wave of the CS technology revolution.

(1) Exploitation of Material Limits for Applications:

New materials have been continuously proposed in the literature with unique or appealing material characteristics. However, most of the proposed materials do not have competitive properties compared to existing technical solutions. The fundamental research community should focus on the measurement of material characteristics and material synthesis techniques to identify these fundamental limits. With clear application goals in mind, the researchers should then selectively focus on those promising material candidates. For example, BN still needs more fundamental research for its low-temperature synthesis and crystal structure engineering while AlN, diamond or β-Ga_2O_3 may be ready for large substrate growth or high performance device demonstrations in the nearer-term.

In addition, the semiconductor industry typically focuses on applications operating around room temperature or meeting military temperature specifications (e.g. between -55 to 125 °C). In reality, such temperature ranges may not be the best operational temperatures from the material property perspective. Using β-Ga_2O_3 as an example, the highest electron mobility happens around 90 K. While emerging applications, such as quantum computing at cryogenic temperatures or high temperature electronics in harsh environments, new innovations can potentially engineer the best materials at those extreme temperatures.

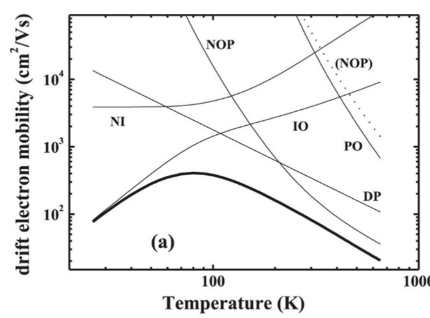

Figure 4: Simulated drift mobility of β-Ga_2O_3 versus temperature. (Figure courtesy of A. Parisini and R. Fornari, University of Parma, and IOP Publishing [2].)

(2) "Engineering" New Material Limits

The next step is to integrate the desired material properties *within* a device or to create a new device structure that can break the traditional device design tradeoffs. For example, an ideal RF switch must handle a large signal power range with low ON resistance and good isolation. Previously, InP HEMT technology has been used for low-loss RF switches. However, the power handling capability of these devices is poor. In fact, there is no ideal CS material to fulfill the needed specifications of emerging systems that require extremely high carrier mobility, large breakdown voltage, high charge density, and exquisite electric static gate control. However, by leveraging the mature epitaxial growth techniques of CS, and the lower mobility GaN channel, a CS material can be stacked to form a 3D multi-channel structure with side gates to achieve extremely low ON resistance while supporting high power swing [3].

Within-device heterogeneous integration can further expand the device design space. Since only p-type diamond material is currently available and there is no mature gate dielectric options for diamond-based field effect transistors, the current usage of a diamond film is typically for its high thermal conductivity. But researchers have recently demonstrated heterogeneously integrated p-AlGaAs/n-GaAs/p-diamond epitaxial structures made by thin film transfer to form an HBT with a thin diamond collector that supports high breakdown voltages not possible with standard AlGaAs/GaAs HBTs [4].

(3) Adoption of Advanced Fabrication Processes

CS technology is generally considered to be more expensive than silicon in fabrication cost due to smaller wafer size and more expensive substrates. However, the fabrication tools of CS devices are typically relatively out of date compared to advanced silicon technology. As a result, CS devices have not been able to enjoy the advantages of advanced lithography, CMP (chemical mechanical polishing), or planarized multi-level copper interconnect process modules. The consequence of using legacy fabrication processes is that such legacy processes are not scalable for high-yield, high-performance, and low-cost production. To boost manufacturability and reduce costs, the CS industry should consider adopting silicon-like fabrication processes. Recently, reliable GaN-on-Si HEMTs fabricated in a silicon foundry was reported with competitive device performance [5], but further work and investment is required to achieve silicon-like fabrication of CS electronics.

(4) Theoretical Simulation for Technology Affordability

As the complexity of proposed innovations continues to increase, it will become economically infeasible to explore all the possibilities through expensive design of experiments and fabrication runs. However, through continued advancement in high performance computing, it becomes more affordable to first perform intensive theoretical computations, from the atomic to the circuit level, to better understand the ideal and non-ideal characteristics of channel materials, dielectrics, contacts, DC device characteristics, and RF circuit performance. The expected next-generation fully integrated TCAD (Technology Computer-Aided Design) capabilities will significantly reduce the exploration cycle and design space of experiments. Ideally, such new modeling tools will be able to predict a MMIC's transient performance, including a large signal model to capture current collapse behavior across a large range of operating frequencies, at different temperatures, or with various signal waveforms.

CONCLUSIONS

The next revolution of CS is urgently needed to support emerging applications and new industries. A comprehensive development strategy (Figure 5) is proposed to leverage advanced computing to theoretically identify new material candidates and model transient circuit performance. To ensure future technology affordability, adoption of silicon-like fabrication modules and scaling to larger wafer sizes will be critical for the success of the next-generation of compound semiconductors.

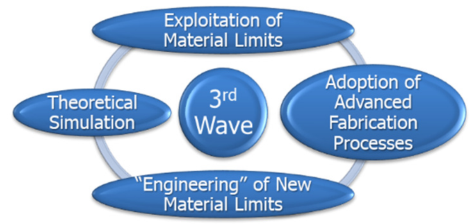

Figure 5: The 3rd Compound Semiconductor Revolution

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