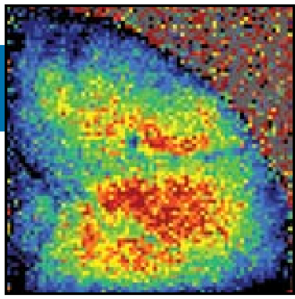


NRL Launches SiC Epitaxial Growth Effort for Future Power Systems

C.R. Eddy, Jr., D.K. Gaskill, K.-K. Lew, B.L. VanMil, R.L. Myers-Ward, and F.J. Kub
Electronics Science and Technology Division

The Navy's desire for an all-electric ship will require the creation of new devices with power performance far exceeding existing technologies. Silicon carbide has been identified as the primary candidate semiconductor to build such advanced devices. In January 2006, NRL dedicated a new state-of-the-art SiC epitaxial growth laboratory permitting fundamental research to address current limitations of the material, namely, basal plane dislocations (BPDs) and minority carrier lifetime. Equipped with customized in-situ process diagnostics and an accelerated research plan, the laboratory has already succeeded in growing material with minority carrier lifetimes near world record and is focusing on multiple BPD reduction approaches. This initial success was achieved in part by monitoring the gas phase carbon-to-silicon ratio, the primary variable linked to intrinsic defect levels. Further, a demonstration of mass spectrometer sensitivity of $<10^{14}$ dopant atoms/cm^3 enables the low, controlled doping required by the device technologies.

NAVY NEEDS IN FUTURE POWER SYSTEMS

The future Navy has a clear need for advanced power systems that will employ integrated electric power architectures on all its ships, boats, and combat vehicles. Such systems significantly improve efficiency, effectiveness, and survivability while simultaneously increasing design flexibility and reducing costs by making the most efficient and effective use of their power plants. Currently, the vast majority of power plant output is dedicated to the propulsion system whether or not the situation requires maximum mobility. Integrated electric power systems utilize a common electrical bus permitting maximum operational flexibility in how the power plant output is distributed to suit the range of payloads, sensors, and propulsion needs for a given tactical situation. Integrated electric power systems will benefit a variety of platforms throughout the Navy including destroyers (DD-21), aircraft carriers (CVN-21), and Virginia-class submarines. Similar benefits are expected in applications to more electric aircraft and all electric combat vehicles throughout the Marine Corps, Army, and Air Force. Because a single common bus will be used for propulsion of future carriers and destroyers, the bus will be operated at high voltages, generally in excess of 10 kV. Such operational requirements place severe demands on the performance of existing power semiconductor device technologies that are based on silicon. Although silicon power device technologies continue to be improved and extended, the realization of a robust, reliable, and high-performance integrated electric power system will require device technologies based on new materials. Significant research over the last decade has identified the wide band gap semiconductor silicon carbide as the new material of choice to satisfy such requirements.

THE PROMISE AND CHALLENGES OF SILICON CARBIDE

Silicon carbide (SiC) is a compound semiconductor made from silicon and carbon atoms bonded in a single crystalline structure. Of the many crystalline atomic arrangements (polytypes) that exist for SiC, the 4H polytype possesses the best combination of electronic, thermal, and chemical properties for robust high-voltage, high-power electronic device applications. The key attributes of SiC are compared to those of silicon in Table 1. The two key attributes that establish SiC as superior to silicon are its high break-

TABLE 1
Comparison of Critical Power Electronic Materials Properties for Silicon and the Wide Bandgap Semiconductor Silicon Carbide.

	Si	4H SiC
Bandgap (eV)	1.1	3.26
Electron Mobility (cm^2/Vs)	1350	1000
2DEG Sheet Density ($\times 10^{12}$ cm^{-2})	10	N/A
Peak Electron Velocity ($\times 10^7$ cm/s)	1	2.0
Critical **E** Field (MV/cm)	0.3	2.0
Thermal Conductivity (W/mK)	110	330
Power Figure of Merit	1	134

down field, which permits large blocking voltages to be attained with minimal semiconductor thicknesses, and wider band gap, which permits efficient operation of the power device at elevated temperatures, thereby relaxing cooling requirements for future integrated electric power systems. Additional benefits of SiC-based power devices include 400 times lower on-resistance, resulting in increased system efficiency; and a 10 times higher switching frequency which permits smaller passive components, resulting in smaller, lighter power systems. Altogether, SiC presents a more than hundred-fold improvement compared to silicon in potential power performance.

These and other properties of SiC have positioned the material to be of considerable commercial importance in a variety of other markets including substrates for visible and white light emitting diodes, short wavelength lasers, and microwave power transistors, as well as an active material for medium-voltage (1200 V or less) power electronics and ultra-high-frequency power transistors. These significant commercial markets have led to considerable research and development efforts over the last 10 years that have matured the materials technology and brought it to the brink of feasibility for employment in the high-voltage, high-power applications of Navy need. However, significant hurdles remain in the areas of extended defect reduction and low, controlled electron concentrations with very long free carrier lifetimes.

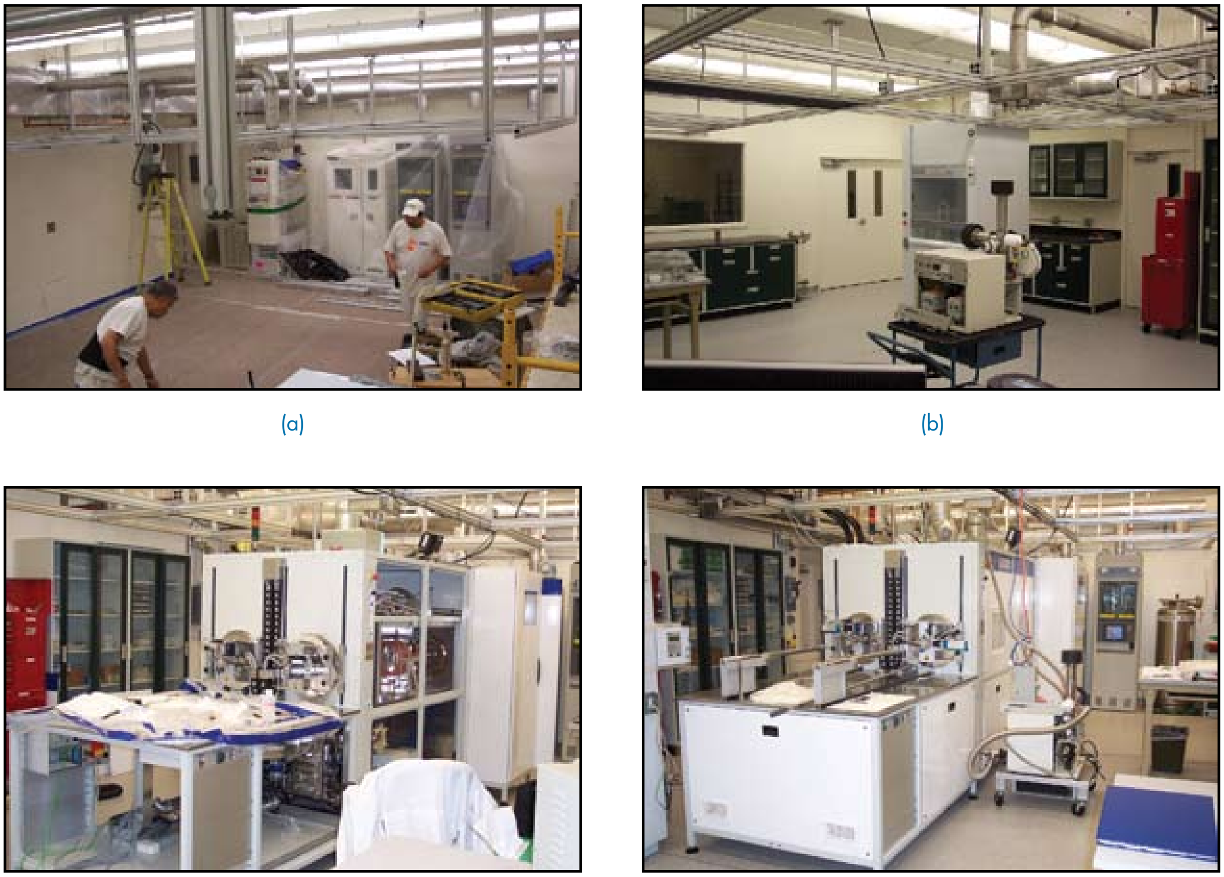
Unfortunately, most commercial applications of SiC materials will not motivate the required materials refinement needed for the high-voltage Navy applications. Recognizing this, researchers in the Electronics Science and Technology Division (ESTD) at NRL began to make a case for the creation of a SiC epitaxial materials research facility that would be charged with further developing the material to enable the realization of high-performance, high-reliability power electronic devices for unique high-voltage Navy applications.

NRL'S ADVANCED SILICON CARBIDE EPITAXIAL RESEARCH LABORATORY (ASCERL)

ESTD's case was presented to NRL management in the fall of 2003 where it received approval to move forward on the establishment of a state-of-the-art facility for SiC epitaxial materials research. Over the course of the next 26 months a customized commercial SiC epitaxial growth reactor was specified, bid, acquired, and qualified. At the same time, a comprehensive facility was specified, bid, and constructed to ensure that a safe, efficient, and effective infrastructure would be in place to support the reactor. Highlights of the facility construction and reactor installation are presented in Fig. 1. On December 21, 2005, NRL took ownership of the facility and reactor. On January 23, 2006, NRL dedicated its new Advanced SiC Epitaxial Research Laboratory (ASCERL); see Fig. 2. NRL's ASCERL is comprised of two adjacent facilities — the Growth Facility and the Immediate Characterization Facility.

The Growth Facility is centered around an Epigress/Aixtron VP508 high-temperature chemical vapor deposition (CVD) reactor that is widely used in the SiC community to deposit homoepitaxial SiC epilayers on SiC substrates. The reactor is configured to enable a wide range of growth activities as it has n- and p-type doping and two process cells for 2-, 3-, and 4-inch substrates. The two growth cells share gas distribution and radio frequency power systems, yet permit independent processes to be run in each cell. A common configuration is to employ one cell for high-purity and nitrogen doping (to create free electrons in the material) and use the other cell for aluminum doping (to create free holes in the material). Another possibility is to employ novel growth chemistries in one cell while maintaining a conventional, high-purity chemistry in the other. NRL's VP508 was further customized to permit research activities that can advance the state of the art in SiC epitaxial materials quality for high-voltage power electronic applications. These customizations include (1) porting of the system for in-situ mass spectrometry characterization of reaction products; (2) a high-temperature option to elevate the growth temperature to 1800 °C (conventional growth temperature is ca. 1600 °C) for increased growth rates to realize thick films needed for high blocking voltage devices; (3) a modification to the gas handling system to permit the use of halogenated precursors and/or the addition of hydrogen chloride gas to the conventional growth process; and (4) optical access ports to permit in-situ, laser-based diagnostics of the epitaxial surface and near-surface regions. These customizations are a significant part of the research plan to advance SiC epitaxial materials through better understanding and control of conventional and advanced growth processes in a technologically relevant commercial tool.

Adjacent to the Growth Facility is the Immediate Characterization Facility which hosts tools that permit researchers to quickly (same day as grown) characterize epitaxial wafers. The available characterization tools include the following: Nomarski microscopy for surface morphological evaluation; wafer-scale cross polarization scanning for full-wafer defect characterization; Hg probe capacitance-voltage (CV) profiling for lateral and depth profiling of free carrier concentrations; and a Thermo-Nicolet FTIR spectrometer for full-wafer, high-precision thickness maps of epitaxial layers. The characterization tools are housed in a softwall clean room (< class 1000) to minimize particulate-based contamination and permit re-growth on characterized films.



(a) (b)

(c) (d)

FIGURE 1
Pictures of the ASCERL facility development: (a) workers install overhead spaceframe for utilities and instrumentation mounting; (b) facility construction completed; (c) installation of SiC epitaxial growth reactor; (d) installation complete.

FIGURE 2
Dedication of ASCERL on 23 January 2006. Participants from left to right: Keith Hull (Public Works Division), Dr. Gerry Borsuk (Superintendent of ESTD), Dr. Charles Eddy (Head, Power Electronic Materials Section), Dr. Bhatka Rath (Associate Director of Research), Dr. Fritz Kub (Head, Power Electronics Branch) and Dr. D. Kurt Gaskill (Power Electronic Materials Section).

A MULTIDISCIPLINARY TEAM, A MULTIFACETED APPROACH

ASCERL researchers routinely collaborate with a large number of physicists, chemists, materials scientists, and electrical engineers in NRL's ESTD who have extensive semiconductor characterization laboratories and who have well-established, world-recognized SiC characterization expertise. These diverse efforts are capable of identifying and analyzing a wide range of materials properties, from the structure, properties, and behaviors of point and extended defects to the physics of reliability of prototype devices. Such close collaborations facilitate rapid progress in research agendas and have helped ASCERL in production of world-class materials during its first year of existence, as described below.

In this first year, ASCERL was visited by representatives from nearly every academic and commercial SiC materials facility in the United States, a tribute to its design, unique capabilities, and people.

PUSHING THE STATE OF THE ART FOR NAVY NEEDS

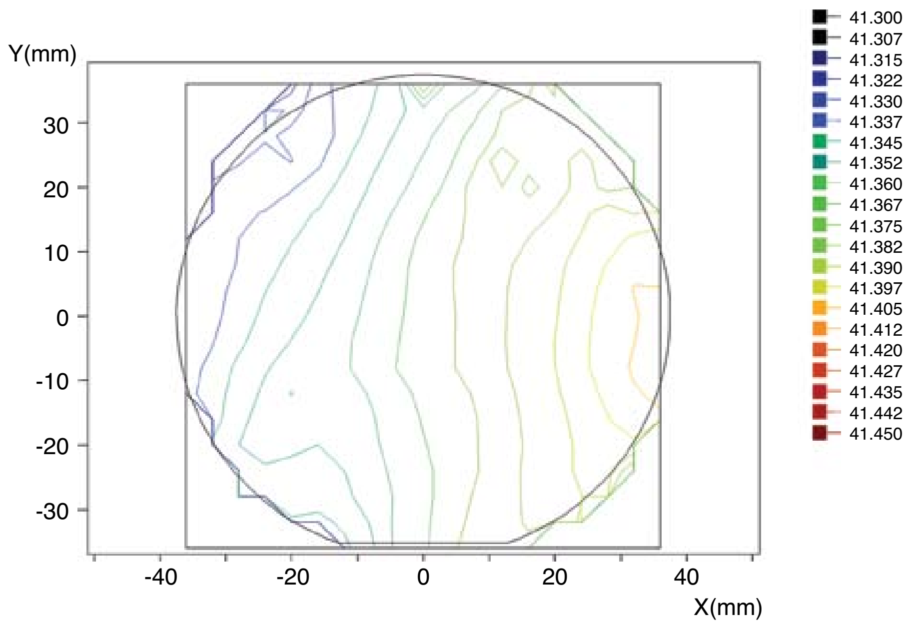
In striving to further refine SiC epitaxial materials and make them suitable for ultimate application in future Navy power systems, several key thrusts were launched in the first year of ASCERL's function. Highlights of advancements in those thrusts are presented here.

Substrates Matter

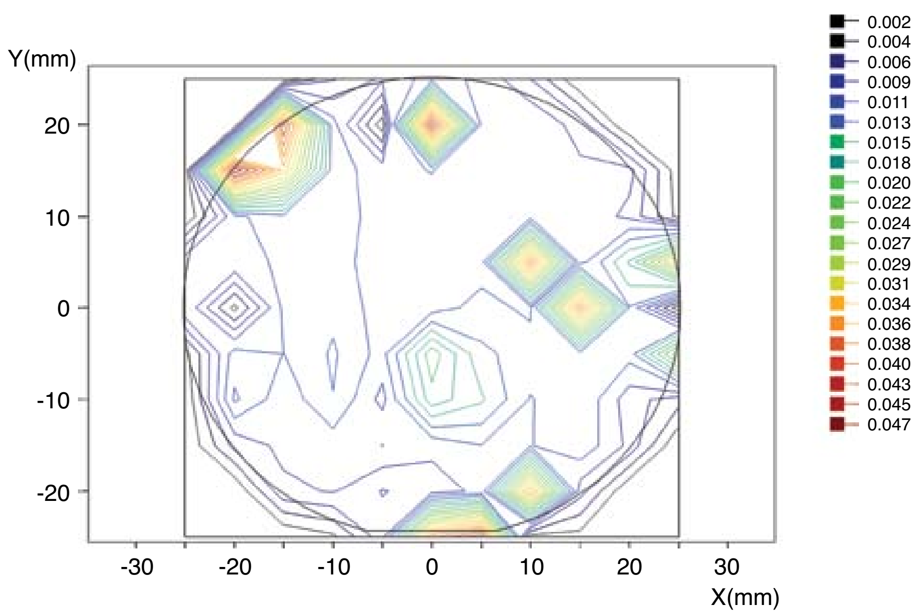
As with any epitaxial materials growth effort, the quality of the substrate is of critical importance to the quality of epilayers grown and intended for device applications. To ensure a thorough understanding of the SiC substrate technology, which demonstrates varying degrees of perfection at this time, a number of full-wafer characterization techniques are employed including X-ray diffraction (XRD) mapping. An example of a full-wafer map of the diffraction peak position (a measure of the direction of crystalline lattice planes) and diffraction peak width (a measure of crystalline quality) are shown in Fig. 3. As shown in Fig. 3(a), the lattice peak position varies across the wafer, indicating a curvature of the lattice plane. This curvature is independent of the mechanical shape of the wafer, which can be quite flat, and is observed in all SiC wafers to varying degrees. Such lattice curvature can have significant impacts on the quality of epitaxial layers grown on top of SiC wafers as it results in varying atomic step heights and terrace widths across the wafer surface. These variations can affect the purity of growth modes of the epitaxial film and impact the defect structure, morphology, and overall quality of the epilayer. The data of Fig. 3(b) presents variations in the overall crystalline quality of the material through measurement of the full width of the diffraction peak at half maximum (FWHM). Wider peak widths are indicative of a more defective nature in the material, which generally leads to more defective epitaxially grown layers. Clearly, a thorough understanding of substrate quality is important not only to refining epitaxial growth processes and material quality, but also to advancing the quality and maturity of SiC substrates. These efforts have shown that X-ray diffraction mapping is a powerful tool in developing this understanding.

What's Going On In There?

The SiC epitaxial growth environment is an extreme environment, to say the least, and a very challenging one to investigate. Typically it is comprised of hydrogen gas under a high flow rate (80 liters per minute) carrying a small mass fraction (<1%) of silane and propane through a reaction zone held at 1600 °C. For this reason, there have been very few efforts to characterize the growth process in situ. However, gaining a better understanding of this environment may be critical to the development of epilayers suitable for high-voltage power electronic devices since the required thick layers of such device structures imply long growths (8–16 hours) and are very sensitive to impurities (at the parts per billion level) and to variations in the gas phase carbon-to-silicon ratio. Through the custom porting of the NRL reactor, we have been able to employ in-situ mass spectrometry to characterize reaction products downstream of the growth zone with surprising sensitivity. An example of such efforts is presented in Fig. 4(a), where the mass spectral signal of the nitrogen partial pressure is tracked during the growth of a "staircase" doping sample. Also shown on the plot is the nitrogen concentration as measured by secondary ion mass spectrometry and the equivalent free carrier density associated with these dopant atoms. This data demonstrates a strong correlation between the mass spectral signals and the ultimate dopant incorporation in the growing layer. As can be seen in Fig. 4(b), at the lowest doping levels, variations in the mass spectral signals for the 28 amu partial pressure correspond to a doping level of ~ 1×10^{14} cm^{-3} (or one nitrogen atom in 10 billion carbon and silicon atoms). Such sensitivity is extremely important to the controlled growth of very thick (100 μm), very lightly doped (5×10^{14} cm^{-3}) drift regions of SiC power devices. Using this first-of-its-kind, in-situ mass spectrometry diagnostic, we will be able to monitor such



(a)



(b)

FIGURE 3
X-ray diffraction maps of a SiC substrate: (a) (0004) peak position and (b) its full width at half maximum.

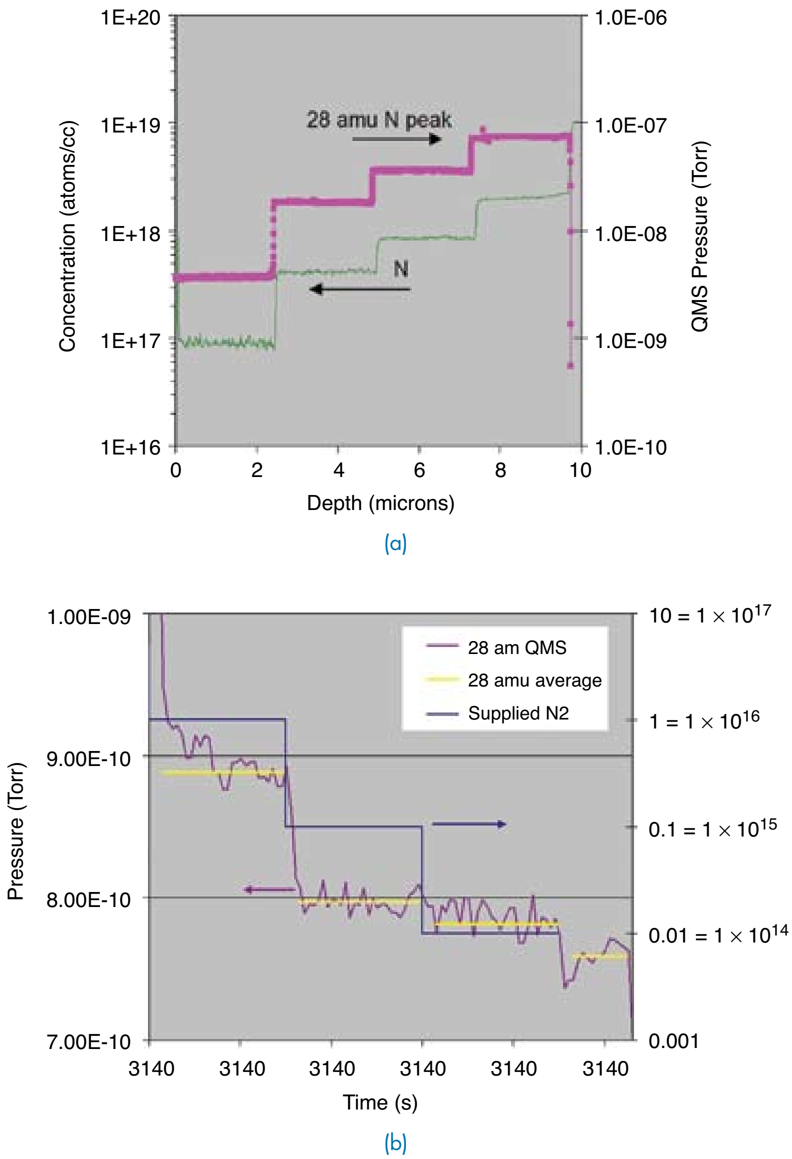


FIGURE 4
(a) Quadrupole mass spectrometry (QMS) results of nitrogen doping staircase demonstrating the correlation between measured nitrogen during the growth and nitrogen incorporation in the film. (b) QMS data demonstrating the high level of sensitivity of the in-situ mass spectrometric diagnostic technique.

low doping levels in real time and adjust the growth to ensure the desired doping structure in the device epilayers. Such control will enhance the performance of power devices fabricated from such layers.

The Proof is in the Pudding

Although tools such as XRD mapping and in-situ mass spectrometry hold great promise in enabling materials advancements, the true test of ASCERL is the synthesis of state-of-the-art materials. Currently, SiC epilayer quality is often judged by two parameters, background concentration of impurities and lifetime of free carriers in unintentionally- or low-doped (n-type) epilayers. Figure 5 presents CV data on the net background carrier concentration in unintentionally doped SiC epilayers grown in ASCERL during its first year. As can be seen, background carrier concentrations of ca. mid-10^{13} cm^{-3} can be routinely achieved. These very low concentrations are attributed to tight control of process conditions and reactor operation, and represent state-of-the-art equivalents. Further, the free carrier lifetime in lightly-doped layers is in the 2–3 microsecond range as measured by photoluminescence transients and the 4–6 microsecond range as measured by microwave photoconductance decay (Fig. 6). Again, these long lifetimes are equivalent to those measured in state-of-the-art materials. Both metrics, background carrier concentration and free carrier lifetime, are critical metrics of materials suitable for high-voltage, high-power electronic devices.

These highlighted advances in the first year of ASCERL's operation demonstrate the immediate relevance of the NRL effort and its potential to be a strong influence in SiC materials refinement for future Navy power needs. Near-term efforts in ASCERL will explore

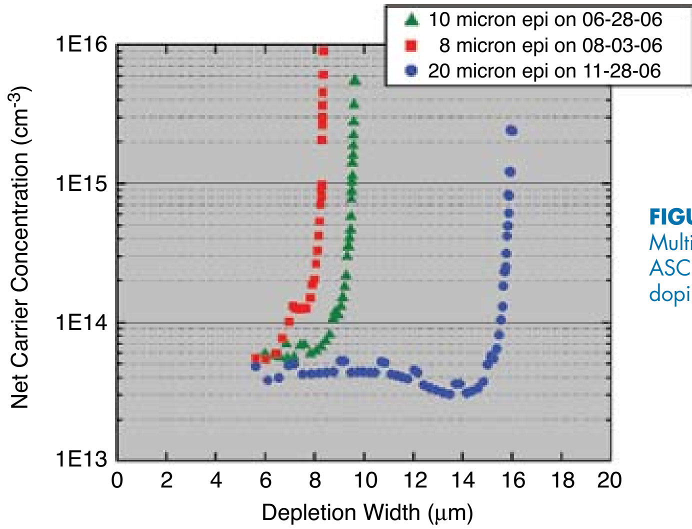


FIGURE 5
Multiple CV traces for unintentionally doped SiC films grown in ASCERL demonstrating ability to routinely achieve background doping levels below 1×10^{14} cm^{-3}.

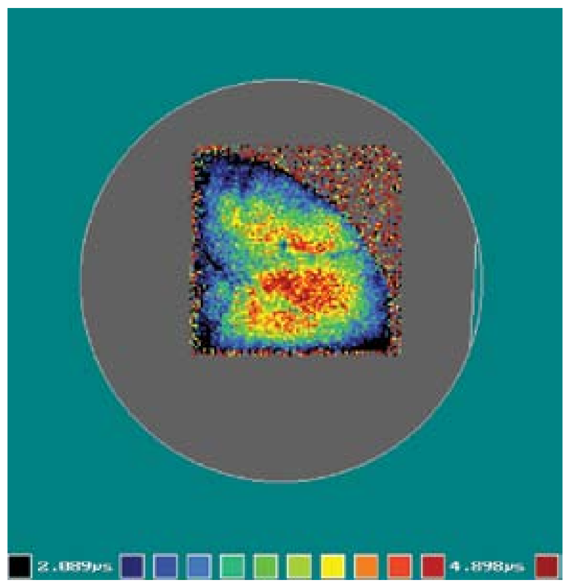


FIGURE 6
Free carrier lifetime map by microwave photoconductance decay method of SiC epilayer grown in ASCERL. Majority of the epilayer has free carrier lifetimes greater than 4 microseconds.

extended defect reduction and enhanced growth rate processes to push the material toward maturity for high-voltage, high-power bipolar device technologies such as PiN diodes, power metal-oxide-semiconductor field effect transistors (MOSFETs), and insulated gate bipolar transistors (IGBTs).

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