Advances in Silicon Carbide Electronics

J.C. Zolper and M. Skowronski, Guest Editors

Abstract

After substantial investment in research and development over the last decade, silicon carbide materials and devices are coming of age. The concerted efforts that made this possible have resulted in breakthroughs in our understanding of materials issues such as compensation mechanisms in high-purity crystals, dislocation properties, and the formation of SiC/SiO_2 interfaces, as well as device design and processing. The progress accomplished over the last eight years in SiC-based electronic materials is summarized in this issue of *MRS Bulletin*.

Keywords: *silicon carbide, electronic materials, high-frequency power electronics, reliability.*

Since the 1950s, we have been living in the "silicon world," with silicon as the foundation of the electronics era. At the beginning of the 21st century, the electronics industry is still dominated by silicon and is likely to remain so for at least another decade. No other semiconducting material can compete with silicon in terms of low defect densities, long minority carrier lifetimes, perfection of the semiconductor/dielectric interface, or doping control. Other materials—for example, GaAs and its alloys—only fill niche applications such as light-emission, where silicon is at a disadvantage due to its indirect bandgap. An indirect bandgap allows for the recombination of electrons and holes only with the participation of a phonon, a four-particle process that is inherently less likely than the three-particle process possible in a direct-bandgap semiconductor.

This situation could soon change in high-voltage switching and high-frequency power devices. The new material that can replace well-established silicon is hexagonal silicon carbide, a related semiconductor, which is the focus of this issue of *MRS Bulletin*. SiC technology is clearly not nearly as mature as that of silicon, and it is still more expensive than silicon, but its inherently superior properties, such as high breakdown field and thermal conductivity, provide a strong driving force for its development and implementation. Materials advances have reduced defect densities and improved the interface properties of SiC, and improvements in design and processing are bringing it to the fore as a serious competitor in electronics applications. For more background on SiC technology, see the article by Dhar in this issue.

Silicon carbide was also the theme of the March 1997 issue of *MRS Bulletin*, eight years ago. At that time, the only commercially available SiC products were conducting wafers (with diameters of up to 1 3/8 in.) and blue light-emitting diodes (LEDs). These were, however, the last days of SiC-based LEDs. They were replaced by more efficient devices based on direct-bandgap GaN and other Group III nitrides. Surprisingly, however, the explosive growth of the nitride LED market and full-color displays had a positive impact on the development of silicon carbide technology. Single-crystal SiC wafers formed an ideal template for nitride epitaxy due to good lattice match and higher thermal conductivity than any other available wafer material, and a stable, sizeable market for silicon carbide wafers was created. This provided support and incentive for the continued development of silicon carbide growth technology. Today, there are six companies—Cree Inc., II–VI Inc., Intrinsic Semiconductor, Dow Corning Compound Semiconductor Solutions, SiCrystal AG, Sixon, and Norstel AB—based in the United States, Europe, and Japan that offer single-crystal SiC substrates. The recent production standard—namely, 2-in.-diameter wafers—is being replaced by 3-in.-diameter wafers, with 100-mm-diameter wafers (4-in.-diameter) in development. Volume production has lowered the cost of a wafer unit area by a factor of 3, compared with 1997 ($1,400 for a 1 3/8 in. wafer in 1997 versus $2,400 for a 3-in.-diameter wafer today).

Although much improved, the quality of silicon carbide materials remains an active area of research and development. In 1997, the predominant material concern was the so-called micropipe defect (Figure 1), which seemed unique to silicon carbide grown by physical vapor transport. Micropipes are tubular voids with diameters between 0.1 μm and 1.0 μm that can extend through the entire SiC crystal. Since then, several different nucleation mechanisms for micropipes have been identified, such as nucleation on second-phase inclusions in SiC crystals[1] and coalescence of elementary screw dislocations.[2] As the result, the micropipe densities have been reduced significantly. They still represent a yield issue for large-area devices, but do not constitute a fundamental, insurmountable problem.

Besides micropipes, considerable effort has been focused in the last three years on basal-plane dislocations. These defects are responsible for the degradation of SiC bipolar devices, most notably high-voltage pin diodes[3] (see the articles by Chow and by Ha and Bergman in this issue). A typical dislocation density in commercial crystals is in the 10^3–10^4 cm^{-2} range, but an exciting breakthrough in material quality was announced just several months ago. A research group at Toyota Central R&D Laboratories and DENSO Corp. reported the growth of SiC boules (2-in.-diameter by 1-in.-thick

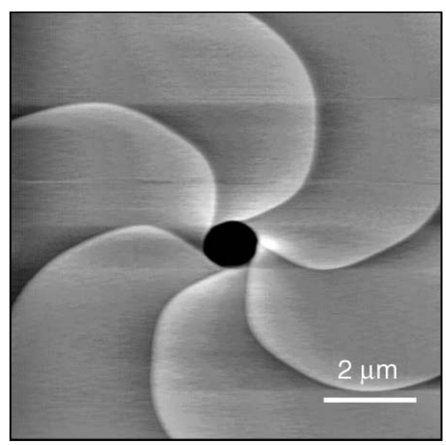


*Figure 1. Atomic force microscopy image of a micropipe defect intersecting the SiC growth surface. The step height in this image is 1.5 nm and corresponds to one unit cell of 6H-SiC. The black area in the middle of the image is an open core of a superscrew dislocation with a Burgers vector of 7*c *(where* c *is the lattice constant along the [0001] axis). Courtesy of G.S. Rohrer.*

https://doi.org/10.1557/mrs2005.73 Published online by Cambridge University Press

bulk crystal) with exceptionally low defect densities using a novel "repeated *a*-face" approach.[4] This method takes advantage of the tendency of extended defects in hexagonal silicon carbide to propagate only along specific crystallographic directions. A sequence of growth experiments using seeds cut along the $[11\bar{2}0]$ direction, followed by growth along the perpendicular [0001] axis, tends to lower defect densities. Two-inch-diameter wafers had total defect densities in the low hundreds per square centimeter, 1–2 orders of magnitude lower than previously reported. This development could lead to the growth of dislocation-free SiC crystals and epilayers, a distinction reserved only to silicon so far. "Dislocation-free" has been used to refer to crystals with dislocation densities below $1/cm^2$; the lowest dislocation density reported for SiC is $75/cm^2$.

Another important accomplishment in bulk growth is the availability of high-resistivity substrates for low-loss, high-frequency devices (see the article by Sumakeris et al. in this issue). The original approach to fabricating such material was intentional compensation of shallow residual impurities (with electron binding energies on the order of kT at room temperature) by deep electron levels induced by vanadium doping.[5] This approach reliably produced crystals with the Fermi level pinned by deep vanadium levels far from the conduction- and valence-band edges. However, a high density of vanadium centers resulted in the trapping of electrons in the substrate and a gradual reduction of the transconductance during operation of SiC metal semiconductor field-effect transistors (MESFETs). Such drift of the rf performance is known as current collapse.[6]

An alternative approach was the development of high-purity material, which relies on compensation due to deep levels associated with native point defects.[7] One of the most attractive characteristics of silicon carbide is the high breakdown field (3.5 MV/cm, six times higher than that of silicon; see Table I) due to its strong bonds and large bandgap. This, together with the availability of low-defect-density material, makes silicon carbide ideally suited for next-generation high-voltage switching devices (discussed by Zhao and by Chow in this issue). The first such device, namely, the Schottky diode, became commercially available in 2001. These devices, rated for 300–1200 V, are competing with silicon pin diodes for applications in power supplies of such ubiquitous products as personal computers and industrial electric motor controls.

SiC-based diodes are still significantly more expensive than their silicon counterparts, but they offer one considerable advantage: better energy efficiency. Every time the voltage reverses sign, the injected minority carriers in a silicon bipolar diode cause the current to flow until they are eliminated by recombination. This "current overshoot" is a major part of efficiency loss. Enter silicon carbide: the much higher energy barrier in SiC Schottky structures makes it possible to replace the Si bipolar device with a SiC unipolar metal–semiconductor junction. Since there is no minority carrier injection, the current overshoot is eliminated, and the switching losses are reduced by about an order of magnitude. At times of abundant cheap energy, this would not be a major consideration, but in the era of the Kyoto Protocol and the impact of greenhouse gas on the planet's climate, it represents a definite advantage.

For blocking voltages in excess of about 3 kV, the Schottky diode ON-state resistance becomes prohibitively high, and for such applications, the SiC pin diode appears to be the rectifier of choice. The already mentioned high breakdown field of SiC allows one to make these devices with blocking layers having one-sixth of the thickness of their silicon counterpart with the same nominal blocking voltage. This results in much lower ON-state losses and increased energy efficiency. The more advanced high-voltage switching devices currently under development include metal oxide semiconductor field-effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs).

MOSFET structures could enter the commercial market as soon as 2006. They employ a native thermally grown oxide layer as the gate insulator, using the same approach that has been successfully used in silicon technology. In the SiC case, however, the making of a perfect SiO_2/semiconductor interface is more difficult than in the case of SiO_2/Si. For one, silicon carbide has two types of atoms and, therefore, two types of potential dangling bonds: carbon and silicon. Second, since the bandgap in the 4H polytype* of SiC is 3.2 eV and about three times that of silicon, the states associated with dangling bonds are more likely to induce levels located within the bandgap. The interface charge associated with dangling bonds contributes to the scattering of electrons and low electron mobilities in MOSFETs. A recent breakthrough in post-oxidation nitrous oxide annealing reduced the interface charge density to an acceptable level.[8] A detailed discussion of SiC/SiO_2 interfaces is presented in the article by Dhar et al. in this issue.

Another intriguing intrinsic property of silicon carbide is its high saturated electron velocity (v_{sat}). This parameter corresponds to the velocity of electrons traveling through the material in the high electric fields that are encountered in field-effect transistors. It is used to determine the material figure of merit for high-frequency power devices (Table I), as it controls the gain in FETs. It is quite apparent that silicon carbide has significant potential in this field as well. The possible applications range from commercial base stations for cell phones to military S-band radar. It is worth noting that as early as 1996, Westinghouse Electric/CBS demonstrated high-definition TV broadcasting using a solid-state SiC-based transmitter. Cree Inc. has developed and is marketing a range of MESFETs. These devices offer lower loss, higher input and output impedances that are easier to match to antenna impedances, and higher power densities than standard Si- or GaAs-based components. In terms of frequencies, SiC will likely be used for intermediate-frequency applications, while GaN will work better in high-frequency situations.

In summary, silicon carbide electronics appears to be on the verge of wide commercial production. The material issues are being resolved, multiple device structures

Table I: Comparison of Material Properties and Figures of Merit for High-Voltage Switching and High-Frequency Devices.

Property	Silicon	GaAs	4H-SiC	GaN
Bandgap (eV)	1.1	1.43	3.2	3.4
Breakdown field (MV/cm)	0.6	0.65	3.5	3.5
Saturated electron velocity ($\times 10^7$ cm/s)	1	1	2	1.5
Bulk electron mobility (cm^2/V s)	1400	8000	800	900
Combined figure of merit (normalized to Si)	1	10	136	153

* Silicon carbide can crystallize in many different forms, called polytypes, corresponding to different stacking sequences of closely packed planes of atoms. The most commonly used forms of SiC are 4H-SiC and 6H-SiC, having four or six Si-C bilayers in the unit cell, respectively. These are intermediate structures between purely a hexagonal form called 2H and a cubic form called 3C. The 4H polytype of SiC is strongly preferred for silicon carbide electronic devices due to its higher electron mobility compared with 6H-SiC.

are gaining increasing acceptance in the marketplace, and additional new applications such as high-temperature electronics are waiting to be developed.

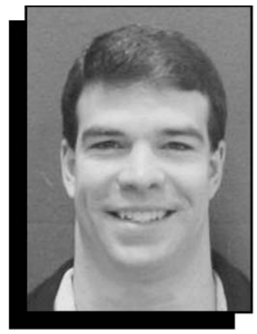
References

1. V. Balakrishna, R.H. Hopkins, G. Augustine, G. Donne, and R.N. Thomas, *Inst. Phys. Conf. Ser.* **160** (1997) p. 321; J. Giocondi, G.S. Rohreer, M. Skowronski, V. Balakrishna, G. Augustine, H.M. Hobgood, and R.H. Hopkins, *J. Cryst. Growth* **181** (1997) p. 351; M. Dudley, X.R. Huang, W. Huang, A. Powell, S. Wang, P. Neudeck, and M. Skowronski, *Appl. Phys. Lett.* **75** (1999) p. 784.
2. P. Pirouz, *Philos. Mag. A* **78** (1998) p. 727; T.A. Kuhr, E.K. Sanchez, M. Skowronski, W.M. Vetter, and M. Dudley, *J. Appl. Phys.* **89** (2001) p. 4625.
3. J.P. Bergman, H. Lendenmann, P.A. Nilsson, U. Lindefelt, and P. Skytt, *Mater. Sci. Forum* **353–356** (2001) p. 299.
4. D. Nakamura, I. Gunjishima, S. Yamaguchi, T. Ito, A. Okamoto, H. Kondo, S. Onda, and K. Takatori, *Nature* **430** (2004) p. 1009.
5. H.M. Hobgood, R.C. Glass, G. Augustine, R.H. Hopkins, J.R. Jenny, M. Skowronski, W.C. Mitchel, and M. Roth, *Appl. Phys. Lett.* **66** (1995) p. 1364.
6. O. Noblanc, C. Arnodo, C. Dua, E. Chartier, and C. Brylinski, *Mater. Sci. Forum* **338–342** (2000) p. 1247.
7. J.R. Jenny, S.T.G. Mueller, A. Powell, V.F. Tsvetkov, H.M. Hobgood, R.C. Glass, and C.H. Carter Jr., *J. Electron. Mater.* **31** (2002) p. 366.
8. G.Y. Chung, C.C. Tin, R.J. Williams, K. McDonald, M. Di Ventra, S.T. Pantelides, L.C. Feldmann, and R.A. Weller, *Appl. Phys. Lett.* **76** (2000) p. 1713. □

John C. Zolper, Guest Editor for this issue of *MRS Bulletin*, is the director of the Microsystems Technology Office (MTO) of the U.S. Defense Advanced Research Projects Agency (DARPA). MTO sponsors research in advanced electronics, photonics, MEMS, and integrated microsystems for the Department of Defense. Zolper holds a BA degree in physics from Gettysburg College and a PhD degree in electrical engineering from the University of Delaware. In 1988, Zolper spent time as a postdoctoral fellow at the University of New South Wales in Sydney, working on high-efficiency silicon solar cells. He then joined Sandia National Laboratories as a senior member of technical staff, where he developed advanced III–V semiconductor processes and devices. In 1997, he was a program officer in the Electronics Division of the Office of Naval Research (ONR), at which time he was responsible for managing the ONR's basic and applied research programs in advanced electronics. His programs included several of the premier academic and industrial teams developing Group III nitride and SiC electronics.

John C. Zolper

Marek Skowronski



Scott T. Allen

J. Peder Bergman

He joined DARPA in 2001 as a program manager to initiate a program in wide-bandgap electronics, was appointed deputy director of MTO in 2002, and was made director of MTO in 2005.

Zolper is the author or co-author of more than 150 journal articles and conference papers and seven book chapters, and he holds five U.S patents.

Zolper can be reached by e-mail at jzolper@darpa.mil.

Marek Skowronski, Guest Editor for this issue of *MRS Bulletin*, has been a professor in the Department of Materials Science and Engineering at Carnegie Mellon University since 1988. He received his PhD degree in solid-state physics from Warsaw University in Poland, after which he was a visiting scientist at the Massachusetts Institute of Technology, working on junction spectroscopy of point defects in GaAs. He then worked as a senior research associate at Cabot Corp., where he studied the growth and characterization of semi-insulating GaAs single crystals.

His current research interests are in crystal growth of wide-bandgap semiconductors and complex oxides, characterization and control of extended and point defects in crystals, and reliability of electronic devices. He is the author or co-author of more than 150 journal articles, conference papers, book chapters, and other publications.

Skowronski can be reached at the Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA, 15213 USA; tel. 412-268-2710, fax 412-268-7596, and e-mail ms3s@andrew.cmu.edu.

Scott T. Allen is the RF Engineering Manager at Cree Inc. and has been with the company for more than 10 years. He holds a BS degree from Cornell University; an MS degree from the University of Massachusetts, Amherst; and a PhD degree from the University of California, Santa Barbara, all in electrical engineering. At Cree, he has been involved with the development of all aspects of transistor and MMIC technologies for both SiC MESFETs and GaN devices and is leading the team of scientists and engineers responsible for the development of SiC and GaN microwave transistors. He also has experience in MMIC design stemming from his four years as a design engineer at the Lockheed Martin (formerly GE) Electronics Laboratory in Syracuse, N.Y. He holds several issued and pending U.S. patents pertaining to SiC and GaN device technology.

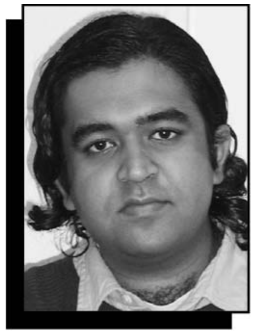
Allen can be reached by e-mail at scott_allen@cree.com.

J. Peder Bergman is an associate professor in the Materials Science Group within the Department of Physics and Measurement Technology at Linköping University in Sweden, where he also earned his PhD degree in 1991. In addition to his university association, Bergman has held joint appointments at ABB and Okmetic AB. His research activities include structural, electrical, and optical characterization of semiconductor and electronic devices. He is the author or co-author of more than 200 technical publications.

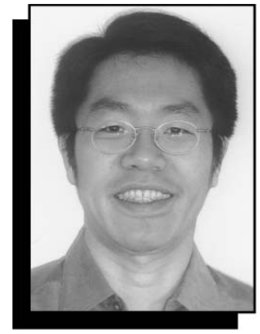
Bergman can be reached at the Department of Physics and Measurement Technology, Linköping University, Linköping, Sweden; tel. 46-13-282382, fax 46-13-142337, and e-mail ped@ifm.liu.se.

https://doi.org/10.1557/mrs2005.73 Published online by Cambridge University Press


T. Paul Chow


Sarit Dhar


Leonard C. Feldman


Seoyong Ha


Saptharishi Sriram


Joseph J. Sumakeris


Shurui Wang

T. Paul Chow is a professor in the Electrical, Computer, and Systems Engineering Department of Rensselaer Polytechnic Institute, where he received his PhD degree in electrical engineering in 1982.

From 1977 to 1989, he worked at General Electric Corporate Research and Development, where he developed CVD processes and studied the characterization of doped tin oxide and indium oxide thin films for transparent electrode applications in solid-state imagers, refractory metals, and metal silicides for Si MOS VLSI applications.

From 1982 to 1989, he participated in research and development for new discrete and integrable MOS-gated unipolar and bipolar devices. He also worked on the process architecture and integration of high-voltage integrated circuits. Chow's present research interests are in developing new device concepts, integrated processes, and circuit models for high-voltage power devices and integrated circuits of silicon and wide-bandgap compound semiconductors. Since 1998, Chow has led the Advanced Power Semiconductors Thrust for the Center for Power Electronics Systems, an NSF-sponsored Engineering Research Center consortium headed by Virginia Tech.

Chow has published more than 90 papers in refereed scientific journals, presented over 180 conference talks, contributed six chapters in technical textbooks, and holds over ten patents. He received the Solid-State Science and Technology Young Author Award from the Electrochemical Society in 1982 and the Horizon Award from Augustana College in 1986. He is a senior member of the IEEE and a member of the Electrochemical Society.

Chow can be reached by e-mail at chowt@rpi.edu.

Sarit Dhar is a PhD student in materials science at Vanderbilt University. He received his MS degree in physics from the Indian Institute of Technology in Kharagpur, India, in 2000. His research focuses on processing and characterization of the SiO_2/SiC interface for MOS applications.

Dhar can be reached by e-mail at sarit.dhar@vanderbilt.edu.

Leonard C. Feldman is the Stevenson Professor of Physics and a professor of materials science and engineering at Vanderbilt University. He holds simultaneous positions as a distinguished visiting scientist at Oak Ridge National Laboratory and an adjunct professor of physics at Fisk University. He received his PhD degree in physics from Rutgers University in 1967.

From 1967 to 1996, he carried out fundamental research and served as a department head at Bell Labs/AT&T/Lucent, leading efforts in thin-film science, ceramics, radiation physics, and semiconductor materials research, after which he joined Vanderbilt. His research interests focus on the formation and characterization of nanoscale structures and thin films.

Feldman won the 1999 David Adler Lectureship Award from APS. He is a fellow of the American Association for the Advancement of Science, the American Physical Society, and the American Vacuum Society, and was elected to the Royal Danish Academy of Science and Letters. He is the author or co-author of 350 publications and three books on materials physics, and he holds 20 patents.

Feldman can be reached by e-mail at leonard.c.feldman@vanderbilt.com.

Seoyong Ha is a senior research engineer at Samsung Corning Precision Glass in Chungnam, South Korea. He received his BS and MS degrees in metallurgical engineering from Seoul National University. From 1994 to 1997, he worked as a research engineer for LG Cable R&D Center in South Korea. He earned his PhD degree from the Department of Materials Science and Engineering at Carnegie Mellon University in 2002. He then accepted a research associate position in the same department, where he focused his research on SiC crystal growth, characterization of extended defects, and SiC device reliability. This work was performed in collaboration with ABB and Cree Inc. He is also an author of more than 20 technical publications.

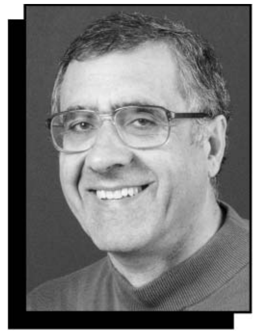
Ha can be reached at Samsung Corning Precision Glass, 544 Myungam-Ri, Tangjung-Myun Asan, Chungnam, 336–840, South Korea; tel. 82-41-520-1892 and e-mail seoyong@gmail.com.

Jason Henning is a device scientist at Cree Inc., where he works on SiC MESFET and MMIC programs. He received an associate degree in 1986, at which point he began working as an engineering technician at Rockwell Collins Radio, concentrating on antenna designs for radar systems. In 1994, he received a BS degree in electrical engineering from the University of Iowa and worked as a microwave design engineer at Rockwell Collins. In 1995, Henning entered Purdue University, earning an MS degree in electrical engineering in 1997 and a PhD degree in 1999. From 1999 to 2001, Henning was the engineering manager for OptoLynx, a startup company in the Purdue incubator specializing in high-frequency fiber optics.

https://doi.org/10.1557/mrs2005.73 Published online by Cambridge University Press

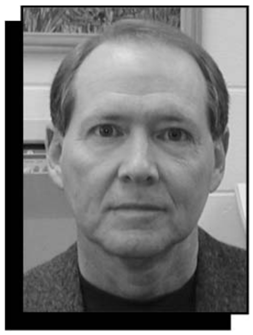

Jason Henning

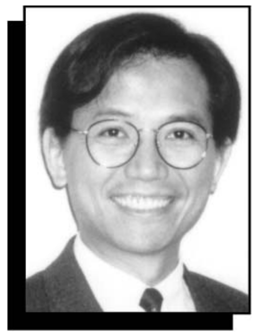

Jason R. Jenny


Sokrates T. Pantelides


Adrian R. Powell


Allan Ward


John R. Williams


Jian H. Zhao

Henning can be reached by e-mail at jason_henning@cree.com.

Jason R. Jenny is a scientist in the SiC crystal growth group at Cree Inc. He received his PhD degree in materials science and engineering from Carnegie Mellon University in 1996, where he focused on the characterization of vanadium-doped SiC. He then worked on an NRC fellowship at Wright-Patterson Air Force Base, evaluating Ga desorption during molecular-beam epitaxial growth of GaN materials, accepting his present position in 1997. His current research is directed at understanding the growth and characterization of semi-insulating materials.

Jenny is the author or co-author of more than 35 publications, and he holds three U.S. patents.

Jenny can be reached by e-mail at jason_jenny@cree.com.

Sokrates T. Pantelides is the William A. and Nancy F. McMinn Professor of Physics at Vanderbilt University. He also holds an appointment as a distinguished visiting scientist at Oak Ridge National Laboratory. He received his PhD degree in physics from the University of Illinois at Urbana-Champaign in 1973. After a postdoctoral appointment at Stanford University, he joined the IBM T.J. Watson Research Center in 1975, where he carried out theoretical research in semiconductors and served as manager, senior manager, and program director. He joined Vanderbilt University in 1994.

His research focuses on the structure, defect dynamics, and electronic properties of electronic materials; radiation effects; transport in molecules and thin films; and catalysis.

Pantelides is a fellow of the American Physical Society and the American Association for the Advancement of Science. He is also an author or co-author of 300 research articles and the editor of eight books.

Pantelides can be reached by e-mail at pantelides@vanderbilt.edu.

Adrian R. Powell is a senior research scientist in the SiC crystal growth group at Cree Inc. He earned a PhD degree in physics from the University of Warwick in 1992 for his doctoral work on the growth and characterization of SiGe.

From 1992 to 1994, he worked at the IBM T.J. Watson Research Center on molecular-beam epitaxial growth of SiGe and SiGeC structures on Si. He then joined the SiC group at ATMI Inc., where he focused on developing 2-in.-diameter SiC substrates until 1999, when he accepted his current position.

His specific research interests include bulk and epitaxial growth of wide-bandgap semiconductors and defect characterization within these materials. He is the author or co-author of over 40 publications and holds three U.S. patents.

Powell can be reached by e-mail at adrian_powell@cree.com.

Saptharishi Sriram joined Cree Inc. in 2000, where he is responsible for the development of SiC MESFETs for high-power and broadband defense and communications applications. He holds a BE degree in electronics and communication engineering from the Regional Engineering College at the University of Madras in Madras, India, an ME degree in electrical communication engineering from the Indian Institute of Science in Bangalore, and a PhD degree in electrical engineering from the Pennsylvania State University.

From 1975 to 1979, he was with Bharat Electronics Ltd. in Bangalore, where he worked on CMOS integrated circuits and solar cells. In 1983, he joined Westinghouse Research and Development Center in Pittsburgh (later known as the Science and Technology Center, Electronic Sensors and Systems Sector, of Northrop Grumman Corp.), where he later became an advisory engineer.

He holds seven patents, with six pending in various technical areas.

Sriram can be reached by e-mail at sriram@cree.com.

Joseph J. Sumakeris has been with the SiC epi group at Cree Inc. since 1995, when he received his PhD degree in materials science and engineering from North Carolina State University.

His primary responsibilities at Cree include epitaxial growth of SiC for MESFETs, addressing forward-voltage stability in bipolar devices, and developing annealing procedures for implant activation. He is the author or co-author of more than 30 publications, and he holds six U.S. patents.

Sumakeris can be reached by e-mail at joe_sumakeris@cree.com.

Shurui Wang is pursuing research at Auburn University on the 4H-SiC/SiO_2 interface to enhance the performance of SiC MOSFETs. In 2001, she earned a PhD degree in semiconductor physics from the Institute of Semiconductors at the Chinese Academy of Sciences. She then completed a year of postdoctoral work on SiC high-voltage devices at Centre de Génie Électrique de Lyon (CEGELY), a laboratory within INSA (Institut National des Sciences Appliquées) in Lyon, France.

Wang can be reached by e-mail at shurui@physics.auburn.edu.

https://doi.org/10.1557/mrs2005.73 Published online by Cambridge University Press

Allan Ward is the manager for advanced device reliability at Cree Inc. He holds a BS degree in electrical engineering (1990), an MS degree in materials engineering (1992), and a PhD in electronic materials science (1996), all from the Virginia Polytechnic Institute and State University.

Between 1993 and 1995, he was with the ITT GaAs Technology Center, working in the area of microwave device reliability. He was then an assistant professor in the Electrical Engineering Department at Virginia Tech, with research interests in power electronic packaging performance and reliability, until 1997. From then to 1999, he worked as a senior scientist at the Naval Research Laboratory on the reliability of optical microwave systems. Before moving to Cree, he worked for RF Microdevices as the lead scientist for GaAs device and packaged product reliability.

Ward is currently developing measurement techniques and assessing the reliability of SiC and GaN technologies for power electronic and broadband transmission devices.

Ward can be reached by e-mail at allan_ward@cree.com.

John R. Williams is the Thomas and Jean Walter Professor in the Physics Department at Auburn University. His research interests include technology development for wide-bandgap semiconductors and materials modification and analysis using MeV ion accelerators. He is a member of the American Physical Society and the Materials Research Society.

Williams can be reached at the Physics Department, 310 Leach Science Center, Auburn University, AL 36849 USA; tel. 334-844-4678, fax 334-844-2359, and e-mail williams@physics.auburn.edu.

Jian H. Zhao is a professor of electrical and chemical engineering at Rutgers University, where he heads research on SiC power and optoelectronic device development at the SiCLAB, the Silicon Carbide Power Device Research Center.

He received his PhD degree in electrical engineering from Carnegie Mellon University in 1988 with a thesis on GaAsSb heterostructures grown by MBE. He has been working on photonic and electronic devices based on SiC, GaN, InGaAs, AlGaAs, and GaAsSb, as well as waveguide devices. Together with his students and collaborators, he has published more than 200 papers and book chapters, as well as two books. He holds six U.S. patents on semiconductor devices.

Zhao can be reached by e-mail at jzhao@ece.rutgers.edu and via the Web at www.ece.rutgers.edu/~zhao. □

https://doi.org/10.1557/mrs2005.73 Published online by Cambridge University Press