Comprehensive Text Explains SiC Technology From Ingots To Circuits

Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications, Tsunenobu Kimoto, James A. Cooper, IEEE Press-Wiley, ISBN 978-1-118-31352-7, glossy hardback, 538 pages, 2014.

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This book is obviously about the new and emerging silicon carbide (SiC) semiconductor technology. While SiC and also GaN are emphasized in it as semiconductor materials showing some performance parameters well beyond that of Si, the book also has good general coverage of semiconductor electronics, beginning with crystal structure and developing through solid-state physics, device processes and processing, semiconductor diodes, BJTs, power JFETs, IGBTs, MOSFETs, MESFETs, and conductivity-modulated FETs or COMFETs. All the major device types seem to be covered, including variations on MOSFETs such as "trench" or "U groove" or UMOSFETs, as the authors call them, and DMOSFETs. Devices are explained in gratifying detail, including the BJT Rittner effect and the Kirk effect, which causes secondary breakdown in silicon power BJTs.

In case you are wondering what the Rittner effect is (as explained on page 366), under high-level injection in BJTs—that is, at high currents—the hole concentration in the base of an npn BJT is so high that it becomes comparable to that of the electron minority carriers coming in from the emitter across the forward-biased base-emitter junction. Ordinarily, the thermal voltage, $V_T = k_B \cdot T/q_e \approx 26$ mV is just that, but in the more complete model (and for diodes especially), there is a slope factor, the emission coefficient, n_E: $k_B \cdot T/n_E \cdot q_e$ where $1/n_E$ for the forward-biased base-emitter junction is the slope of the $\log I_C/\log V_{BE}$ plot.

At medium currents, the emission coefficient is 1 but during high-level injection, numerous holes are back-injected across the *b-e* junction, causing base current to increase and β to decrease. The main reason the emitter is so much more highly doped than the base is to maintain high emitter-injection efficiency, which is what keeps $n_E = 1$. Then most of what is crossing the junction are electrons with only a few holes, which keeps base current low and β high. The Rittner effect is the change of n_E from 1 to 2 at high currents. If you like these kinds of explanations of transistor behaviors, which are often ignored in other treatments of the subject—with the equations included—this book is for you.

Chapter two starts at rock-bottom with crystal structure and moves into solid-state physics. It includes non-electronic properties such as the thermal conductivity and mechanical hardness of the new materials. SiC in its three major crystal configurations has a much higher thermal conductivity (4.9 W/cm·K) than Si. SiC is also one of the hardest known materials, reminiscent of the diamond configuration of C.

How is SiC made? Chapter three covers the growth of ingots and describes the various crystal defects. Doping and insulating and free-carrier traps, high-temperature chemical vapor deposition (HTCVD), and wafer slicing and polishing are topics in this chapter. Chapter four continues the processing theme with epitaxial SiC growth including some discussion of the reactor design for growing layers. Doping control and defects follow (micropipes, dislocations, stacking faults, point defects), and homoepitaxy—all topics deep into semiconductor processing.

Chapter five is still submerged in SiC defect characterization—with plenty of charts chemists would like—and slowly introduces device model topics such as carrier-lifetime measurements, reverse recovery—then back into chemical etching, x-ray topography, photoluminescence mapping, deep-level transient spectroscopy, and electron paramagnetic resonance—nothing too familiar to power-circuits engineers but useful if and when subtle problems require diving deeper into device construction.

Circuit designers begin to see some daylight in chapter six, which ascends from pure processing to device construction. For a while it is back to processing topics such as ion implantation, annealing, etching, and oxidation—all nicely covered in their own right. Then the *C-V* curves of MOS capacitors appear to reawaken the dozing circuit designer, a circuit diagram of a MOSFET capacitor appears on page 223, and the moving scene changes to model parameter characterization. But not for long; more processing (post-oxidation annealing, interface nitridation and instability), then back to a device layout of Hall-effect measurements of a MOSFET. Current-voltage graphs appear and Schottky junction capacitance and contacts are characterized for SiC, along with *p*- and *n*-type ohmic contacts.

Finally, in chapter seven (starting on page 277, about halfway through the book), solid-state electronics at a graduate level (but readable by those versed in undergraduate active-circuits theory, especially if the textbook was by Gray and Searle of MIT) of diodes is presented, including Schottkys. It looks quite familiar to those who know silicon, but some of the values of variables elicit a double-take, like blocking voltages up to 50 kV. And SiC MOSFET on-resistance! I can only quote (page 280):

> "… on-resistance of an optimally designed non-punch-through unipolar [majority carrier, as in MOSFET] device increases as the square of the desired blocking voltage, and is inversely proportional to the *cube* of the critical field. Since the critical field in 4H-SiC is almost an order of magnitude higher than in silicon, the on-resistance for a given blocking voltage will be almost 1000 times lower. This accounts for the great interest in developing power devices in this material …"

Then in chapter eight, we move into power JFET modeling, including UMOS (trench MOSFETs) and DMOSFETs, to bipolar power switching devices in chapter nine, with detailed and readable model development. The Kirk effect is discussed on page 370 because it is a cause for secondary breakdown in power BJTs. For SiC BJTs,

> "The higher critical field of SiC leads to a much higher value for the Kirk current [where second breakdown occurs], effectively eliminating second breakdown as an issue in SiC BJTs."

This means that BJTs as power switches are back in the running with SiC. They have an advantage over FETs with higher current density, which is why IGBTs exist. More SPICE-like modeling equations ensue, and as we fast-forward the page-turning, thyristors appear. Then chapter ten, on optimization and comparison of power devices, shows device design refinements for achieving rather astounding device performance, especially when compared to IGBTs and MOSFETs. A useful performance measure is also developed for power switch comparisons.

In chapter eleven, we move into circuit applications for these devices. Although this chapter has some basic power circuits, the emphasis is on the devices in the context of circuitry. Included are motor drives, off-grid energy conversion, and another comparison of SiC and Si devices. Chapter twelve ends the chapters with a quick coverage of specialized SiC devices: MESFETs, static induction transistors, IMPATT diodes, high-temperature ICs, micro-electromechanical sensors, gas sensors, and optical detectors.

Three appendices present "Incomplete Dopant Ionization in 4H-SiC", "Properties of the Hyperbolic Functions", and "Major Physical Properties of Common SiC Polytypes". The book has a decent index.

If you have any interest in the now-emerging SiC semiconductor devices, this book covers it all and in sufficient depth to answer questions that might arise from process engineers, device modelers, or power-circuits and systems designers. It really is the book to have on SiC, and because of its breadth as well as depth, would be a good supplement to solid-state physics or electronics books, device design or SPICE modeling, or to provide a solid foundation for circuit design with SiC devices.

About The Author

Dennis Feucht has been involved in power electronics for 25 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been doing current-loop converter modeling and converter optimization.

To read Dennis' reviews of other texts on power supply design, magnetics design and related topics, see How2Power's [Power Electronics Book Reviews](#).