Eastern
Economy
Edition

FIFTH EDITION

SOLID STATE ELECTRONIC DEVICES

BEN G. STREETMAN ▪ SANJAY BANERJEE

PHI

SEMICONDUCTOR PHYSICS

Electron Momentum: $\mathsf{p} = m\mathsf{v} = \hbar\mathbf{k} = \dfrac{h}{\lambda}$ Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \dfrac{1}{2}m\mathsf{v}^2 = \dfrac{1}{2}\dfrac{\mathsf{p}^2}{m} = \dfrac{\hbar^2}{2m^*}\mathbf{k}^2$ (3–4) Effective mass: $m^* = \dfrac{\hbar^2}{d^2E/d\mathbf{k}^2}$ (3–3)

Total electron energy $= P.E. + K.E. = E_c + E(\mathbf{k})$

Fermi-Dirac e^- distribution: $f(E) = \dfrac{1}{e^{(E-E_F)/kT}+1} \cong e^{(E_F-E)/kT}$ for $E \gg E_F$ (3–10)

Equilibrium: $n_0 = \displaystyle\int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c-E_F)/kT}$ (3–15)

$N_c = 2\left(\dfrac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ $N_v = 2\left(\dfrac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (3–16), (3–20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F-E_v)/kT}$ (3–19)

$n_i = N_c e^{-(E_c-E_i)/kT}$, $p_i = N_v e^{-(E_i-E_v)/kT}$ (3–21)

$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\dfrac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$ (3–23), (3–26)

Equilibrium: $\begin{array}{l} n_0 = n_i e^{(E_F-E_i)/kT} \\ p_0 = n_i e^{(E_i-E_F)/kT} \end{array}$ (3–25) $n_0 p_0 = n_i^2$ (3–24)

Steady state: $\begin{array}{l} n = N_c e^{-(E_c-F_n)/kT} = n_i e^{(F_n-E_i)/kT} \\ p = N_v e^{-(F_p-E_v)/kT} = n_i e^{(E_i-F_p)/kT} \end{array}$ (4–15) $np = n_i^2 e^{(F_n-F_p)/kT}$ (5–38)

$\mathcal{E}(x) = -\dfrac{d\mathcal{V}(x)}{dx} = \dfrac{1}{q}\dfrac{dE_i}{dx}$ (4–26)

Poisson: $\dfrac{d\mathcal{E}(x)}{dx} = -\dfrac{d^2\mathcal{V}(x)}{dx^2} = \dfrac{\rho(x)}{\epsilon} = \dfrac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$ (5–14)

$\mu \equiv \dfrac{q\bar{t}}{m^*}$ (3–40a) Drift: $\mathsf{v}_d \cong \dfrac{\mu\mathcal{E}}{1 + \mu\mathcal{E}/\mathsf{v}_s}\left\{\begin{array}{l} = \mu\mathcal{E} \text{ (low fields, ohmic)} \\ = \mathsf{v}_s \text{ (high fields, saturated vel.)} \end{array}\right.$ (Fig. 6–9)

Drift current density: $\dfrac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathcal{E}_x = \sigma\mathcal{E}_x$ (3–43)

$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}$$

Conduction Current: drift diffusion (4–23)

$$J_p(x) = q\mu_p p(x)\mathscr{E}(x) - qD_p \frac{dp(x)}{dx}$$

$$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C\frac{dV}{dt}$$

Continuity: $\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \qquad \frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n}$ (4–31)

For steady state diffusion: $\frac{d^2\delta n}{dx^2} = \frac{\delta n}{D_n\tau_n} \equiv \frac{\delta n}{L_n^2} \qquad \frac{d^2\delta p}{dx^2} = \frac{\delta p}{L_p^2}$ (4–34)

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\frac{D}{\mu} = \frac{kT}{q}$ (4–29)

p-n JUNCTIONS

Equilibrium: $V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_a}{n_i^2/N_d} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_aN_d}{n_i^2}$ (5–8)

$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$ (5–10) $W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2}$ (5–57)

One-sided abrupt p^+-n: $x_{n0} = \frac{WN_a}{N_a + N_d} \simeq W$ (5–23) $V_0 = \frac{qN_dW^2}{2\epsilon}$

$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$ (5–29)

$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$ (5–31b)

Ideal diode: $I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$ (5–36)

Non-ideal: $I = I_0'(e^{qV/\mathbf{n}kT} - 1)$ ($\mathbf{n} = 1$ to 2) (5–74)

With light: $I_{\text{op}} = qAg_{\text{op}}(L_p + L_n + W)$ (8–1)

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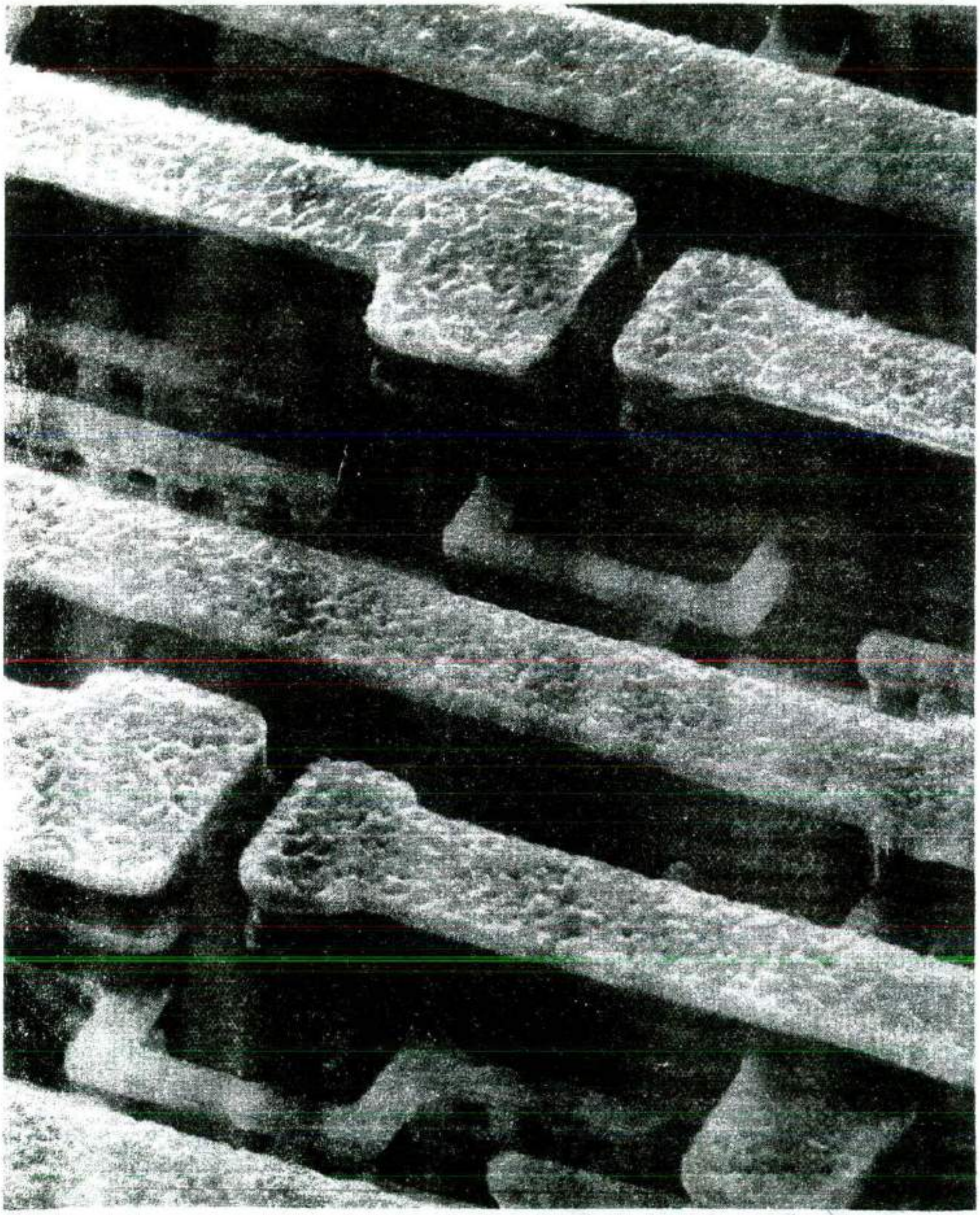

Multi-level copper metallization of a complementary metal oxide semiconductor (CMOS) chip. This scanning electron micrograph (scale: 1 cm = 3.5 microns) of a CMOS integrated circuit shows six levels of copper metallization that are used to carry electrical signals on the chip. The inter-metal dielectric insulators have been chemically etched away here to reveal the copper interconnects. (Photograph courtesy of IBM.)

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STREETMAN AND SANJAY BANERJEE

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PREFACE

This book is an introduction to semiconductor devices for undergraduate electrical engineers, other interested students, and practicing engineers and scientists whose understanding of modern electronics needs updating. The book is organized to bring students with a background in sophomore physics to a level of understanding which will allow them to read much of the current literature on new devices and applications.

GOALS

An undergraduate course in electronic devices has two basic purposes: (1) to provide students with a sound understanding of existing devices, so that their studies of electronic circuits and systems will be meaningful; and (2) to develop the basic tools with which they can later learn about newly developed devices and applications. Perhaps the second of these objectives is the more important in the long run; it is clear that engineers and scientists who deal with electronics will continually be called upon to learn about new devices and processes in the future. For this reason, we have tried to incorporate the basics of semiconductor materials and conduction processes in solids, which arise repeatedly in the literature when new devices are explained. Some of these concepts are often omitted in introductory courses, with the view that they are unnecessary for understanding the fundamentals of junctions and transistors. We believe this view neglects the important goal of equipping students for the task of understanding a new device by reading the current literature. Therefore, in this text most of the commonly used semiconductor terms and concepts are introduced and related to a broad range of devices.

READING LISTS

As a further aid in developing techniques for independent study, the reading list at the end of each chapter includes a few articles which students can read comfortably as they study this book. Some of these articles have been selected from periodicals such as *Scientific American* and *Physics Today*, which specialize in introductory presentations. Other articles chosen from books and the professional literature provide a more quantitative treatment of the material. We do not expect that students will read all articles recommended in the reading lists; nevertheless, some exposure to periodicals is useful in laying the foundation for a career of constant updating and self-education.

PROBLEMS

One of the keys to success in understanding this material is to work problems that exercise the concepts. The problems at the end of each chapter are designed to facilitate learning the material. Very few are simple "plug-in" problems. Instead, they are chosen to reinforce or extend the material presented in the chapter.

UNITS In keeping with the goals described above, examples and problems are stated in terms of units commonly used in the semiconductor literature. The basic system of units is rationalized MKS, although cm is often used as a convenient unit of length. Similarly, electron volts (eV) are often used rather than joules (J) to measure the energy of electrons. Units for various quantities are given in Appendices I and II.

PRESENTATION In presenting this material at the undergraduate level, one must anticipate a few instances which call for a phrase such as "It can be shown . . ." This is always disappointing; on the other hand, the alternative is to delay study of solid state devices until the graduate level, where statistical mechanics, quantum theory, and other advanced background can be freely invoked. Such a delay would result in a more elegant treatment of certain subjects, but it would prevent undergraduate students from enjoying the study of some very exciting devices.

The discussion includes both silicon and compound semiconductors, to reflect the continuing growth in importance for compounds in optoelectronic and high-speed device applications. Topics such as heterojunctions, lattice matching using ternary and quaternary alloys, variation of band gap with alloy composition, and properties of quantum wells add up to the breadth of the discussion. Not to be outdone by the compounds, silicon-based devices have continued their dramatic record of advancement. The discussion of FET structures and Si integrated circuits reflects these advancements. Our objective is not to cover all the latest devices, which can only be done in the journal and conference literature. Instead, we have chosen devices to discuss which are broadly illustrative of important principles.

The first four chapters of the book provide background on the nature of semiconductors and conduction processes in solids. Included is a brief introduction to quantum concepts (Chapter 2) for those students who do not already have this background from other courses. Chapter 5 describes the p-n junction and some of its applications. Chapters 6 and 7 deal with the principles of transistor operation. Chapter 8 covers optoelectronics and Chapter 9 discusses integrated circuits. Chapters 10 and 11 apply the theory of junctions and conduction processes to microwave and power devices. All of the devices covered are important in today's electronics; furthermore, learning about these devices should be an enjoyable and rewarding experience. We hope this book provides that kind of experience for its readers.

ACKNOWLEDGMENTS

The fifth edition benefits greatly from comments and suggestions provided by students and teachers of the first four editions. The book's readers have generously provided comments which have been invaluable in developing the present version. We remain indebted to those persons mentioned in the Preface of the first four editions, who contributed so much to the development of the book. In particular, Nick Holonyak has been a source of continuing information and inspiration for all five editions. Additional thanks go to our colleagues at UT-Austin who have provided special assistance, particularly Joe Campbell, Ray Chen, Dennis Deppe, Russ Dupuis, Archie Holmes, Dim-Lee Kwong, Jack Lee, Christine Maziar, Dean Neikirk, and Al Tasch. Kay Shores and Qingyou Lu provided useful assistance with the typing. We thank the many companies and organizations cited in the figure captions for generously providing photographs and illustrations of devices and fabrication processes. Kobi Benzvi and Pradipto Mukherjee at Motorola, Shubneesh Batra and Mary Miller at Micron, and Tom Way at IBM deserve special mention. Finally, we recall with gratitude many years of association with the late Greg Stillman, a valued colleague and friend.

Ben G. Streetman
Sanjay Banerjee

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ABOUT THE AUTHORS

Ben G. Streetman is Dean of the College of Engineering at The University of Texas at Austin and holds the Dula D. Cockrell Centennial Chair in Engineering. He is a Professor of Electrical and Computer Engineering and was the founding Director of the Microelectronics Research Center (1984–96). His teaching and research interests involve semiconductor materials and devices. After receiving a Ph.D. from The University of Texas at Austin (1966) he was on the faculty (1966–1982) of the University of Illinois at Urbana-Champaign. He returned to The University of Texas at Austin in 1982. His honors include the Education Medal of the Institute of Electrical and Electronics Engineers (IEEE), the Frederick Emmons Terman Medal of the American Society for Engineering Education (ASEE), and the Heinrich Welker Medal from the International Conference on Compound Semiconductors. He is a member of the National Academy of Engineering. He is a Fellow of the IEEE and the Electrochemical Society. He has been honored as a Distinguished Alumnus of The University of Texas at Austin and as a Distinguished Graduate of the UT College of Engineering. He has received the General Dynamics Award for Excellence in Engineering Teaching, and was honored by the Parents' Association as a Teaching Fellow for outstanding teaching of undergraduates. He has served on numerous panels and committees in industry and government, and several corporate boards. He has published more than 270 articles in the technical literature. Thirty-three students of Electrical Engineering, Materials Science, and Physics have received their Ph.D.s under his direction.

Sanjay Kumar Banerjee is Professor of Electrical and Computer Engineering, and Director of the Microelectronics Research Center at The University of Texas at Austin, where he currently holds the Cullen Trust Endowed Professorship in Engineering No. 1 as well as being a Fellow of the Cockrell Family Regent's Chair. His research interests include silicon-based heterostructure devices, device modeling and ultra-large-scale IC technology. He received his B.Tech from the Indian Institute of Technology, Kharagpur, and his M.S. and Ph.D. from the University of Illinois at Urbana-Champaign in 1979, 1981 and 1983, respectively, all in electrical engineering. At Texas Instruments from 1983–1987, he worked on polysilicon transistors and dynamic random access memory cells used in the world's first 4Megabit DRAM, for which he was the co-recipient of the Best Paper Award at the 1986 IEEE International Solid State Circuits Conference. His honors include the NSF Presidential Young Investigator Award (1988), Engineering Foundation Advisory Council Halliburton Award (1991) for teaching excellence, and the Texas Atomic Energy Centennial Fellowship (1990–1997). He has more than 225 archival referred publications, has presented over 200 talks at conferences, and has 12 U.S. patents. He has supervised 18 Ph.D. and 35 MS students. He is a Distinguished National Lecturer for the IEEE Electron Devices Society (1997–), and Fellow of the IEEE (1996).