SEMICONDUCTOR POWER DEVICES

PHYSICS OF OPERATION AND FABRICATION TECHNOLOGY

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Properties of Silicon

Atomic number	14
Atomic weight	28.06
Atom density	$5.02\times 10^{22}/\mathrm{cm}^3$
Density	$2.33\ \mathrm{g/cm}^3$
Crystal structure	Diamond
Lattice constant (cube edge), a	5.43 Å
Tetrahedral radius, r_0	1.18 Å
Coefficient of thermal expansion (300°K)	$2.6\times 10^{-6}/°\mathrm{C}$
Specific heat (300°K)	0.7 joules/g-°C
Thermal conductivity (300°K)	1.45 W/cm-°C
Thermal diffusivity (300°K)	$0.9\ \mathrm{cm}^2/\mathrm{sec}$
Melting point	1412°C
Energy gap, E_g	1.11 eV
Conductivity effective mass (electrons)	$0.26\ m_0$
(holes)	$0.38\ m_0$
Density-of-states effective mass (electrons)	$1.1\ m_0$
(holes)	$0.59\ m_0$
Effective density of states at the valence band edge, N_v	$1.02\times 10^{19}(T/300)^{3/2}/\mathrm{cm}^3$
Effective density of states at the conduction band edge, N_c	$2.8\times 10^{19}(T/300)^{3/2}/\mathrm{cm}^3$
Intrinsic carrier concentration, n_i	$1.38\times 10^{10}/\mathrm{cm}^3$
Lattice mobility for electrons, μ_n	$1350\ \mathrm{cm}^2/\mathrm{volt\text{-}sec}$
Lattice mobility for holes, μ_p	$480\ \mathrm{cm}^2/\mathrm{volt\text{-}sec}$
Relative permittivity, ϵ	12

Useful Physical Constants

Boltzmann's constant, k	8.62×10^{-5} ev/°K
Electron rest mass, m_0	9.11×10^{-28} g
Energy associated with 1 eV	1.6×10^{-12} erg
Magnitude of the electronic charge, q	1.6×10^{-19} coulomb
Permittivity of free space, ϵ_0	8.86×10^{-14} farad/cm
Planck's constant, h	4.14×10^{-15} eV-sec
Room temperature value of kT	0.0259 eV
Velocity of light, c	3×10^{10} cm/sec
Angstrom unit, Å	10^{-8} cm
Micron, μm	10^{-4} cm
Thousandth of an inch, mil	25.4 μm

Semiconductor Power Devices

Thyristor devices. Courtesy of the General Electric Company, Semiconductor Products Dept., Auburn, N.Y.

To

MY FATHER

in memoriam

PREFACE

The use of solid state techniques for electrical power control coincides with the development of large area, single crystal rectifiers in the early 1950s, followed by the development of power transistors. Today such devices have an important part in this field, with silicon being the almost universal choice of material. A true revolution did not take place, however, until the announcement of the *p-n-p-n* device* by the Bell Laboratories. This device was originally developed for use as a cross-point switch in telephone networks. The General Electric Company was the first to exploit its potential in high power control applications, with the successful demonstration of a silicon device capable of operation at high current levels. Originally called the Silicon Controlled Rectifier, devices of this type (together with a number of derivative structures) are now grouped under the generic name of *thyristor*, and are the most important members of the family of semiconductor power devices. They have found their way into applications ranging from speed control in home appliances to switching and power inversion in high voltage d-c transmission lines.

For a long time, semiconductor power devices (and thyristors in particular) were not considered part of the mainstream of solid state endeavor, which was dominated by the area of microelectronics. Research in the field was confined to a small group of workers, and reported in the specialist literature. The first attempt to integrate this material was made in 1964 in a book[†] that described the principles and circuit applications of thyristor devices. Since that time, most new books have been restricted to circuit applications of these devices.

The present volume is concerned with the physics of operation and the fabrication technology of power diodes, transistors, and thyristors. It has

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*J. L. Moll, M. Tannenbaum, J. M. Goldey, and N. Holonyak Jr., "*p-n-p-n* Transistor Switches", *Proc. IRE*, **44**, No. 9, pp. 1174–1182 (1956).

[†] F. E. Gentry, F. W. Gutzwiller, N. Holonyak, Jr., and E. E. Von Zastrow, *Semiconductor Controlled Rectifiers*, Prentice-Hall, Englewood Cliffs, N.J. (1964).

been written to meet the needs of a rapidly increasing body of engineers who are becoming involved in the field of power control. This includes engineers who must design advanced circuits using these devices, and thus need to better understand the physics of device behavior, as well as those who must specify device characteristics that are necessary for the new circuit applications. It will also meet the needs of those who must design and fabricate these new devices.

Finally, this book has been written to provide a text that can bring this material into the academic curriculum. Many students are interested in this area because of its growing importance to industry. Unfortunately, university courses in semiconductor power devices have been initiated only recently, since the required information has been scattered through the technical literature. This book should give the necessary impetus for such course offerings—it coordinates and unifies this material into a logical form.

The book is directed at readers who already are familiar with the physics of operation and the fabrication technology of transistors and microcircuits. This has been done to avoid repeating material already adequately presented in a number of books and to keep the book to a reasonable size. I have attempted to emphasize areas that are unique and of special importance to semiconductor power devices, organizing material so as to bring out these areas in some detail.

Chapter 1 deals with such fundamental considerations as lifetime, with emphasis placed on high level effects and on Auger processes. Also included is a discussion of transport phenomena in high resistivity materials, and the development of ambipolar parameters for their characterization. A major section of this chapter deals with single and double injection, which leads to the formation of microplasmas and mesoplasmas with eventual destruction by second breakdown.

Chapter 2 deals with the characteristics of diodes with high reverse breakdown voltage. Techniques for obtaining these characteristics are developed. Included are discussions of the use of guard rings, field plates, and surface contouring methods, all of which are unique to power devices. Instabilities that can be encountered during operation in this mode are also described.

Chapter 3 is about the forward-biased diode. Here device operation at high injection levels is considered, together with the special problems of highly doped emitters. The main emphasis is on the p^+-i-n^+ structure which closely represents the behavior of a thyristor in its ON state. Both static and dynamic characteristics of this device are considered in some detail. Thermal instabilities in forward-biased diodes are also examined.

Chapter 4 deals with the special characteristics of high voltage, high power transistors. These include double saturation effects in their output characteristics, as well as falloff in current gain and in gain-bandwidth product at high injection levels. An important part of this chapter treats phenomena leading to the formation of mesoplasmas and second breakdown, as well as corrective measures for alleviating these effects.

Chapter 5 discusses thyristors and related devices such as gate-controlled switches, diacs, and triacs. Topics include a study of various modes of device operation, such as reverse blocking, forward blocking, and forward conduction. Dynamic processes are considered together with the special problems of turn-on and reverse recovery. Techniques involving the use of shorts and amplifying gates are covered in detail. Additional topics include light-activated thyristors, amplifying gate thyristors, and reverse conducting thyristors, as well as gate-assisted turn-off devices. Mechanisms for device instability are also outlined.

Chapter 6 deals with fabrication technology. The emphasis again is on aspects that are unique to power devices, since it is assumed that the reader has some familiarity with the basic materials and processing problems and techniques encountered with lower power devices and microcircuits.* Topics such as neutron doping, deep diffusions, stress-free processing, the control of lifetime, and special packaging problems for these devices are emphasized. Hard and soft solder systems are considered for device mounting, as is the use of intermediate materials for the reduction of interfacial stress during thermal cycling. Finally, integrated circuit packaging techniques are described, since these present an important area for control applications at medium power levels.

I have attempted to be as comprehensive as possible. However, progress in this field is very rapid, and any attempt to be encyclopaedic in coverage would only result in early obsolescence. Consequently, the emphasis is on the basic principles of device operation to enable the reader to understand and evaluate new developments in the field as they are announced. With this in mind, no attempt has been made to use references as a means for giving credit to the persons who did the original research; rather, references have been chosen to provide a useful mechanism for further study. In like manner, a number of problems have been provided, many of which were selected from practical situations and are intended to bring out points not covered in detail in the text.

I am indebted to many people who have contributed, directly or indirectly, to the preparation of this book. Many thanks are due to Dr. A. P. Ferro and Dr. D. Schaefer, as well as to R. Guess, all of the General Electric Corporate Research and Development Center, for providing the

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*See, for example, S. K. Ghandhi, *The Theory and Practice of Microelectronics*, John Wiley and Sons, New York, 1968.

stimulus for a power semiconductor program at Rensselaer. I am also indebted to the faculty members in our solid state program, with whom I have had many fruitful discussions. These include Drs. J. M. Borrego, B. K. Bose,* P. K. Das, R. J. Gutmann, K. Rose, and A. J. Steckl. In addition, technical discussions with many friends at the General Electric Company, which took place during the presentation of a series of lectures on this subject, are gratefully acknowledged. I must single out Dr. B. Jayant Baliga of the Power Semiconductor Branch, General Electric Corporate Research and Development Center, for his friendly but critical review of the manuscript and for his detailed, constructive suggestions. His interest has been very helpful and stimulating and has greatly enhanced the relevance of this work to modern practice in the field.

The material of this book has been taught, in one form or another, to graduate students over the last four years. They deserve my heartfelt thanks and sympathy. Their penetrating questions have often led to rethinking and reworking of this text over the years. Finally, credit for the typing of this manuscript and its many revisions must go to R. Carla Rafun, who also played a major role in editing and checking the manuscript, right from its typed version up to the page proof stage. I am sure this manuscript would never have been completed were it not for her selfless and enthusiastic participation in what could easily have been considered just one more item of overwork.

SORAB K. GHANDHI

Niskayuna, New York
June 1977

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*Now with the General Electric Research and Development Center, Schenectady, N.Y.

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CHAPTER 1

Fundamental Considerations

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AT FIRST GLANCE, it would appear that the physics of semiconductor power devices is identical to that of their low power counterparts. Certainly device operation is the same, regardless of physical size. Nevertheless, many aspects of device physics take on a different sense of importance under conditions of high power operation. Furthermore, certain device structures, such as *p-i-n* diodes and *p-n-p-n* thyristors, have unique advantages for high power applications and are used primarily in these situations alone.

This chapter outlines some fundamental considerations that arise in a study of semiconductor power devices. A priori, such devices must be capable of dissipating large amounts of power, under both steady state and transient conditions. Thus the problems of heat removal represent an important aspect of fabrication and packaging technology. In addition, the devices must be operated in a switching mode. In such operation, the power handling capacity of a device is directly related to its ability to support high reverse voltages in the OFF state, and to conduct at high forward current levels in the ON state.

The reverse breakdown voltage of a junction diode is determined by the resistivity of the *p*- and *n*-regions, and by its doping profile. This problem is considered in detail in Chapter 2. Qualitatively, however, it is seen that the ability to hold off high reverse voltages mandates the use of materials with high starting resistivity. Values as high as 500 ohm-cm are encountered in diodes designed to support reverse potentials in the kilovolt range. By way of comparison, the starting resistivity of devices used in digital integrated circuits is typically 0.15–0.2 ohm-cm!

The ability to handle large forward currents necessitates device operation at high levels of injected carrier concentration, often well in excess of the initial concentration of thermally ionized carriers present in the semiconductor. Thus the background concentration of the semiconductor becomes relatively unimportant in determining the device behavior. Furthermore, the total electron and hole concentrations become approximately equal in magnitude, so that injection at high levels shares many common characteristics with injection into intrinsic materials. It is appropriate, therefore, to give special consideration to transport phenomena in materials that exhibit intrinsic conduction, especially in lightly doped semiconductors. For silicon, material with carrier concentrations up to $10^{15}/\text{cm}^3$ is classed as high resistivity material. In high voltage devices, the initial carrier concentration is often as low as $10^{13}/\text{cm}$.

1.1 LIFETIME

A semiconductor is said to be in *thermal equilibrium* with its environment if for any process, there is an inverse process that occurs at the same rate.

At any given temperature, this results in the continual generation and recombination of hole-electron pairs with identical generation and recombination rates. The end result is an equilibrium concentration of holes $\bar{p}$ and electrons $\bar{n}$ such that $\bar{p}\bar{n}=n_i^2=\text{constant}$. If such a system is excited (e.g., by illumination with steady penetrating light), both carrier generation and recombination rates will be altered until new steady state conditions are reached. At this point, the electron and hole concentrations are given by

$$n=\bar{n}+n' \tag{1.1a}$$

$$p=\bar{p}+p' \tag{1.1b}$$

where n',p' are the time-dependent concentrations of excess electrons and holes, respectively, and $\bar{n},\bar{p}$ are their thermal equilibrium values. Upon removal of this stimulus, a process of recombination occurs, until the system returns to its thermal equilibrium value. In an n-type semiconductor, the recombination process for minority carriers can be approximated by a power series, such that

$$-\frac{\partial p'}{\partial t}=\gamma_1 p'+\gamma_2 p'^2+\gamma_3 p'^3+\cdots \tag{1.2}$$

Here the different terms can be expected to dominate over different regimes of carrier concentration. From a physical point of view, the second-order term is characteristic of *band-to-band recombination*, accompanied by photon emission. Radiative processes of this type are highly improbable in indirect gap materials such as silicon, and recombination is more appropriately described by

$$-\frac{\partial p'}{\partial t}=\gamma_1 p'+\gamma_3 p'^3 \tag{1.3}$$

for this material. For a very wide range of injection levels, the first term predominates, and is useful in characterizing *phonon-assisted recombination*, via deep impurity levels. The parameter $1/\gamma_1$ is referred to as the *minority carrier lifetime* τ_p. The evaluation of this term has been extensively treated in the literature [1, 2] and is reviewed here for the case of a single recombination center. The situation for multiple levels is extremely complex [3] and is often treated in terms of the single level case.

Consider an n-type semiconductor, with a density of recombination centers N_r at an energy level E_r. For the purposes of discussion it is assumed that these centers are donors. In thermal equilibrium, some of these are neutral and the rest ionized. Thus $N_r=\bar{N}_r^+ + \bar{N}_r^0$, where the bar indicates thermal equilibrium values. Under *steady state nonequilibrium* conditions, the concentrations of neutral and ionized recombination centers are altered, and we have $N_r = N_r^+ + N_r^0$.

The rate of capture of electrons from the conduction band is proportional to the electron concentration and to the concentration of positively ionized centers. Thus

$$R_{cn} = \alpha_n n N_r^+ \tag{1.4a}$$

where α_n is a rate constant, given by the product of the electron capture cross section and the electron thermal velocity.

The rate of emission of electrons to the conduction band is proportional to the concentration of neutral centers and to the density of available states at the conduction band edge. Thus

$$R_{en} = C_1 N_r^0 (N_c - n) \cong C_1 N_r^0 N_c \tag{1.4b}$$

where C_1 is a proportionality factor, and N_c is the density of states at the conduction band edge.

In like manner, the capture and emission rates of holes with respect to the valence band are given by

$$R_{cp} = \alpha_p p N_r^0 \tag{1.5a}$$

$$R_{ep} = C_2 N_r^+ N_v \tag{1.5b}$$

where C_2 is a proportionality factor, and N_v is the density of states at the valence band edge.

The factors C_1 and C_2 may be evaluated by using the conditions for thermal equilibrium (i.e., $\overline{R}_{cn} = \overline{R}_{en}$ and $\overline{R}_{cp} = \overline{R}_{ep}$). Making these substitutions into (1.4a) and (1.4b) and solving, gives

$$R_{cn} - R_{en} = -\frac{dn'}{dt} = \alpha_n \left(n N_r^+ - n_1 N_r^0 \right) \tag{1.6}$$

where

$$n_1 = N_c \exp -\left(\frac{E_c - E_r}{kT} \right) \tag{1.7}$$

In like manner, the rate of change of the excess hole concentration is given by

$$R_{cp} - R_{ep} = -\frac{dp'}{dt} = \alpha_p \left(p N_r^0 - p_1 N_r^+ \right) \tag{1.8}$$