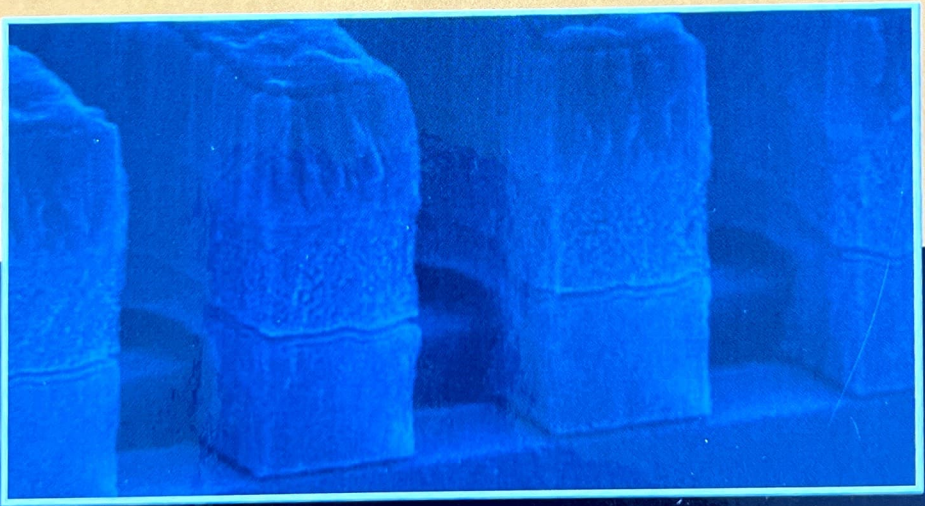


PHYSICS OF SEMICONDUCTOR DEVICES



T H I R D E D I T I O N

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Physics of Semiconductor Devices

Third Edition

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Description of cover photograph:

A scanning electron micrograph of an array of the floating-gate nonvolatile semiconductor memory (NVSM) magnified 100,000 times. NVSM was invented at Bell Telephone Laboratories in 1967. There are more NVSM cells produced annually in the world than any other semiconductor device and, for that matter, any other human-made item. For a discussion of this device, see Chapter 6. Photo courtesy of Macronix International Company, Hsinchu, Taiwan, ROC.

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Contents

Introduction	1
---------------------	----------

Part I Semiconductor Physics

Chapter 1 Physics and Properties of Semiconductors—A Review	7
--	----------

- 1.1 Introduction, 7
- 1.2 Crystal Structure, 8
- 1.3 Energy Bands and Energy Gap, 12
- 1.4 Carrier Concentration at Thermal Equilibrium, 16
- 1.5 Carrier-Transport Phenomena, 28
- 1.6 Phonon, Optical, and Thermal Properties, 50
- 1.7 Heterojunctions and Nanostructures, 56
- 1.8 Basic Equations and Examples, 62

Part II Device Building Blocks

Chapter 2 p-n Junctions	79
--	-----------

- 2.1 Introduction, 79
- 2.2 Depletion Region, 80
- 2.3 Current-Voltage Characteristics, 90
- 2.4 Junction Breakdown, 102
- 2.5 Transient Behavior and Noise, 114
- 2.6 Terminal Functions, 118
- 2.7 Heterojunctions, 124

Chapter 3 Metal-Semiconductor Contacts	134
---	------------

- 3.1 Introduction, 134
- 3.2 Formation of Barrier, 135
- 3.3 Current Transport Processes, 153
- 3.4 Measurement of Barrier Height, 170
- 3.5 Device Structures, 181
- 3.6 Ohmic Contact, 187

Chapter 4 Metal-Insulator-Semiconductor Capacitors

- 4.1 Introduction, 197
- 4.2 Ideal MIS Capacitor, 198
- 4.3 Silicon MOS Capacitor, 213

Part III Transistors

Chapter 5 Bipolar Transistors

- 5.1 Introduction, 243
- 5.2 Static Characteristics, 244
- 5.3 Microwave Characteristics, 262
- 5.4 Related Device Structures, 275
- 5.5 Heterojunction Bipolar Transistor, 282

Chapter 6 MOSFETs

- 6.1 Introduction, 293
- 6.2 Basic Device Characteristics, 297
- 6.3 Nonuniform Doping and Buried-Channel Device, 320
- 6.4 Device Scaling and Short-Channel Effects, 328
- 6.5 MOSFET Structures, 339
- 6.6 Circuit Applications, 347
- 6.7 Nonvolatile Memory Devices, 350
- 6.8 Single-Electron Transistor, 360

Chapter 7 JFETs, MESFETs, and MODFETs

- 7.1 Introduction, 374
- 7.2 JFET and MESFET, 375
- 7.3 MODFET, 401

Part IV Negative-Resistance and Power Devices

Chapter 8 Tunnel Devices

- 8.1 Introduction, 417
- 8.2 Tunnel Diode, 418
- 8.3 Related Tunnel Devices, 435
- 8.4 Resonant-Tunneling Diode, 454

Chapter 9 IMPATT Diodes

- 9.1 Introduction, 466

- 9.2 Static Characteristics, 467
- 9.3 Dynamic Characteristics, 474
- 9.4 Power and Efficiency, 482
- 9.5 Noise Behavior, 489
- 9.6 Device Design and Performance, 493
- 9.7 BARITT Diode, 497
- 9.8 TUNNETT Diode, 504

Chapter 10 Transferred-Electron and Real-Space-Transfer Devices 510

- 10.1 Introduction, 510
- 10.2 Transferred-Electron Device, 511
- 10.3 Real-Space-Transfer Devices, 536

Chapter 11 Thyristors and Power Devices 548

- 11.1 Introduction, 548
- 11.2 Thyristor Characteristics, 549
- 11.3 Thyristor Variations, 574
- 11.4 Other Power Devices, 582

Part V Photonic Devices and Sensors

Chapter 12 LEDs and Lasers 601

- 12.1 Introduction, 601
- 12.2 Radiative Transitions, 603
- 12.3 Light-Emitting Diode (LED), 608
- 12.4 Laser Physics, 621
- 12.5 Laser Operating Characteristics, 630
- 12.6 Specialty Lasers, 651

Chapter 13 Photodetectors and Solar Cells 663

- 13.1 Introduction, 663
- 13.2 Photoconductor, 667
- 13.3 Photodiodes, 671
- 13.4 Avalanche Photodiode, 683
- 13.5 Phototransistor, 694
- 13.6 Charge-Coupled Device (CCD), 697
- 13.7 Metal-Semiconductor-Metal Photodetector, 712
- 13.8 Quantum-Well Infrared Photodetector, 716
- 13.9 Solar Cell, 719

Chapter 14 **Sensors**

- 14.1 Introduction, 743
- 14.2 Thermal Sensors, 744
- 14.3 Mechanical Sensors, 750
- 14.4 Magnetic Sensors, 758
- 14.5 Chemical Sensors, 765

Appendixes

- A. List of Symbols, 775
- B. International System of Units, 785
- C. Unit Prefixes, 786
- D. Greek Alphabet, 787
- E. Physical Constants, 788
- F. Properties of Important Semiconductors, 789
- G. Properties of Si and GaAs, 790
- H. Properties of SiO_2 and Si_3N_4 , 791

Index

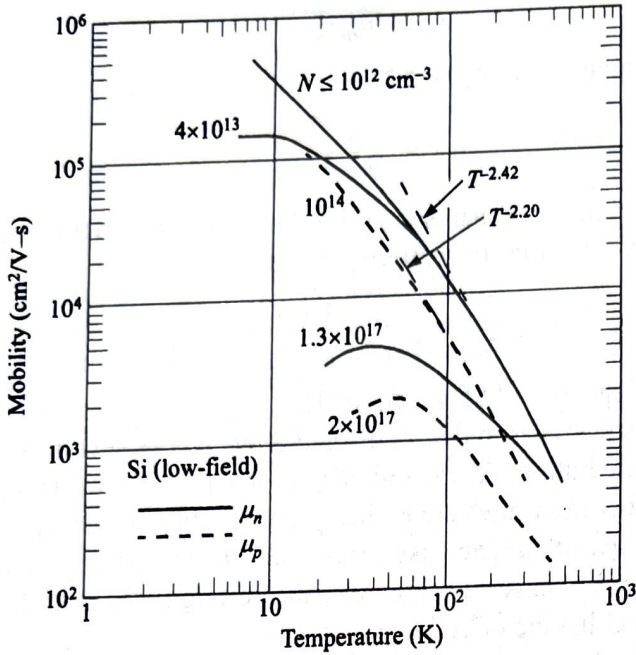


Fig. 16 Mobility of electrons and holes in Si as a function of temperature. (After Ref. 41.)

pure materials, near room temperature, the mobility varies as $T^{-2.42}$ and $T^{-2.20}$ for n - and p -type Si, respectively; and as $T^{-1.0}$ and $T^{-2.1}$ for n - and p -type GaAs (not shown), respectively.

The mobilities discussed above are the conductivity mobilities, which have been shown to be equal to the drift mobilities.³⁴ They are, however, different from but related to the Hall mobilities considered in the next section.

1.5.2 Resistivity and Hall Effect

For semiconductors with both electrons and holes as carriers, the drift current under an applied field is given by

$$\begin{aligned} J &= \sigma \mathcal{E} \\ &= q(\mu_n n + \mu_p p) \mathcal{E} \end{aligned} \quad (56)$$

where σ is the conductance

$$\sigma = \frac{1}{\rho} = q(\mu_n n + \mu_p p) \quad (57)$$

and ρ is the resistivity. If $n \gg p$, as in n -type semiconductors,

$$\rho = \frac{1}{q\mu_n n} \quad (58)$$

and

$$\sigma = q\mu_n n. \quad (59)$$

The most-common method for measuring resistivity is the four-point probe method (insert, Fig. 17),^{42,43} A small constant current is passed through the outer two probes and the voltage is measured between the inner two probes. For a thin wafer with thickness W much smaller than either a or d , the sheet resistance $R_{\square}$ is given by

$$R_{\square} = \frac{V}{I} \cdot CF \quad \Omega/\square \quad (60)$$

where CF is the correction factor shown in Fig. 17. The resistivity is then

$$\rho = R_{\square} W \quad \Omega\text{-cm}. \quad (61)$$

In the limit when $d \gg S$, where S is the probe spacing, the correction factor becomes $\pi/\ln 2$ (≈ 4.54).

Figure 18a shows the measured resistivity (at 300 K) as a function of the impurity concentration (n -type phosphorus and p -type boron) for silicon. Resistivity is not a linear function of concentration because mobility is not constant and usually decreases with increasing concentration. Figure 18b shows the measured resistivities for GaAs. We can obtain the impurity concentration of a semiconductor if its resistivity is known and vice versa. Note that the impurity concentration may be different from the carrier concentration because of incomplete ionization. For example, in a p -type silicon with 10^{17} cm^{-3} gallium acceptor impurities, unionized acceptors at room temperature make up about 23% (from Eq. 35, Figs. 10 and 14); in other words, the carrier concentration is only $7.7 \times 10^{16} \text{ cm}^{-3}$.

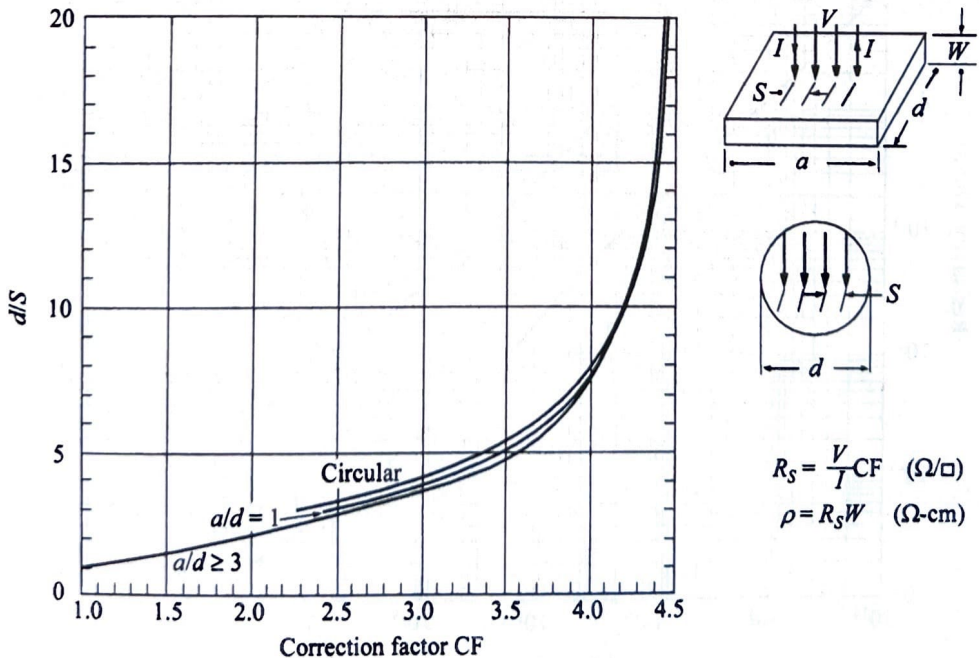
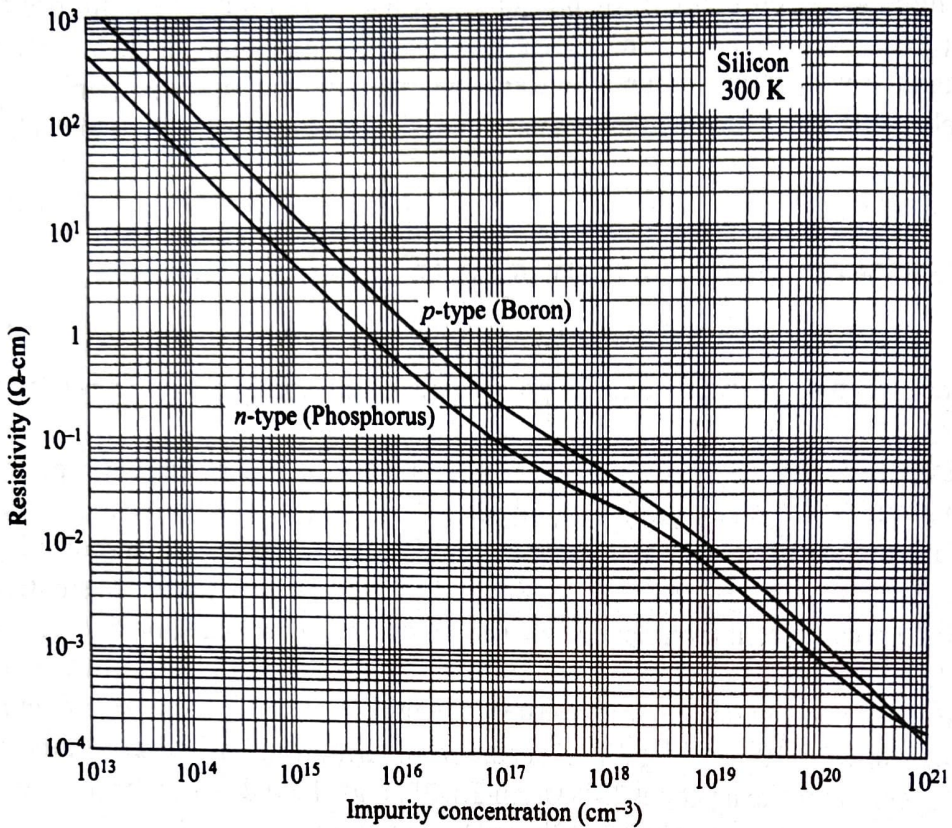
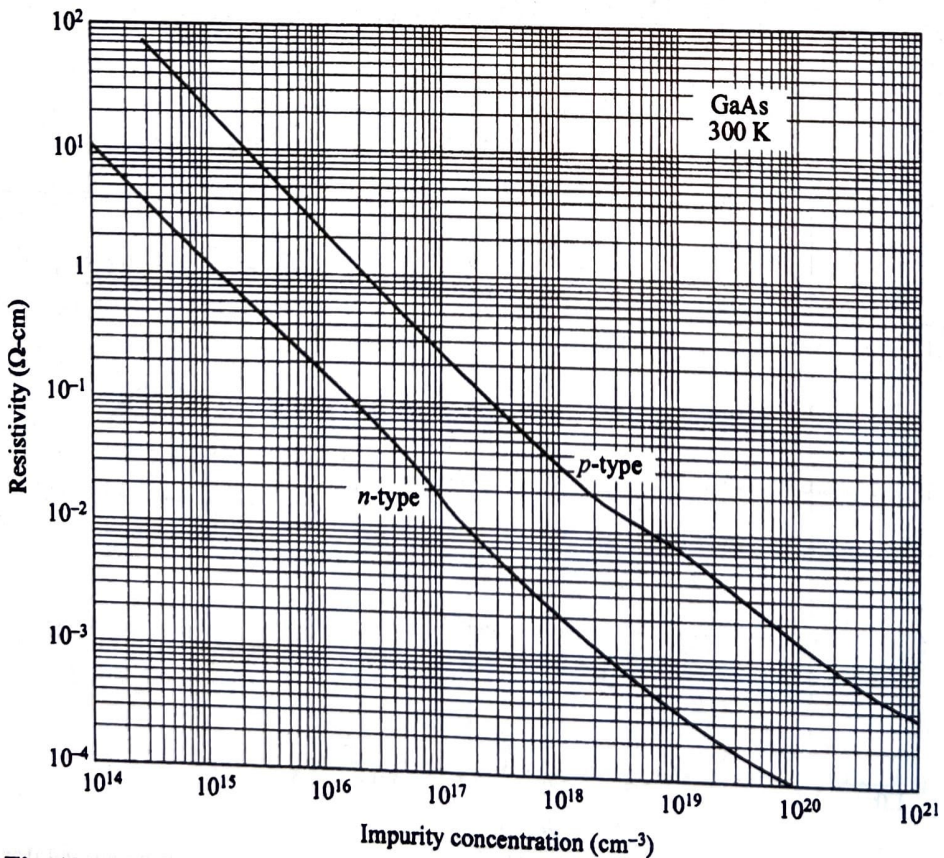


Fig. 17 Correction factor for measurement of resistivity using a four-point probe. (After Ref. 42.)



(a)



(b)

Fig. 18 Resistivity vs. impurity concentration at 300 K for (a) silicon (after Ref. 40) and (b) GaAs (after Ref. 35).

Hall Effect. Measurement of the resistivity only gives the product of the mobility and carrier concentration. To measure each parameter directly, the most-common method uses the Hall effect. The Hall effect is named after the scientist who made the discovery in 1879.⁴⁴ Even today it remains one of the most fascinating phenomena and is both fundamentally interesting and practical. Examples include the recent study of the fractional quantum Hall effect and the applications as magnetic-field sensors. The Hall effect is used in common practice to measure certain properties of semiconductors: namely, the carrier concentration (even down to a low level of 10^{12} cm^{-3}), the mobility, and the type (n or p). It is an important analytical tool since a simple conductance measurement can only give the product of concentration and mobility, and the type remains unknown.

Figure 19 shows the basic setup where an electric field is applied along the x -axis and a magnetic field is applied along the z -axis.⁴⁵ Consider a p -type sample. The Lorentz force exerts an average downward force on the holes

$$\text{Lorentz force} = qv_x \times B_z, \quad (62)$$

and the downward-directed current causes a piling up of holes at the bottom side of the sample, which in turn gives rise to an electric field $\mathcal{E}_y$. Since there is no net current along the y -direction in the steady state, the electric field along the y -axis (Hall field) balances exactly the Lorentz force such that the carriers travel in a path parallel to the applied field $\mathcal{E}_x$. (For n -type material, electrons also pile up at the bottom surface, setting up a voltage of opposite polarity.)

The carrier velocity v is related to the current density by

$$J_x = qv_x p. \quad (63)$$

Since for each carrier the Lorentz force must be equal to the force exerted by the Hall field,

$$q\mathcal{E}_y = qv_x B_z, \quad (64)$$

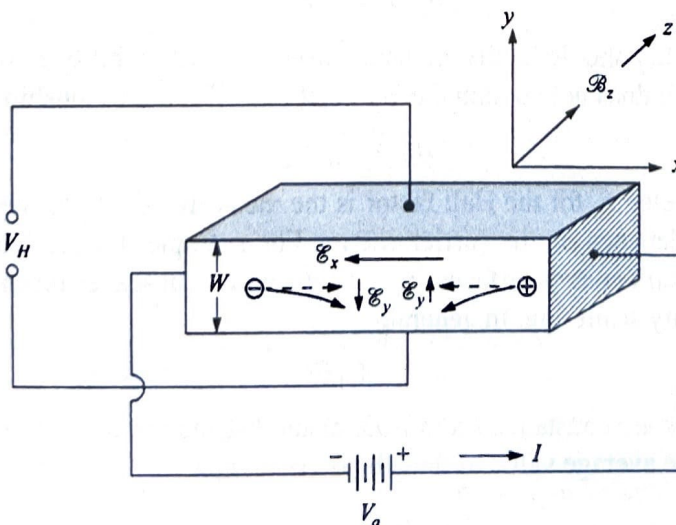


Fig. 19 Basic setup to measure carrier concentration using the Hall effect.

this Hall voltage can be measured externally and is given by

$$V_H = \mathcal{E}_y W = \frac{J_x \mathcal{B}_z W}{qp}. \quad (65)$$

When scattering is taken into account, the Hall voltage becomes

$$V_H = R_H J_x \mathcal{B}_z W \quad (66)$$

where R_H is the Hall coefficient and is given by

$$R_H = \frac{r_H}{qp} \quad p \gg n, \quad (67a)$$

$$R_H = -\frac{r_H}{qn} \quad n \gg p, \quad (67b)$$

with a Hall factor

$$r_H \equiv \frac{\langle \tau_m^2 \rangle}{\langle \tau_m \rangle^2}. \quad (68)$$

Thus, the carrier concentration and carrier type (electrons or holes from the polarity of the Hall voltage) can be obtained directly from the Hall measurement, provided that one type of carrier dominates and r_H is known.

Equation 67a or b also assumes conduction by a single type of carrier. A more-general solution is described by⁵

$$R_H = \frac{r_H}{q} \frac{\mu_p^2 p - \mu_n^2 n}{(\mu_p p + \mu_n n)^2}. \quad (69)$$

It can be seen in Eq. 69 that the sign of R_H and thus V_H reveals the majority type of the semiconductor sample.

The Hall mobility μ_H is defined as the product of the Hall coefficient and conductivity:

$$\mu_H = |R_H| \sigma. \quad (70)$$

The Hall mobility should be distinguished from the drift mobility μ_n (or μ_p) as given in Eq. 59 which does not contain the Hall factor r_H . Their relationship is given by

$$\mu_H = r_H \mu. \quad (71)$$

The parameter τ_m for the Hall factor is the mean free time between carrier collisions, which depends on the carrier energy. For example, for semiconductors with spherical constant-energy surfaces, $\tau_m \propto E^{-1/2}$ for phonon scattering and $\tau_m \propto E^{3/2}$ for ionized impurity scattering. In general,

$$\tau_m = C_1 E^{-s}, \quad (72)$$

where C_1 and s are constants. From Boltzmann distribution for nondegenerate semiconductors, the average value of the n th power of τ_m is

$$\langle \tau_m^n \rangle = \int_0^\infty \tau_m^n E^{3/2} \exp\left(-\frac{E}{kT}\right) dE \bigg/ \int_0^\infty E^{3/2} \exp\left(-\frac{E}{kT}\right) dE, \quad (73)$$

so that using the general form of τ_m , we obtain

$$\langle \tau_m^2 \rangle = \frac{C_1^2 (kT)^{-2s} \Gamma(\frac{5}{2} - 2s)}{\Gamma(\frac{5}{2})} \quad (74)$$

and

$$\langle \tau_m \rangle = \frac{C_1 (kT)^{-s} \Gamma(\frac{5}{2} - s)}{\Gamma(\frac{5}{2})} \quad (75)$$

where $\Gamma(n)$ is the gamma function defined as

$$\Gamma(n) \equiv \int_0^\infty x^{n-1} e^{-x} dx. \quad (76)$$

[$\Gamma(1/2) = \sqrt{\pi}$.] From the expression above we obtain $r_H = 3\pi/8 = 1.18$ for phonon scattering and $r_H = 315\pi/512 = 1.93$ for ionized-impurity scattering. In general r_H lies in the range of 1–2. At very high magnetic fields, it approaches a value slightly below unity.

In the preceding discussion the applied magnetic field is assumed to be small enough that there is no change in the resistivity of the sample. However, under strong magnetic fields, a significant increase in the resistivity is observed, the so-called magnetoresistance effect, resulting from carriers travelling in a path that deviates from the applied electric field. For spherical-energy surfaces the ratio of the incremental resistivity to the bulk resistivity at zero magnetic field is given by⁵

$$\frac{\Delta\rho}{\rho_0} = \left\{ \left[\frac{\Gamma^2(\frac{5}{2})\Gamma(\frac{5}{2}-3s)}{\Gamma^3(\frac{5}{2}-s)} \right] \left(\frac{\mu_n^3 n + \mu_p^3 p}{\mu_n n + \mu_p p} \right) - \left[\frac{\Gamma(\frac{5}{2})\Gamma(\frac{5}{2}-2s)}{\Gamma^2(\frac{5}{2}-s)} \right]^2 \left(\frac{\mu_n^2 n - \mu_p^2 p}{\mu_n n + \mu_p p} \right)^2 \right\} \mathcal{B}_z^2. \quad (77)$$

The ratio is proportional to the square of the magnetic field component perpendicular to the direction of the current flow. For $n \gg p$, $(\Delta\rho/\rho_0) \propto \mu_n^2 \mathcal{B}_z^2$. A similar result can be obtained for the case $p \gg n$.

1.5.3 High-Field Properties

In the preceding sections we considered the effect of low electric field on the transport of carriers in semiconductors. In this section we briefly consider some special effects and properties of semiconductors when the electric field is increased to moderate and high levels.

As discussed in Section 1.5.1, at low electric fields the drift velocity in a semiconductor is proportional to the field and the proportionality constant is the mobility that