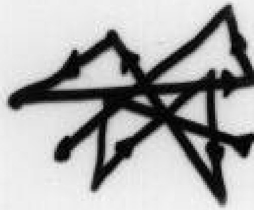
FREE CARRIERS IN SEMICONDUCTORS

EQUILIBRIUM

THERMAL MOTION :



COLLISIONS WITH LATTICE IMPURITIES

EQUIPARTITION OF ENERGY

$$\frac{1}{2} m_n^* v_{th}^2 = \frac{3}{2} k_B T$$

T : ABSOLUTE TEMPERATURE

m_n^* : ELECTRON EFFECTIVE MASS

v_{th} : THERMAL VELOCITY

$v_{th}(T=300K) = 2.3 \times 10^7$ cm/s FOR Si

⇒ NET ELECTRONIC DISPLACEMENT = 0

DEFINITION: MEAN FREE PATH : ℓ_c : AVERAGE DISTANCE BETWEEN COLLISIONS

MEAN FREE TIME : τ_c : —— TIME

$$\ell_c = v_{th} \tau_c$$

NON EQUILIBRIUM : ELECTRIC FIELD $\vec{\mathcal{E}} \neq 0$

DRIFT VELOCITY : $\vec{v}_d = -\frac{q\vec{\mathcal{E}}}{m_n^*} \tau_c$ → $\vec{v}_{dn} = -\mu_n \vec{\mathcal{E}}$

MOBILITY : $\mu_n = \frac{q\tau_c}{m_n^*}$ → $\vec{v}_{dp} = \mu_p \vec{\mathcal{E}}$

CURRENT DENSITY : $\vec{J}_n = nq\mu_n \vec{\mathcal{E}}$ $\quad \vec{J} = (nq\mu_n + pq\mu_p)\vec{\mathcal{E}}$

$\vec{J}_p = pq\mu_p \vec{\mathcal{E}}$

CONDUCTIVITY : $\sigma = q(n\mu_n + p\mu_p)$

PP 54-55

1.3 Properties of Semiconductors and Insulators (at 300 K Unless Otherw

Property	Symbol	Units	Si	Ge
structure			Diamond	Diamond
Electric field at breakdown	$\mathscr{E}_1$	V cm^{-1}	3×10^5	8×10^4
Effective mass				
Electron	m_n^*/m_0		N_c → 1.08[a] σ → 0.26[b]	N_c → 0.55[a] σ → 0.12[b]
Hole	m_p^*/m_0		N_v → 0.81[a] σ → 0.386[b]	0.3
Electron affinity	$q\chi$	eV	4.05	4.00
Average energy loss per phonon scattering		eV	0.063	0.037
Optical phonon mean-free path				
Electron	l_{ph}	nm	6.2	6.5
Hole	l_{ph}	nm	4.5	6.5

Sources: A. S. Grove, *Physics and Technology of Semiconductor Devices*, Wiley, New Yo ed., Wiley, New York (1981); D. E. Hill, *Some Properties of Semiconductors* (table), Mon Wiley, New York (1971).

[a] Used in density-of-state calculations.

[b] Used in conductivity calculations.

$$\sigma = q(n\mu_n + p\mu_p)$$

$$\rho = \frac{1}{\sigma}$$

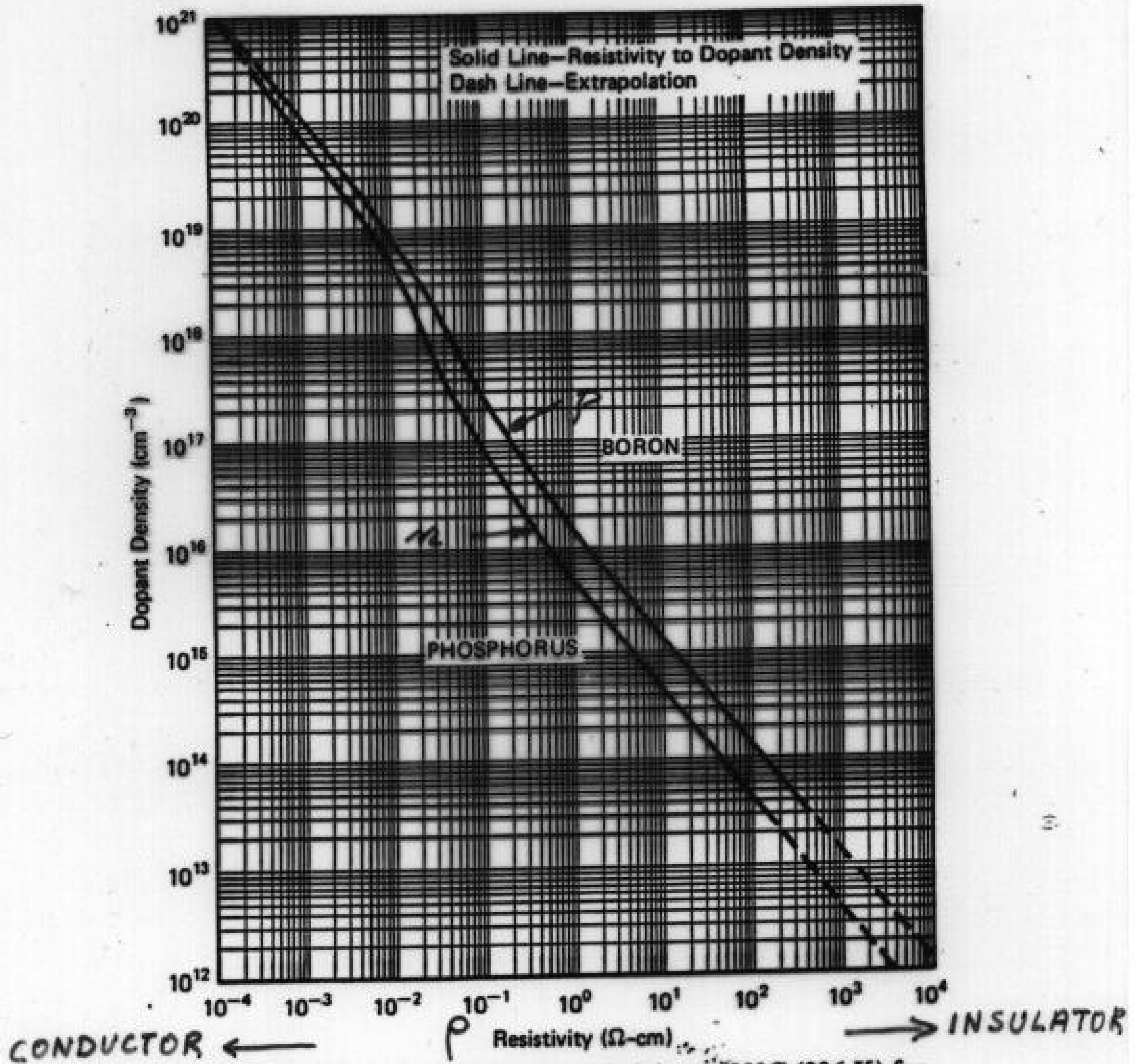


Figure 1.14 Dopant density versus resistivity at 23°C (296 K) for silicon doped with phosphorus and with boron. The curves can be used with little error to represent conditions at 300 K. [W. R. Thurber, R. L. Mattis, and Y. M. Liu, National Bureau of Standards Special Publication 400–64, 42 (May 1981)].

DOPING DEPENDENCE

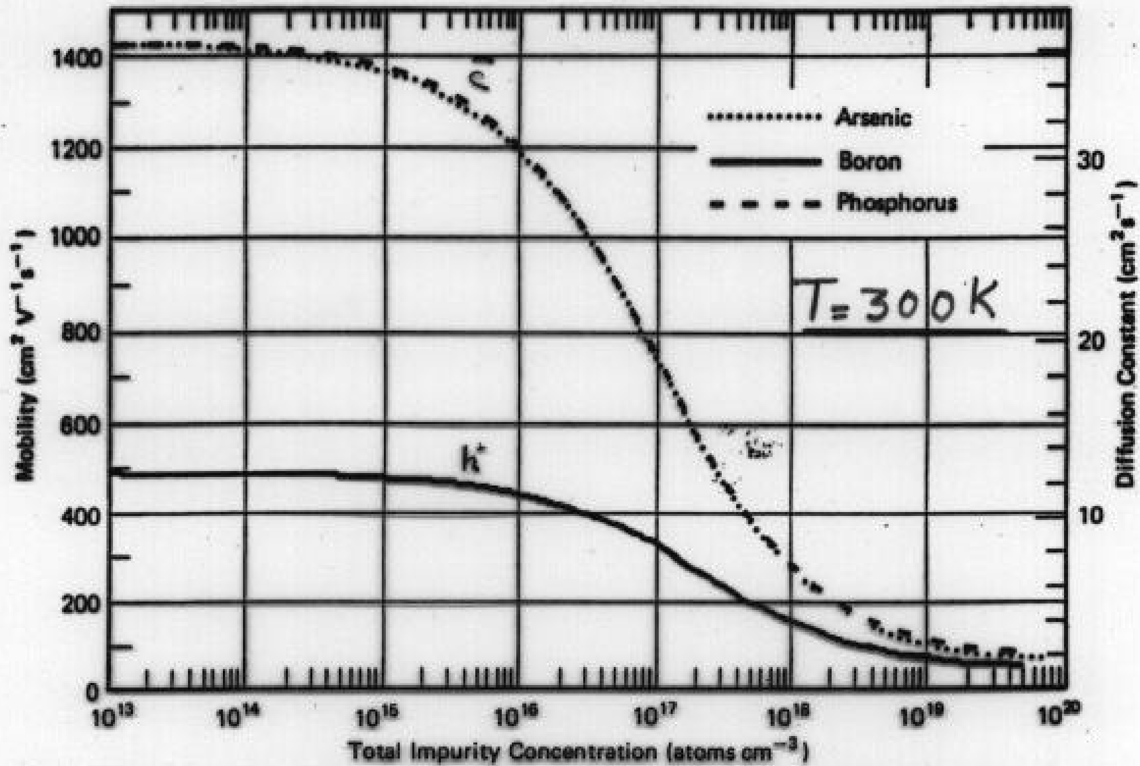


Figure 1.15 Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration. The values plotted are the results of curve fitting measurements from several sources. The mobility curves can be generated using Equation 1.2.10 with the following parameter values:[3]

Parameter	Arsenic	Phosphorus	Boron
μ_{min}	52.2	68.5	44.9
μ_{max}	1417	1414	470.5
N_{ref}	9.68×10^{16}	9.20×10^{16}	2.23×10^{17}
α	0.680	0.711	0.719

$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + (N/N_{ref})^{\alpha}}$$

TEMPERATURE DEPENDENCE

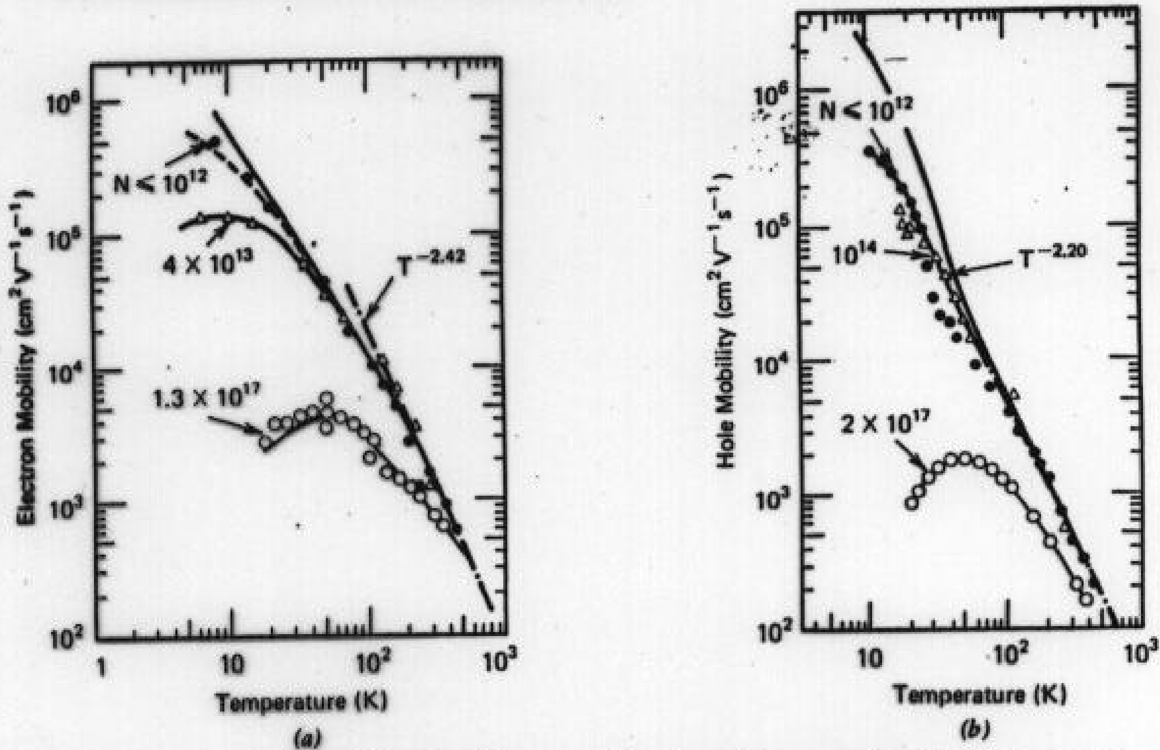


Figure 1.16 Low-field mobility in silicon as a function of temperature for electrons (*a*), and for holes (*b*). The continuous lines represent the theoretical predictions for pure lattice scattering.[5]

$$\frac{1}{\tau_I} = \frac{A_I}{T^{3/2}} : \begin{cases} \text{LARGE AT LOW } T \\ \text{SMALL AT HIGH } T \end{cases} \qquad A_I \propto N_I$$

$$\frac{1}{\tau_L} = A_L T^{3/2} : \begin{cases} \text{SMALL AT LOW } T \\ \text{LARGE AT HIGH } T \end{cases}$$

$$\mu_n = 88\, T_n^{-0.57} + \frac{7.4 \times 10^8\, T^{-2.33}}{1 + [N/(1.26 \times 10^{17}\, T_n^{2.4})]\, 0.88\, T_n^{-0.146}}$$

$$\mu_p = 54.3\, T_n^{-0.57} + \frac{1.36 \times 10^8\, T^{-2.23}}{1 + [N/(2.35 \times 10^{17}\, T_n^{2.4})]\, 0.88\, T_n^{-0.146}} \qquad (1.2.11)$$

where $T_n = T/300$ with T measured in K (Kelvin scale), and N is the total dopant density in the silicon. Equation 1.2.11 is useful up to dopant densities of $10^{20}\ \text{cm}^{-3}$ and for temperatures between 250 and 500 K.

$$\frac{1}{\tau} = \frac{1}{\tau_I} + \frac{1}{\tau_L} \Rightarrow \frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L} \qquad \text{MATTHIESSEN'S RULE.}$$