Chapter 3-1. Carrier action

Topics to be covered in this chapter:

Response of carriers (holes and electrons) under perturbed conditions:

- Drift
- Diffusion
- Recombination-generation
- Equations of state

Thermodynamic equilibrium vs. steady state

Thermodynamic equilibrium: *Thermodynamic* or *thermal equilibrium* refers to the condition in which a specimen is not subjected to external excitations except a uniform temperature. That is, ***no*** voltages, electric fields, magnetic fields, illumination, etc. are applied. Under thermal equilibrium conditions, ***every process is balanced in detail by an opposing process***. This is called the ***principle of detailed balance***.

Example: A semiconductor in the dark at $T = 300$ K with no excitation is in thermal equilibrium. Thermal generation is exactly balanced by recombination, *i. e*. *principle of detailed balance* is fulfilled.

Steady state: Steady state refers to a non-equilibrium condition in which all processes are constant in time.

Example: A LED driven at a constant current is in the steady state. Note that the *principle of detailed balance* does not apply.

Carrier drift

Drift, by definition, is charged particle motion in response to an applied electric field. Because of collisions with ionized impurity atoms and thermally agitated lattice atoms, the carrier acceleration is frequently interrupted (called scattering).

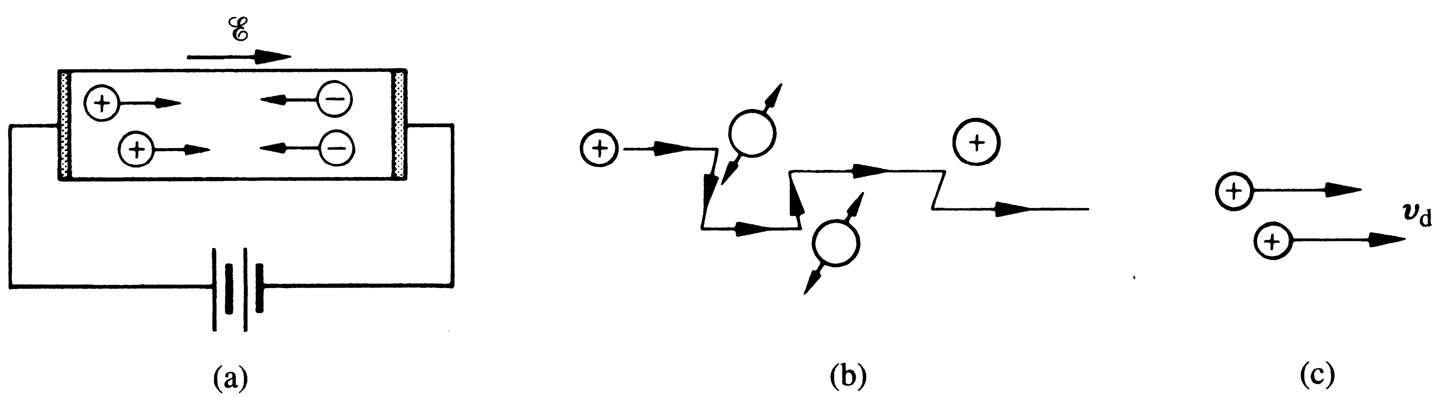
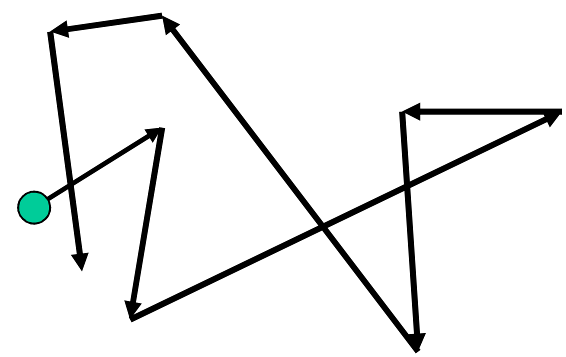


Figure 3.1

Drift velocity, v_d and thermal velocity, v_{th}

The net result is carrier motion generally along the direction of $\mathcal{E}$-field. The resultant motion of each carrier type under the influence of $\mathcal{E}$-field can be described in terms of a constant drift velocity, v_d.

Thermal Motion: Note that the carrier thermal-velocity is very large (~10^7 cm/s at 300 K), but this does not contribute to current transport. Why?



Random thermal motion of carriers

$$\frac{1}{2} m^* v_{th}^2 = \frac{3}{2} kT$$

$$v_{th} = \sqrt{3kT / m^*}$$

Drift current

Drift current is the current flowing within a semiconductor as a result of carrier drift. By definition,

I (current) = the charge per unit time crossing an arbitrarily chosen plane of observation oriented normal to the direction of current flow.

= Q / t

Ampere = Coulomb / second

J (current density) = current per unit area = I / A

Drift current

Consider a p-type semiconductor:

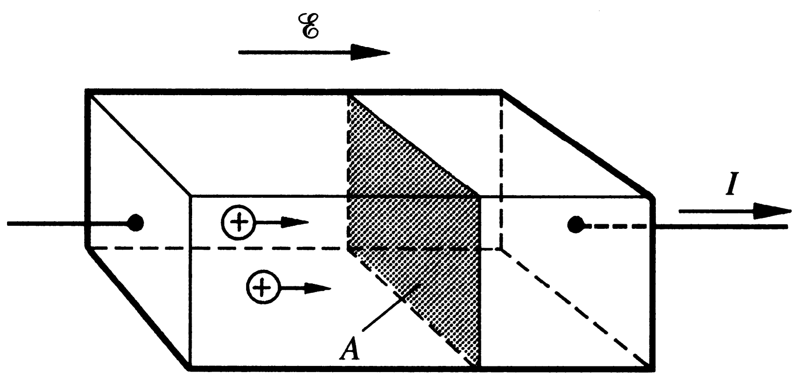


Figure 3.3

$v_d t$	. . .	All holes this distance back from the v_d-normal plane will cross the plane in a time t.
$v_d tA$	. . .	All holes in this volume will cross the plane in a time t.
$pv_d tA$	. . .	Holes crossing the plane in a time t.
$qpv_d tA$	. . .	Charge crossing the plane in a time t.
$qpv_d A$	. . .	Charge crossing the plane per unit time.

Drift current

$q\, p\, v_d A$ is the "charge crossing the plane per unit time" and by definition is the "hole drift current", I_{drift}

By inspection, the current density associated with hole drift is

$$J_{p\,|\,drift} = q\, p\, v_d$$

Since drift current arises in response to $\mathcal{E}$-field, we need to find the relationship between drift current and $\mathcal{E}$-field. At low electric field, it is found that drift velocity is proportional to $\mathcal{E}$-field.

$$J_{p\,|\,drift} = q\, p\, \mu_p\, \mathcal{E}$$

where μ_p is the proportionality constant (called *hole mobility*)

Drift velocity vs. electric field in Si

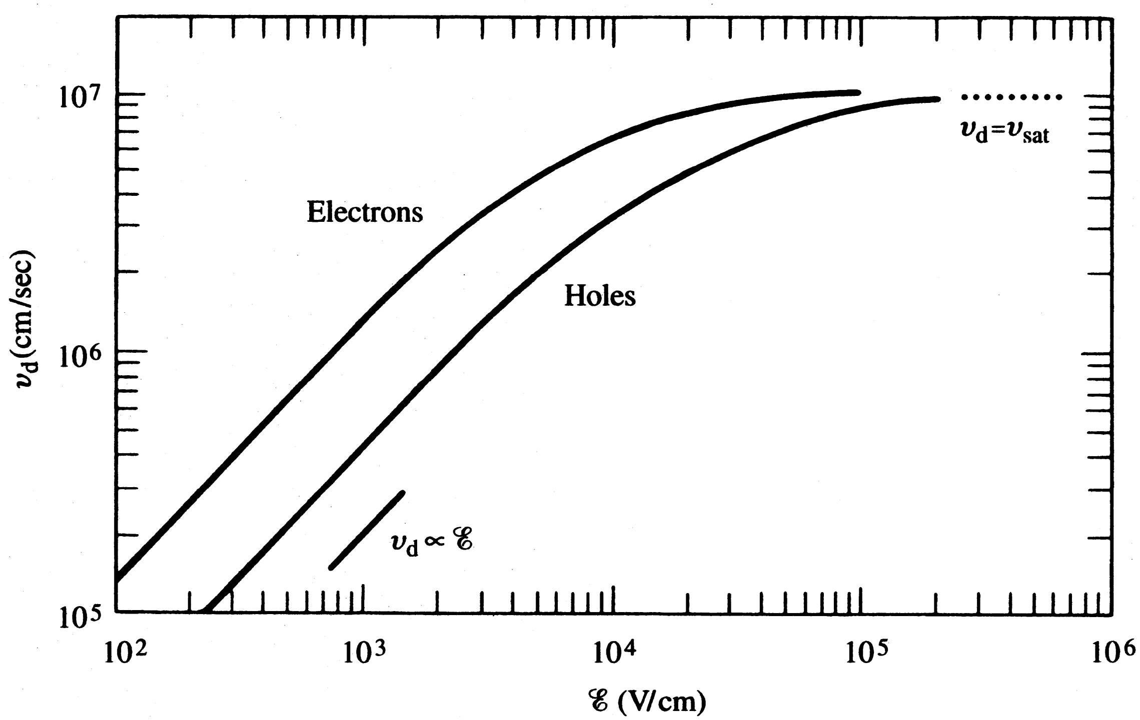


Figure 3.4

Hole and electron drift current density

$$\boxed{\mathbf{J}_{\mathrm{P}|\mathrm{drift}} = q\mu_{\mathrm{p}}\,p\mathscr{E}}$$

(3.4a)

$$\boxed{\mathbf{J}_{\mathrm{N}|\mathrm{drift}} = q\mu_{\mathrm{n}}\,n\mathscr{E}}$$

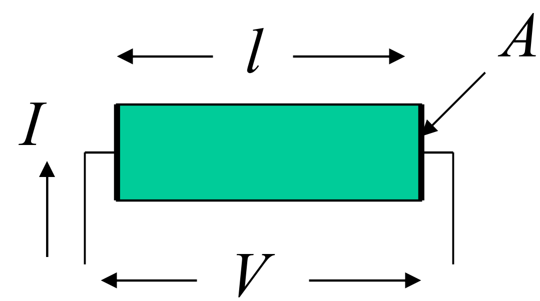
(3.4b)

Resistivity, ρ

The resistivity is a measure of a material's inherent resistance to current flow. The total current density in a semiconductor due to drift is given by:

$$J_{\text{drift}} = J_{\text{p}\,|\,\text{drift}} + J_{\text{n}\,|\,\text{drift}} = (q\,p\,\mu_{\text{p}} + q\,n\,\mu_{\text{n}})\,\mathcal{E}$$

$$I = J\,A = V\,/\,R = V\,/\,(\rho\,l\,/\,A) = (V/l\,) \times (A\,/\,\rho)$$

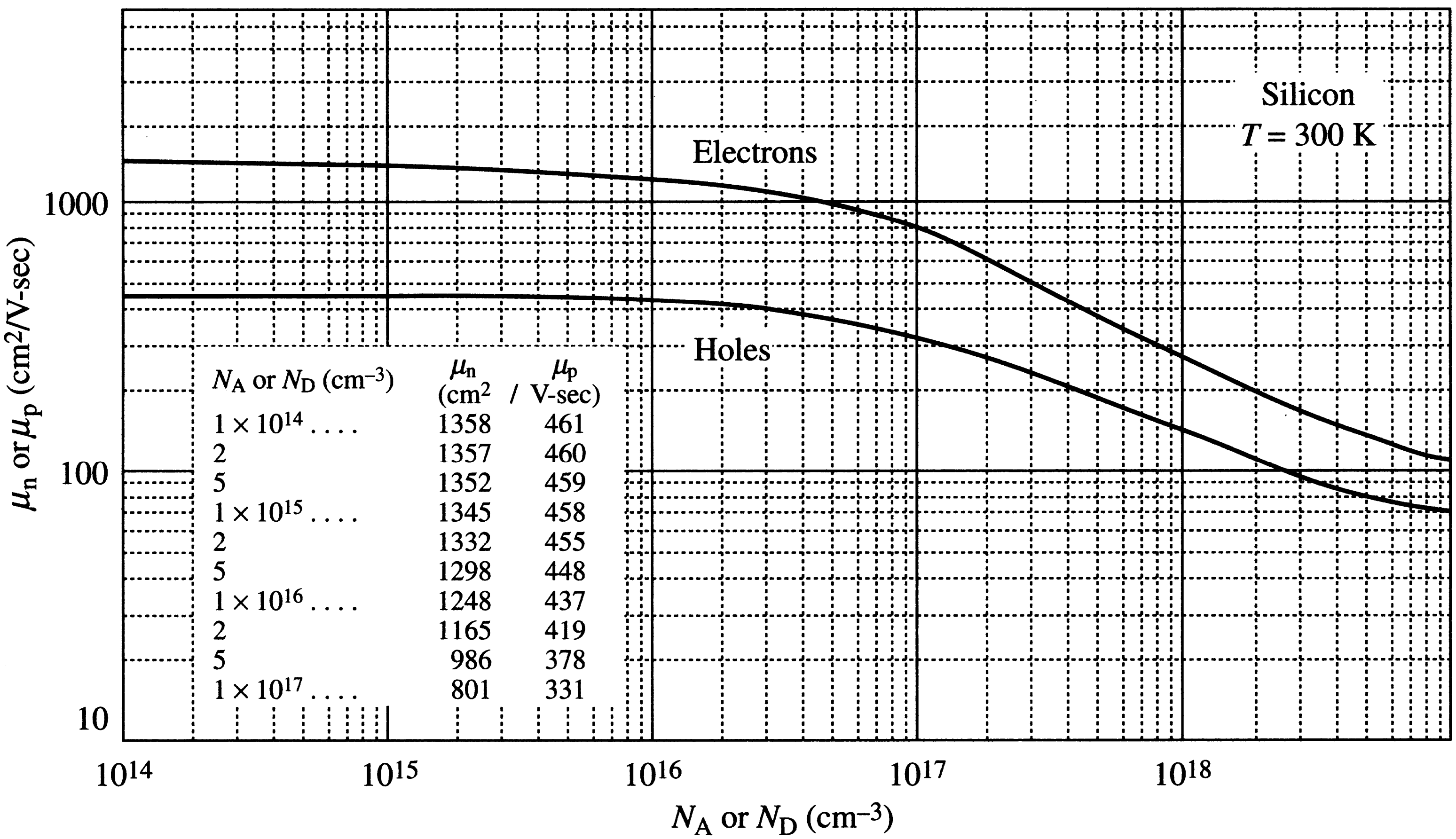


$\Rightarrow\ J = \mathcal{E}\,/\,\rho$

Comparing the above equations, we get:

$$\boxed{\rho = \frac{1}{q\,p\,\mu_{\text{p}} + q\,n\,\mu_{\text{n}}}}$$

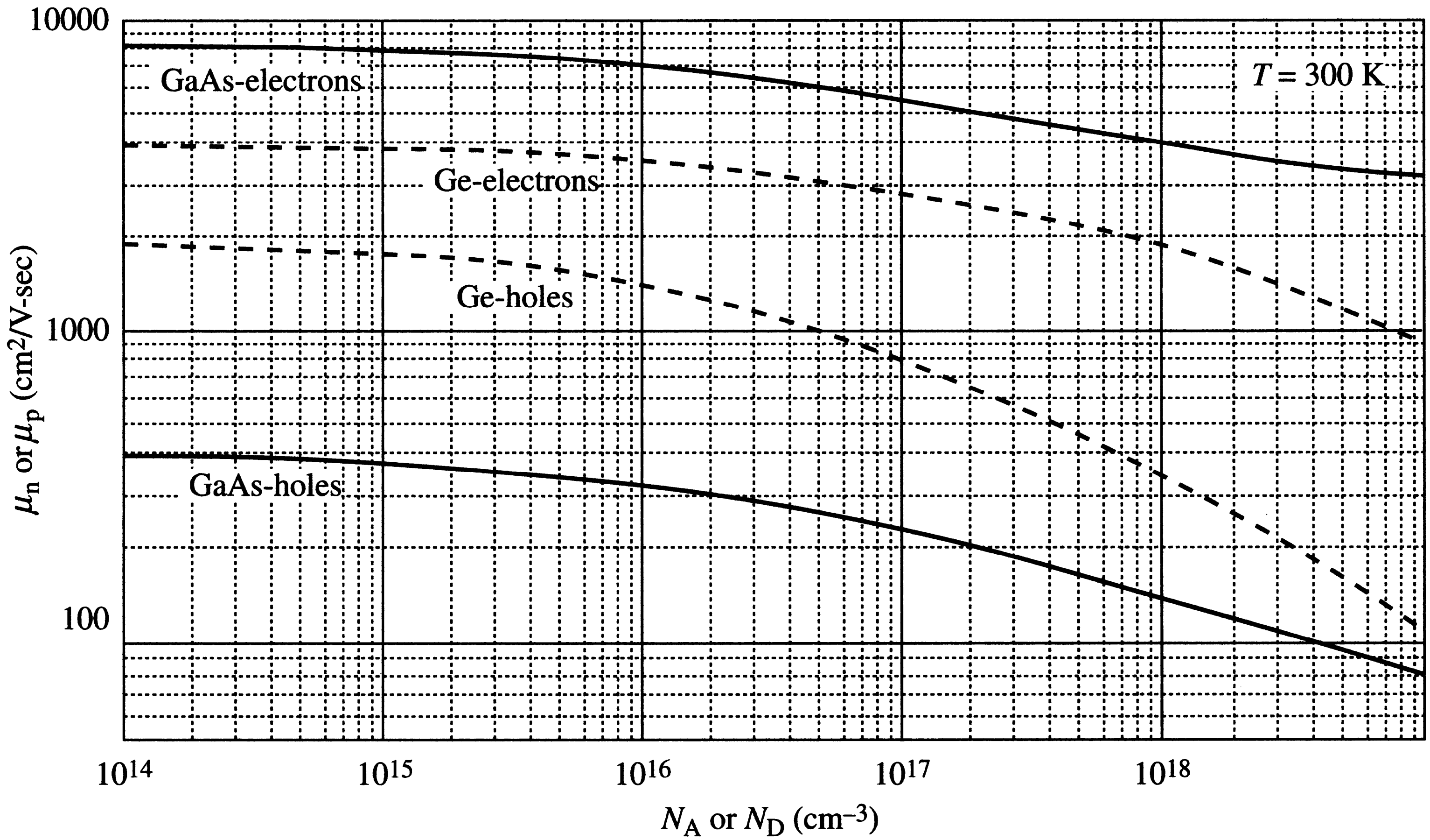
Mobility vs. dopant concentration for Si at 300 K



N_A or N_D (cm^{-3})	μ_n (cm^2	μ_p / V-sec)
1×10^{14}	1358	461
2	1357	460
5	1352	459
1×10^{15}	1345	458
2	1332	455
5	1298	448
1×10^{16}	1248	437
2	1165	419
5	986	378
1×10^{17}	801	331

(a)

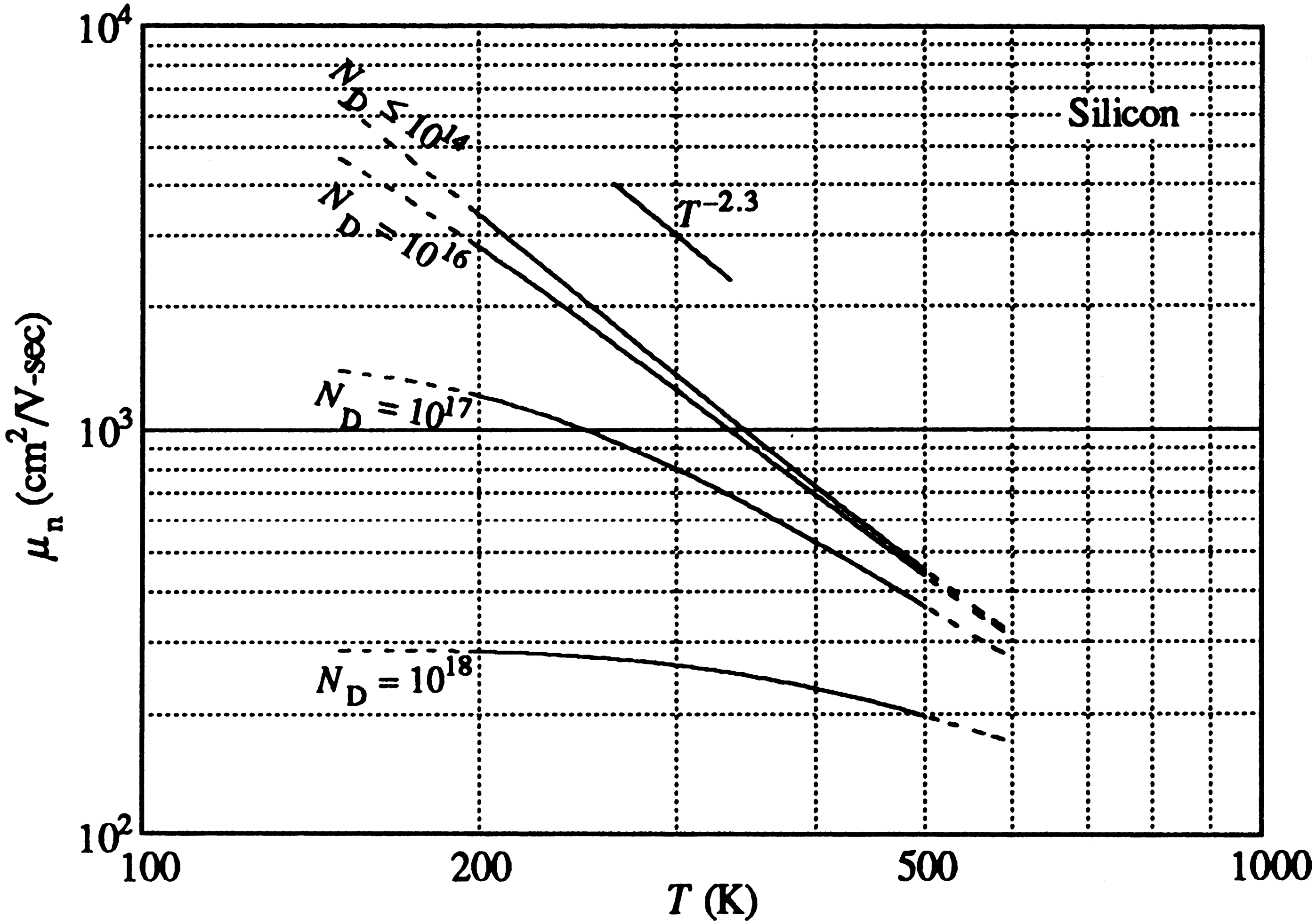
Mobility versus doping concentration for Ge and GaAs at 300 K



(b)

Figure 3.5

Temperature dependence of electron mobility



(a)

Temperature dependence of hole mobility

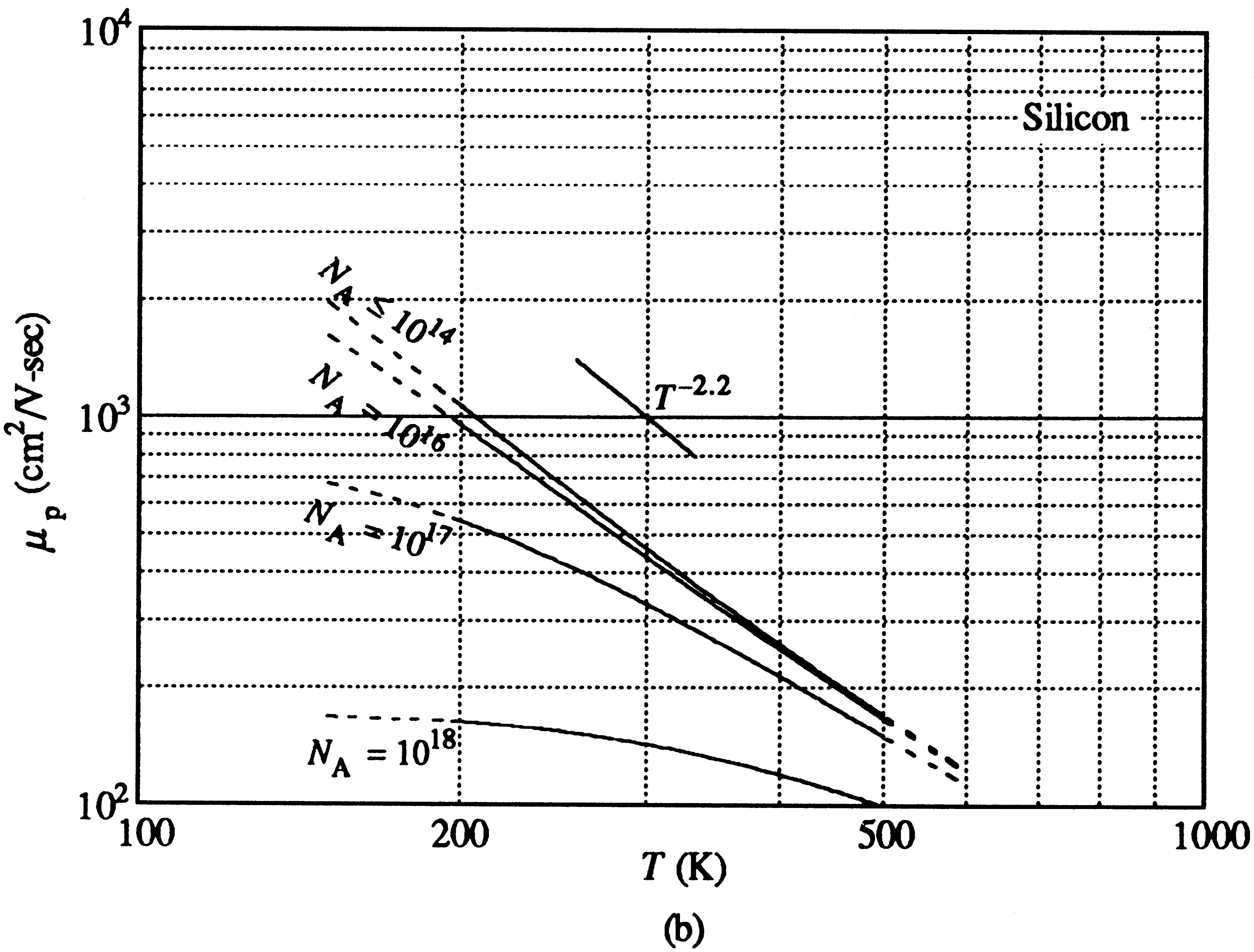
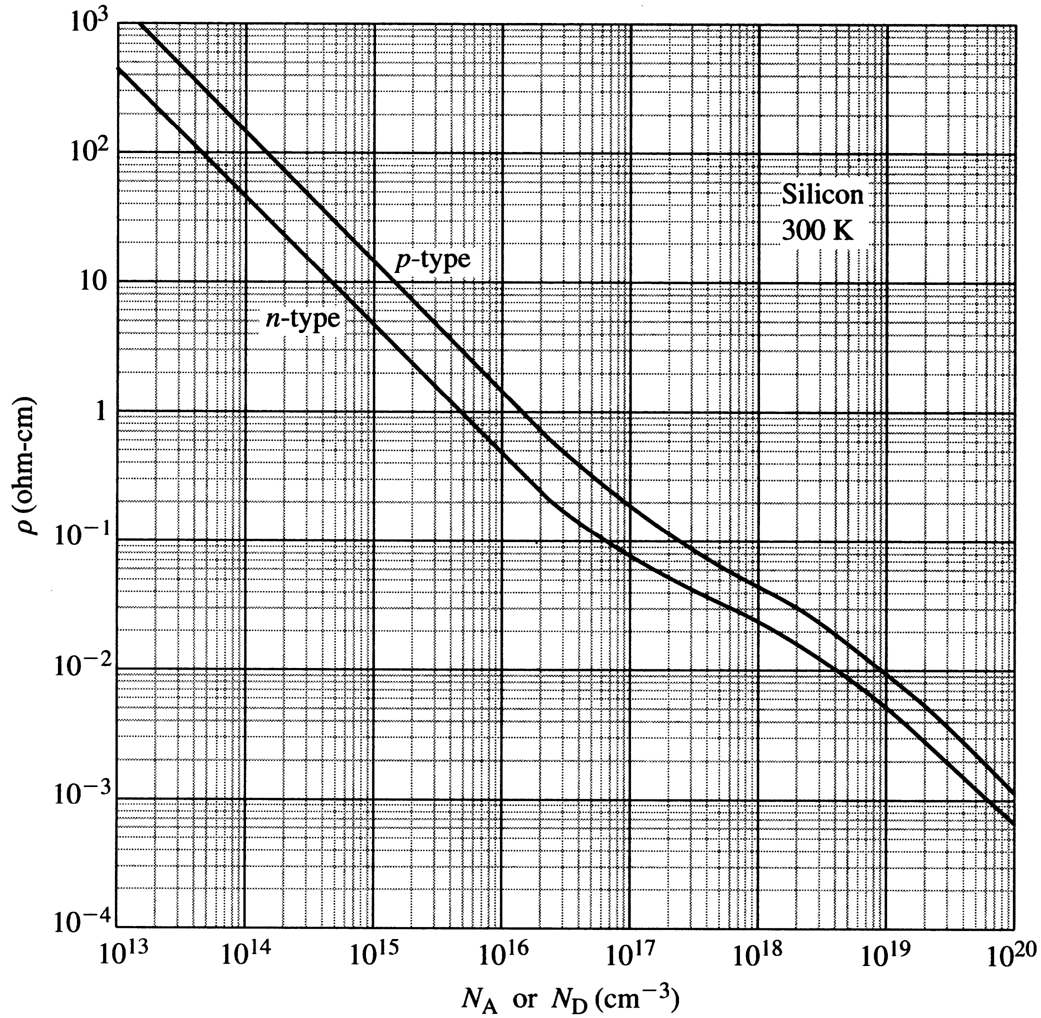


Figure 3.7

Silicon (Si) resistivity vs. doping concentration at 300K



(a)

Figure 3.8

Resistivity vs. doping concentration at 300K: Other semiconductors

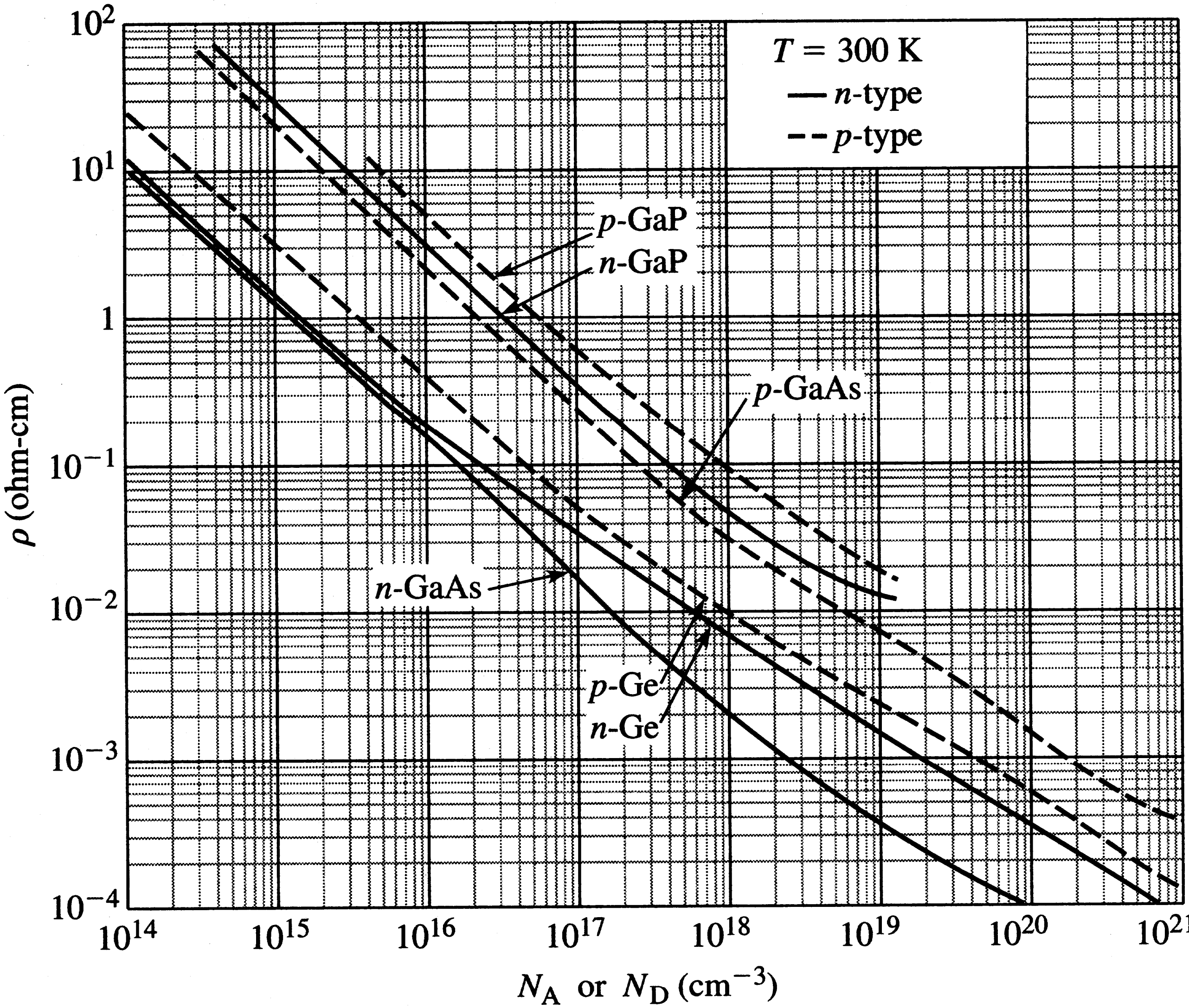
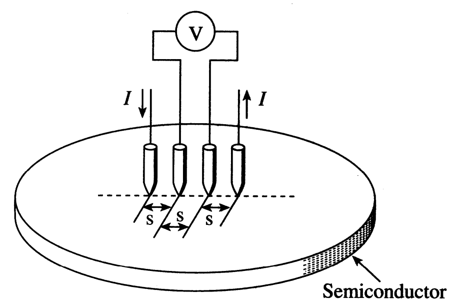
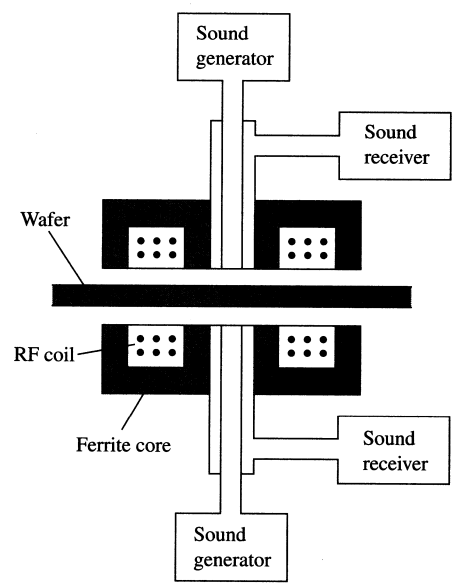


Figure 3.8 (b)

Resistivity measurement:
(a) 4-point probe (b) eddy-current apparatus



(a)



(b)

Figure 3.9

Example 1:

Calculate the resistivity of intrinsic Ge at room temperature.

First find, n and p at room temperature. Since intrinsic, from page 34, $n = p = n_i = 2 \times 10^{13}\ \mathrm{cm}^{-3}$

Then, estimate μ_p and μ_n at room temperature. From Fig. 3.5, extending the curve to $N_A + N_D = 0$, we get

$$\mu_p = 2000\ \mathrm{cm}^2/(\mathrm{Vs}) \text{ and } \mu_n = 4000\ \mathrm{cm}^2/(\mathrm{Vs})$$

Calculate ρ from the equation:

$$\boxed{\rho = \frac{1}{qp\mu_P + qn\mu_n}}$$

Note: One summand in the denominator of the above equation may or may not be neglected when calculating ρ (Explain!)

Example 2:

Calculate the resistivity of 10^{13} cm^{-3} phosphorous-doped Si at room temperature.

First find, n and p at room temperature. Since phosphorous is a donor, $n = N_D = 10^{13}$ cm^{-3}. (Note $N_D >> n_i$; and N_A=0)
$n\,p = n_i^2 \Rightarrow p = 10^7$ cm^{-3}.

Then, estimate μ_p and μ_n at room temperature. From Fig. 3.5, extending the curve to $N_A + N_D = 10^{13}$ cm^{-3} , we get

μ_n= 1350 cm^2/(Vs) and μ_p = 450 cm^2/(Vs)

Calculate ρ from the equation:

$$\rho = \frac{1}{qp\mu_P + qn\mu_n}$$