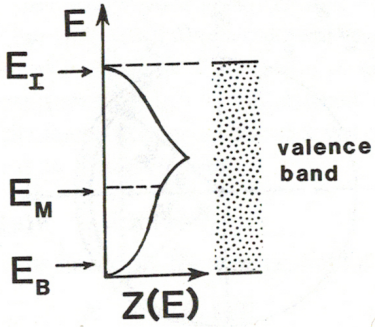

Figure 7.6. Schematic representation of the density of states (Fig. 6.6) and thus, with minor modifications, also the population density (6.7). Examples for highest electron energies for a monovalent metal (E_M), for a bivalent metal (E_B), and for an insulator (E_I) are indicated.

electrons near the Fermi surface. For example, monovalent metals (such as copper, silver, or gold) have partially filled valence bands, as shown in Figs. 5.22 or 6.7. Their electron population densities near their Fermi energy are high (Fig. 7.6), which results in a large conductivity according to (7.26). Bivalent metals, on the other hand, are distinguished by an overlapping of the upper bands and by a small electron concentration near the bottom of the valence band, as shown in Fig. 6.7(c). As a consequence the electron population near the Fermi energy is small (Fig. 7.6), which leads to a comparatively low conductivity. Finally, insulators and semiconductors have, under certain conditions, completely filled electron bands which results in a virtually zero population density near the top of the valence band (Fig. 7.6). Thus, the conductivity in these materials is extremely small.

7.5. Experimental Results and Their Interpretation

7.5.1. Pure Metals

The resistivity of a metal, such as copper, decreases linearly with decreasing temperature until it reaches a finite value (Fig. 7.7) according to the empirical equation

$$\rho_2 = \rho_1[1 + \alpha(T_2 - T_1)], \tag{7.27}$$

where α is the linear temperature coefficient of resistivity. We postulate that thermal energy causes lattice atoms to oscillate about their equilibrium positions, thus increasing the incoherent scattering of the electron waves. The residual resistivity ρ_{res} is interpreted to be due to imperfections in the crystal, such as impurities, vacancies, grain boundaries, or dislocations. The residual

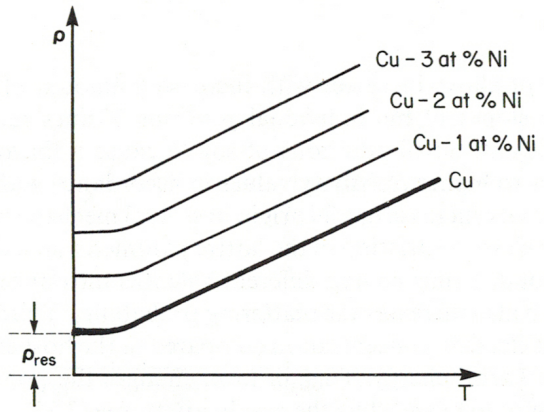

Figure 7.7. Schematic representation of the temperature dependence of the resistivity of copper and various copper–nickel alloys. ρ_{res} is the residual resistivity.

resistivity is essentially not temperature-dependent. According to Matthiessen's rule the resistivity arises from independent scattering processes which are additive, i.e.,

$$\rho = \rho_{th} + \rho_{imp} + \rho_{def} = \rho_{th} + \rho_{res}. \tag{7.28}$$

The thermally induced part of the resistivity ρ_{th} is called the *ideal* resistivity, whereas the resistivity which has its origin in impurities (ρ_{imp}) and defects (ρ_{def}) is summed up in the residual resistivity. The number of impurity atoms is generally constant in a given metal or alloy. The number of vacancies or grain boundaries, however, can be changed by various heat treatments. For example, if a metal is annealed at temperatures close to its melting point and then rapidly quenched into water at room temperature, its room temperature resistivity increases noticeably due to quenched-in vacancies. Frequently, this resistance increase diminishes during room temperature aging or annealing at slightly elevated temperatures due to the annihilation of some vacancies. Likewise, recrystallization, grain growth, and many other metallurgical processes change the resistivity of metals. As a consequence of this, and due to its simple measurement, the resistivity is one of the most widely studied properties in materials research.

It is interesting to compare the thermally induced change in conductivity in light of the quantum mechanical and classical models. The number of free electrons, N_f, essentially does not change with temperature. Likewise, $N(E)$ changes very little with T. However, the mean free path, and thus the relaxation time, decreases with increasing temperature (due to a large rate of collisions between the drifting electrons and the vibrating lattice atoms). This, in turn, decreases σ according to (7.15) and (7.26), in agreement with the observations in Fig. 7.7. Thus, both models accurately describe the temperature dependence of the resistivity.