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Physics & Astronomy

Low Temperature Resistivity

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7/10/2015

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Introduction

Measuring the temperature dependence of resistivity reveals some important differences between metals, insulators, and semiconductors.

There are a variety of factors that influence resistivity (and thus its inverse, conductivity), and identifying these mechanisms and fitting the experimental data can reveal properties of the material, such as the band gap energy, EG, or the temperature coefficient of resistance, α.

Factors contributing to the conductivity of a material

- the availability of free electrons
- the ability of these electrons to move freely through a material

For a conducting metal with free valence electrons, the factor limiting conductivity is the lattice vibrations which scatter moving electrons; as temperature decreases, these vibrations (and thus the resistivity) also decrease. In this investigation, a copper sample is used to demonstrate the resistivity of a metal

Insulator

In an insulator, the electrons are unable to break free from the filled valence band, so there is little conduction.

Semiconductor

the energy gap is small enough that there are some free electrons at higher temperatures. Since the factor limiting conductivity for a semiconductor is the availability of free electrons, resistance increases with decreasing temperature, which is the reverse of the behavior observed in a metal.

Adding small impurities to a pure intrinsic semiconductor results in an extrinsic doped semiconductor, which has a nonlinear relationship between current and voltage.

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Theory for conducting metal

The average number of phonons in a given mode is described by the Planck distribution

$$\langle n \rangle = \frac{1}{e^{\hbar w/kT} - 1}$$

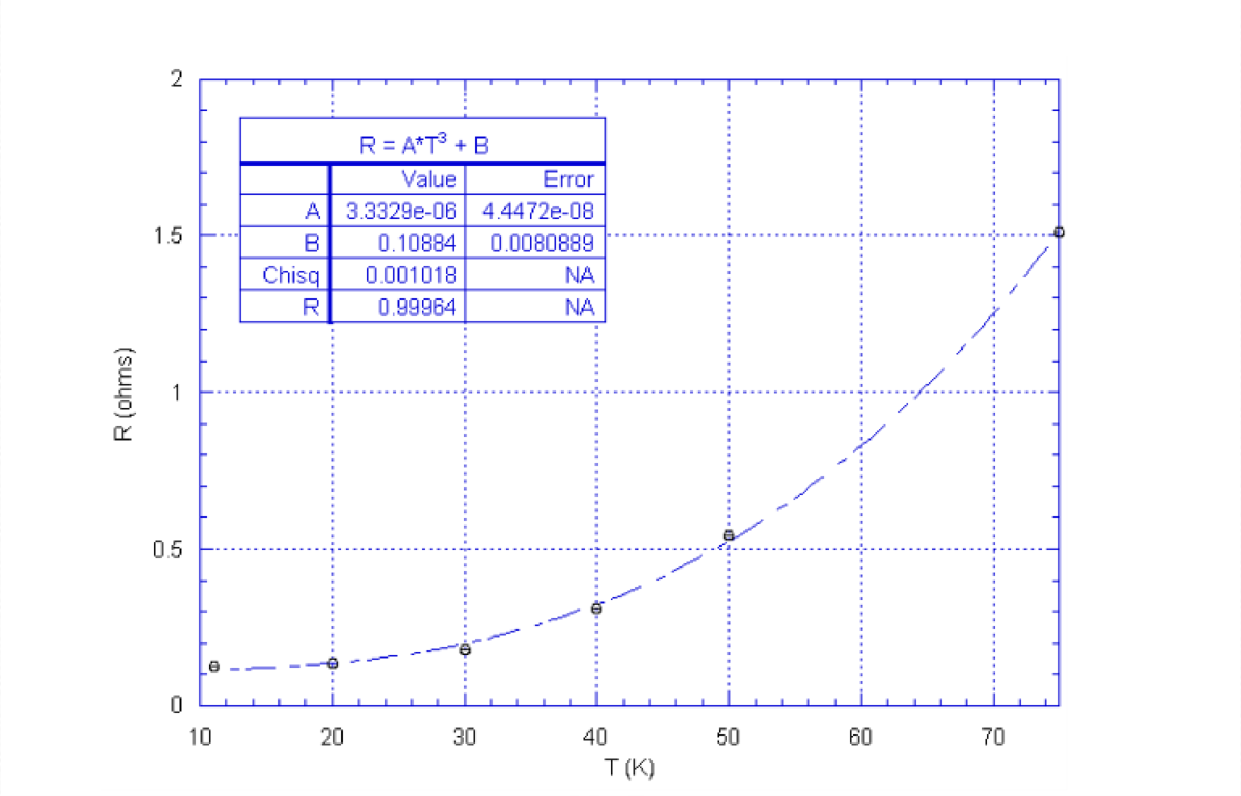
In the Debye model, the density of these modes is given by

$$D(w) = \frac{Vw^2}{2\pi^2 C_s^3}$$

The total average number of phonons in the lattice is given by

$$\langle n_{total} \rangle = \int D(w)\langle n \rangle dw = \frac{3}{2\pi^2 C_s^3}\int_0^{wD} \frac{w^2}{e^{\hbar w/kT} - 1} dw$$

Results and Discussion



Resistance of a copper sample at low temperatures. As Debye theory suggests, ρ ∝ T ^3 . The error bars are smaller than each circle.

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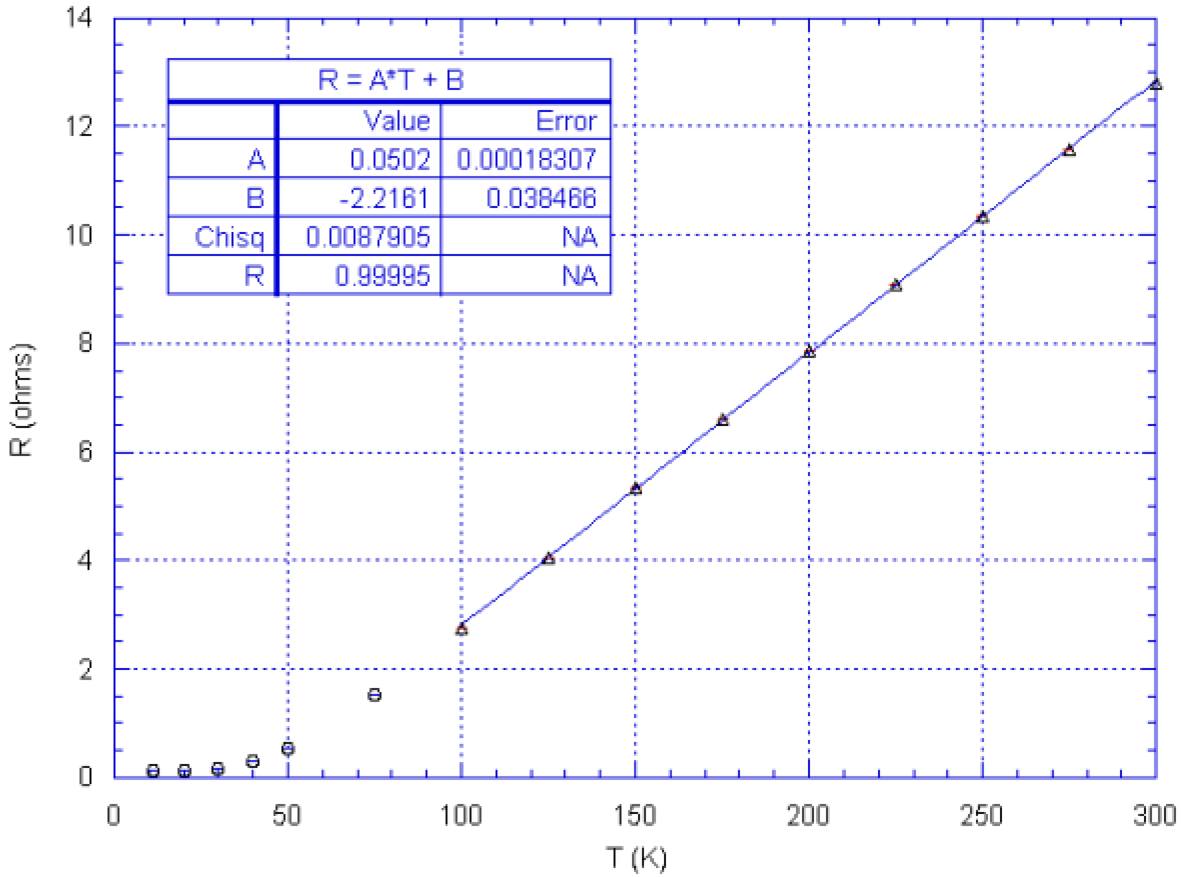


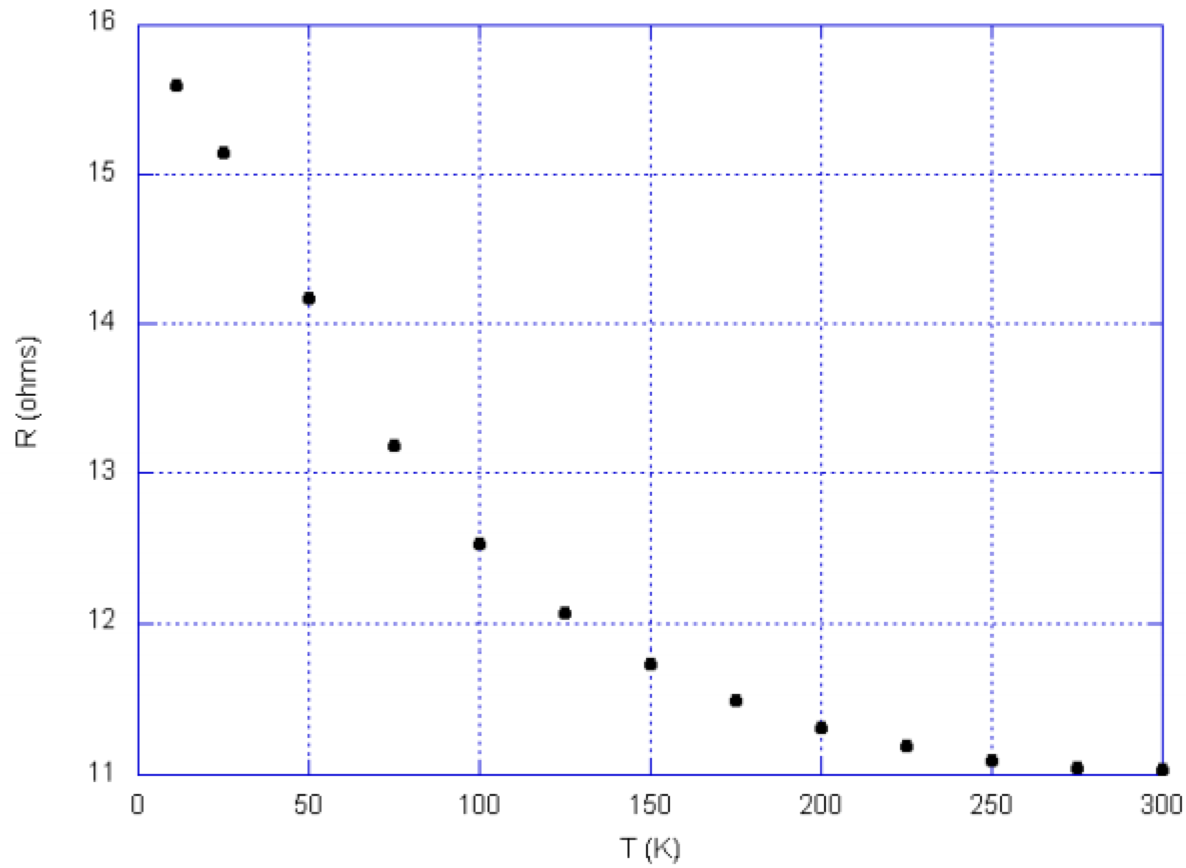
1.Resistance of a copper sample as a function of temperature.
2.The slope of the linear fit can be used to calculate the temperature coefficient of resistivity.

$$R = R_0[1 + a(T - T_0)]$$

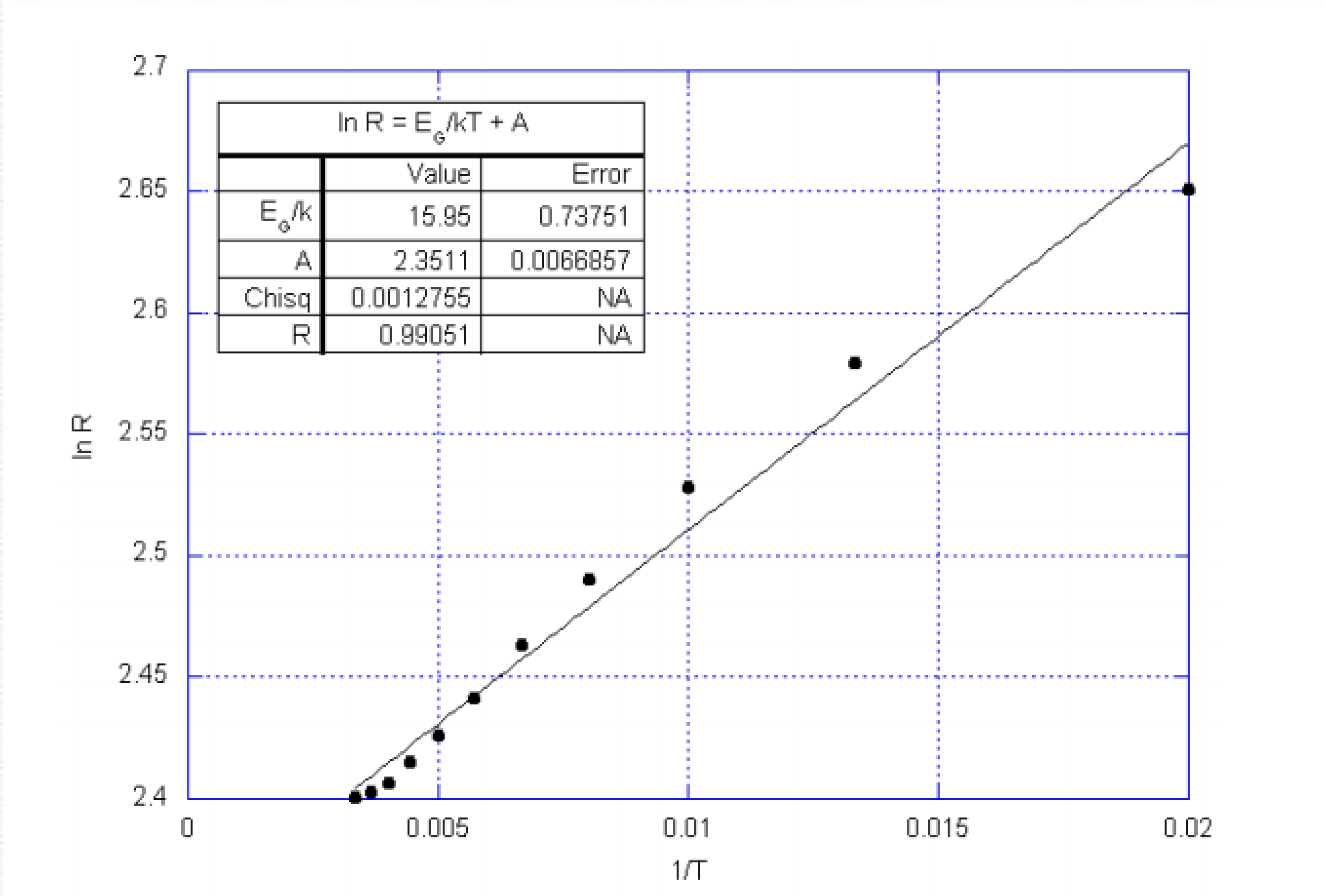
Theory for pure semiconductor

For a pure semiconductor, phonon vibrations still impede the motion of charge carriers at higher temperatures, but the availability of these charge carriers is the most important factor in determining resistivity. At absolute zero, the valence band in a semiconductor is completely full, and the conduction band is empty. The energy that an electron needs to jump to the conduction band is known as the band gap energy, EG, which is typically between 0.5 eV and 2 eV for a semiconductor. The relationship between resistivity and temperature for a pure semiconductor is

$$\rho \text{ is proportional to } T^{-3/2} e^{E_G/kT}$$



Temperature dependence of resistance of carbon resistor.
Attempts to fit this to the curve given in Eq. (6) were unsuccessful.



ln R plotted against 1/T for carbon resistor. If R ∝ e EG/kT , the slope of this line should be EG/k. However, this gives EG = 0.001 eV, which is far too small.

Theory for PN junction

A pn junction is the connection of an n-type semiconductor, in which there are excess electrons, with a p-type semiconductor, in which there are missing electrons. The places where electrons are missing are known as holes, and they behave as positive charge carriers. In this experiment, the pn junction is made from silicon with added dopant. The electrons in the n-type semiconductor and the holes in the p-type semiconductor are the majority carriers, and when a positive voltage is applied from the p region to the n region, there is an exponential increase in current $e^{qV/kT}$

These effects are expressed in a simple model as

$$I = I_0(e^{\frac{qV}{kT}} - 1)$$

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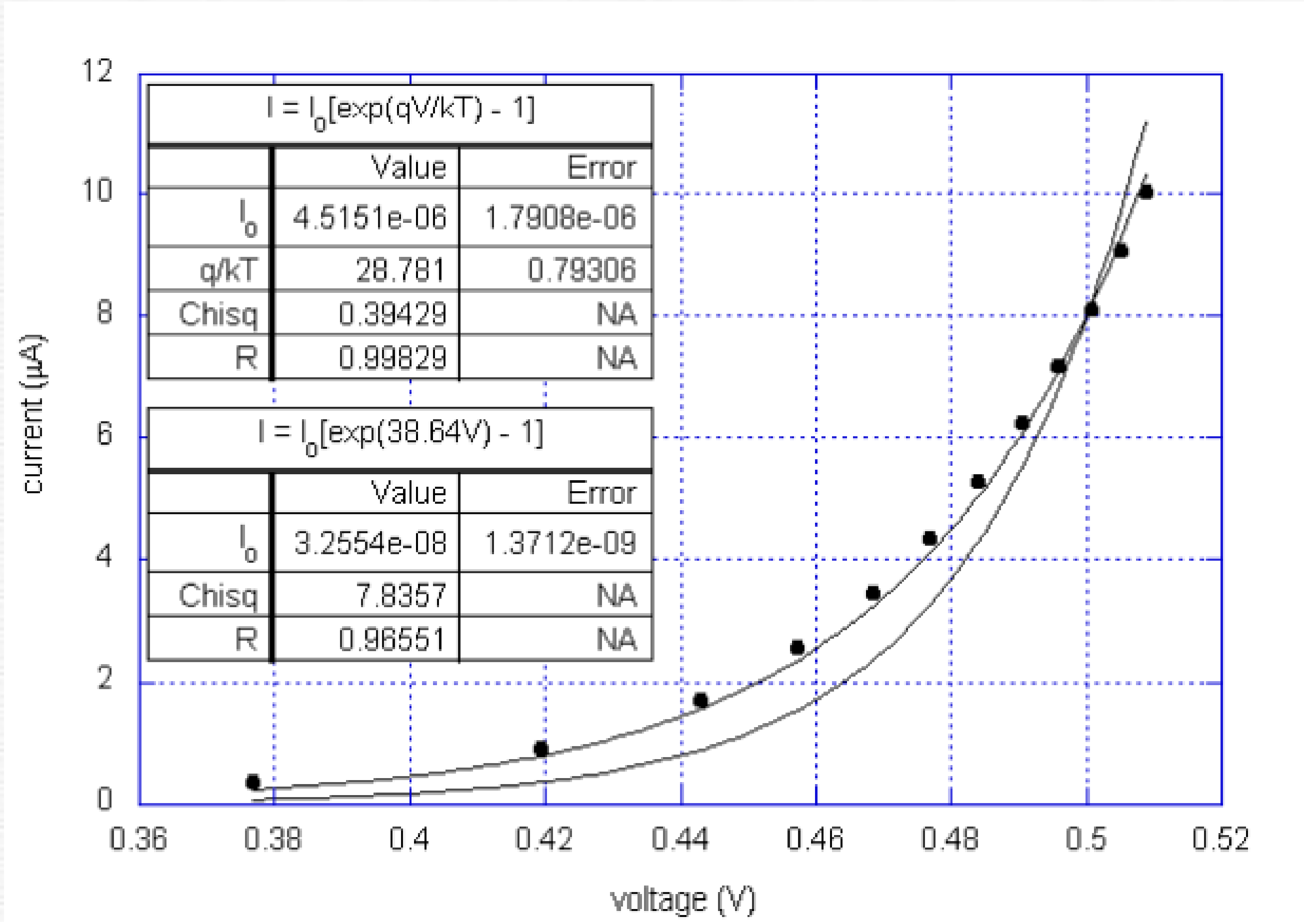

Current through a pn junction as a function of voltage at 300 K

Conclusion

- two mechanisms contributing to resistance: availability of charge carriers and ability of charge carriers to move unimpeded through the solid.
- Studying the resistivity of these materials also allowed us to calculate some of their properties.
- No quantitative measurements could be made from the carbon data, due to limitations in the theory and to the fact that a carbon resistor is not a pure semiconductor.

Thank you!