Electronic Properties of Metals and Semiconductors

Alex Povilus
Physics 441- Fall 2003

December 22, 2003

Abstract

This experiment explored the dependence of conductivity on temperature in both metals and semiconductors. From the conductivity, the energy levels of free electrons and phonons in the samples can be interpreted to provide a understanding of what properties of a material make a it "good" conductor.

Developing an accurate physical model for electrical resistance in metals and semiconductors is a difficult and arduous task, mainly due to the complexity of any given material in relation to elementary particles. Factors that have a strong effect on the resistance of such materials include electron-phonon scattering, electron-electron scattering, impurity and doping scattering, and scattering due to magnetic effects. [1] Calculations, in consideration with all of these factors, for a well-known lattice even give predictions which are offset from experimental values by a factor of 2 or more. However, the macroscopic effects of these factors can be easily seen by comparison of conductivities over a range of temperatures. This report therefore will give basic parameterizations for samples of copper, gold, and doped silicon and give an explanation for their behavior.

I. Apparatus

Measurements were taken of electrical resistance via a four-point probe. A constant current on the order of $20mA$ was passed through the sample and the difference in potential between the voltage leads was recorded. The sample was mounted onto a long feedthrough locked to the top of a 100L liquid helium (LHe) dewar. As the sample was lowered slowly into the dewar and its temperature dropped, the voltage was recorded in 5K intervals. The entire cooling process, from 300K to 4.2K occurred over the course of 30 minutes to ensure minimal errors in feedback. The primary uncertainty in the system was the precise temperature, for which error was found to be about ± 5K above 77K. Other errors included an uncertainty of $\pm 0.35mA$ in the current at any given setting.

II. Copper: 3-Dimensional Bulk Metal

A copper wire with length 1.78m and diameter 1.0mm was used as a bulk metal sample in this experiment. The recorded data for this sample can be seen in Figure 1a. The relationship between temperature and resistivity was found to be nearly linear for high temperatures ($T > 50K$) and has the ratio $\rho/T = ((6.93 \pm 0.03)T) \times 10^{-11}\Omega \cdot m/K$. From this ratio, we can acquire the relaxation time and mean free path of electrons traveling in the metal. These can be expressed as $\tau = m/(\rho n e^2) = (6.05 \pm 0.03) * 10^{-12} sec \cdot K$ and $l = \tau v_f T = (9.54 \pm 0.04) * 10^{-6} m \cdot K$ respectively.

The more interesting portion of this graph however occurs for temperatures less than 50K. At this point, the resistivity becomes constant, leveling off to a constant value of $2 \times 10^{-10}\Omega \cdot m$. This leveling occurs as a result of impurities and strain in our sample. Ideal at such low temperatures, very few phonons exist that can interact with the electrons, creating a nearly ideal lattice through which an electron's wavefunction can easily propagate.[2] However, when impurities or strain are placed in the material, the electron is much more likely to be repelled by perturbations, even without thermal vibrations. Thus, strain and impurities in the material define a lower bound on the resistivity of the material. Unfortunately, for our purposes, this value is entirely empirical since even a computer simulation using a classical argument would be far beyond the scope of this summary.

III. Gold: 2-Dimensional Sheet Metal

The second sample studied was a sheet of gold less than 5 nm thick. Using the Debye model for phonons, one can consider the effects of having an extremely thin dimension. The sheet, being only 10-20 atoms thick at any given time, cannot be vibrated in a mode faster than ω_{max}. However, this means that there can exist only ~ 10 quantized phonons in this dimension. Considering the "Fermi sphere" in phase space, it follow that the available states no longer fill a sphere, but rather a plane. Thus, when considering this sample, it is best to make the approximation that the metal is a 2-dimensional system of electrons and phonons.

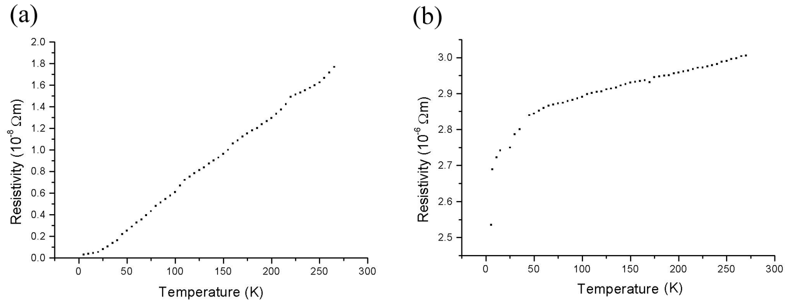

Figure 1: **(a)** This graph shows the relationship between resistivity and temperature in the bulk copper sample. The two regimes of linear and constant are clearly visible. **(b)** This graph same relationship, but instead in the gold 2-dimensional sample. Comparing the two, it is clear that the gold sample has far less dependence on the temperature.

The density of states for a 2-dimensional harmonic oscillator can be expressed as $D(n) = 2\pi n$. Thus, considering the Fermi sphere in phase space the fermi radius and energy are easily shown to be,

$$r_f = \sqrt{\frac{2N}{\pi M}}; E_f = \frac{\hbar}{2m}(\frac{r_f \pi}{L})^2 \tag{1}$$

where M is the number of phonon modes available in the small dimension. The value for the Fermi energy is much higher for large N than that of the two-dimensional case, resulting in a much higher average energy of phonons overall. Having higher energy phonons, the sample is much more likely to perturb electrons until extremely low temperatures. Therefore, the data recorded, as shown in Figure 1b displays a much smaller dependence on temperature.

IV. Silicon: Semiconductor

A semiconductor has a much different energy structure than a metal. Semiconductors, unlike the metals, have a large forbidden zone of energies for free electrons in the material. In order to utilize electrons for conduction in silicon, a certain amount energy must first be placed into the system so that electrons are pumped into the conduction band, creating mobile electrons and holes. Therefore, the number of charge carriers in the system is highly dependent upon the temperature of the semiconductor. This can be observed from the data shown in Figure 2.

The Debye temperature, θ_D of silicon is 645K, which prevents us from interpreting the high-temperature effects of the large 1.1eV conduction band.[3] However, this does not prevent the observation of impurities which act as electron donors in the silicon. The footprint of the impurity in this case is the large drop in conductivity near very low temperatures. In this case, an exponential fit to the low temperature data reveals a donor mobility of $\mu = 21 \pm 4meV$, which corresponds well with the doping effect of phosphorus in silicon. [4]

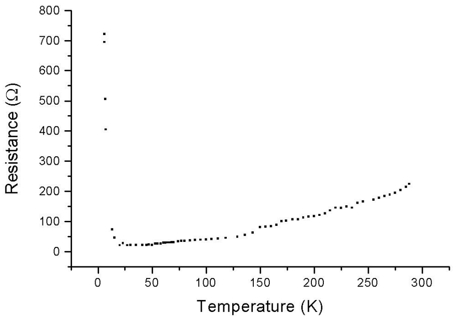

Figure 2: The graph demonstrates the complexity silicon conductivity's dependence on temperature. The sharp rise in resistivity for low temperature is due to doping effects in the semiconductor. The resistance steadily increases with temperature despite increased number of charge carriers since phonons still play a major role in the room-temperature regime.

References:

[1] J. S. Dugdale, *The Electrical Properties of Metals and Alloys* (1977)
[2] [4] H. P. Myers, *Introductory Solid State Physics* (1997)
[3] C. Kittel, *Thermal Physics* (1980)