MICROCOPY RESOLUTION TEST CHART

[Image of a resolution test chart with various line patterns and numbers indicating line spacing.]
The interaction between electrons and phonons in a thin carbon film is investigated. Sound wave propagation in a thin carbon film has a small sound velocity and small damping. The scattering of electrons by phonons associated with the Rayleigh wave is found to be responsible for the anomalous temperature dependence of the resistivity and for the negative magnetoresistance of pregraphitic carbons at low temperatures.
Electron–phonon interaction in a thin carbon film is investigated. Sound wave propagation in a thin carbon film has a small sound velocity and small damping. Electron–phonon scattering associated with the wave is responsible for the anomalous temperature dependence of the resistivity and for the negative magnetoresistance of pregraphitic carbons at low temperatures.

Lattice Vibrations in the Long Wavelength Approximation

We briefly describe the theory of the lattice vibrations in pregraphitic carbons at low temperatures. Wave propagation in a thin carbon film has a small sound velocity and small damping. Electron–Rayleigh wave interaction plays an important role in the anomalous temperature dependence of the resistivity and in the negative magnetoresistance of disordered carbons at low temperature [6].

Pregraphitic carbons heat treated at low temperature have a turbostratic structure and the correlation length along the c-axis is small. Accordingly, it is reasonable to assume that the sample is composed of an assembly of many thin films which are weakly coupled to each other elastically.

To solve Eq. 1 for the case of a thin film, the following boundary conditions are imposed at $z = 0$ and $z = -d$, where $d$ is the film thickness along the c-axis. Strain free and stress free boundary conditions give rise to the same equations:

$$\frac{\partial u_x}{\partial z} + \frac{\partial u_y}{\partial z} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0,$$

at $z = 0$ and $z = -d$. A damped plane wave solution of Eq. 1 is written in the form:

$$\bar{u}(r) = \bar{U}e^{i\omega(t-z/c)}$$

for $\bar{u}$ along the x-axis. The general solution $\bar{u}(r) \propto e^{i(k_z z - \omega t)}$ can be obtained from Eq. 4 by rotating the coordinate axis in the xy-plane. Inserting Eq. 4 into Eq. 1, yields $u_y = 0$ and equations for the $u_x$ and $u_z$ components:

$$(\omega^2 - \nu_x^2 + \nu_z^2)U_x + i\zeta q \nu_x U_z = 0$$

$$(\omega^2 - \nu_y^2 + \nu_z^2)U_z + i\zeta q \nu_y U_x = 0.$$  

Equation (5) is solved to obtain $\nu_z$ as a function of $\omega$. Two positive roots $\nu_1^2$ and $\nu_2^2$ exist, if the Rayleigh wave velocity $\nu_R = \omega/q$ satisfies the condition:

$$\nu_R^2 < \zeta = C_{44}/\rho.$$
One root corresponds to a rapidly damped wave and the other to a weakly damped wave. From these roots, an explicit expression for the displacement vector $\mathbf{u} = (u_x, u_y, 0)$ has been found. By introducing the phonon operators $b^\dagger$ and $b$, the energy of the Rayleigh wave is quantized according to

$$2 \int d^2 \rho \left\{ \frac{1}{2} \frac{\partial \tilde{u}_x}{\partial t}^2 + \frac{1}{2} \frac{\partial \tilde{u}_y}{\partial t}^2 \right\} = \frac{1}{4} \hbar \omega_0 (b^\dagger b + \frac{1}{2}),$$

where $\tilde{u}_x = (u_x, u_y, 0)$. From these equations, explicit expressions for $\mathbf{u}_x$ and $\mathbf{u}_y$ are obtained [6].

The solutions show that the displacements follow a weakly damped Rayleigh wave polarized along the $c-$axis where the in-plane displacement $u_x$ is two orders of magnitude smaller than $u_y$. The following expression for the $k-$dependent relaxation rate due to the scattering by the Rayleigh wave phonons is obtained [6]:

$$\frac{1}{\tau_R(E_k)} \simeq \frac{2 \pi k_B T d^2}{\hbar \rho v_k^2} \sum_{q'} \frac{1}{q^2} \left( 1 - \frac{k'_x}{k_x} \right) g(E_k - E_{q'}) \delta(E_k - E_{q'}),$$

where $g = \tilde{k}'_y - \tilde{k}_x$, and $\tilde{k}_x = (k_x, k_y, 0)$. Here $D$ denotes the electron–phonon coupling constant associated with the out-of-plane vibrations, and in bulk graphite $D \sim 3.7 eV$[7]. In deriving Eq. 8, the introduction of a high temperature approximation for phonons $N_v \sim N_v + 1 \sim k_B T/\hbar \omega_y$ is employed, since $\hbar \omega_y/k_B = \hbar v_R g/\hbar B \simeq 4 \times 10^7 q < 1K$ for $q \sim 10^6 cm^{-1}$. From Eq. 8, we then obtain a temperature dependence for the relaxation rate

$$\frac{1}{\tau_R} \simeq \frac{k_B T}{4 \pi^2 \hbar^2 \rho v_{min}^2} \left( \frac{1}{v_F g_{min}^2} \right) \left( \frac{D}{v_B q_{max}^2} \right)^2,$$

where $g_{min} = 2\pi/L_x$ and $L_x$ denotes the dimension of the thin film in the basal-plane. In evaluating Eq. 9, the following values of the parameters are employed: $v_R = 4.5 \times 10^4 cm/sec$, $d = 70Å$, $L_x = 200Å$, and $v_F = 5 \times 10^7$ cm/sec, yielding a value of $1/\tau_R \sim 3 \times 10^{11} T/secK$. The large magnitude of $1/\tau_R$ compared with other processes in thin carbon films shows that the electron–Rayleigh wave interaction is responsible for the anomalous temperature dependence of negative magnetoresistance of pre-graphitic carbons at low temperatures[6], and for the unusual temperature dependence of the carbon films with low heat treatment temperature $T_{HT} \simeq 1300^\circ C$ [8].

References


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