ANOMALOUS PHONON DRAG EFFECT IN GRAPHITE

K. Sugihara,* H. Ohshima,+ K. Kawamura,+ and T. Tsuzuku+

* Central Research Laboratory, Matushita Electric Industrial Co., Ltd. Moriguchi, Osaka, Japan

\+ Nihon University at Ochanomizu, Tokyo, Japan

§1. Introduction

Detailed investigations on the thermoelectric and thermomagnetic effects of graphite, revealed the appearance of negative dip of the thermopower (S) and the Nernst-Ettingshausen coefficient (A_{NE}) around 35~40K. (1~ 5) These anomalies are related to the phonon drag effect. (6~ 9)

Recently, we have ascertained that well-crystallized kish graphite exhibits a sharp peak of β_{xx} below 20K beside a dip around 35K, where β is related to a current density $\underline{j} = \underline{\sigma}\,\underline{F} - \underline{\beta}\,\underline{\nabla}T$. Under the condition of $H /\!/ z$, and $\nabla_x T \neq 0$, S is given by

$$S(H) = \frac{F_x}{\nabla_x T} = \frac{\sigma_{yy}\beta_{xx} - \sigma_{xy}\beta_{yx}}{\sigma_{xx}\sigma_{yy} - \sigma_{xy}\sigma_{yx}}. \qquad (1.1)$$

The dip is associated with the normal phonon drag effect, while the peak can be ascribed to the two-stage drag effect. (10~ 13) Observed results of $\beta_{xx}(0)$, $\beta_{xx}(H)$ and $\beta_{xy}(H)$ in kish graphite are given in Fig.1.

In the normal phonon drag effect the "electron phonon" which interact with carriers come to a stationary state mainly through the scattering by carriers and short wave phonons. In this case short wave phonons are assumed to be in thermal equilibrium, and so

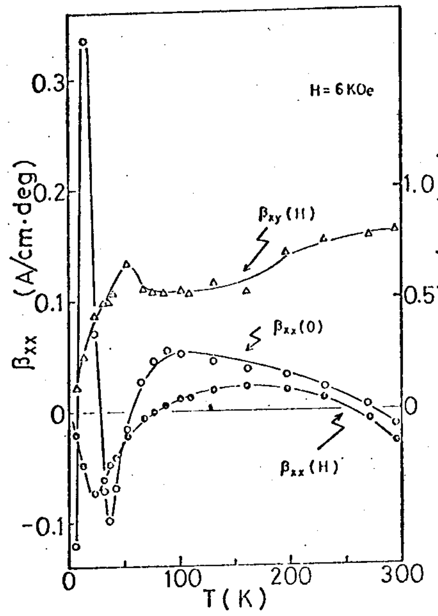

Fig.1 Temperature dependence of $\underline{\beta}$ in kish graphite.

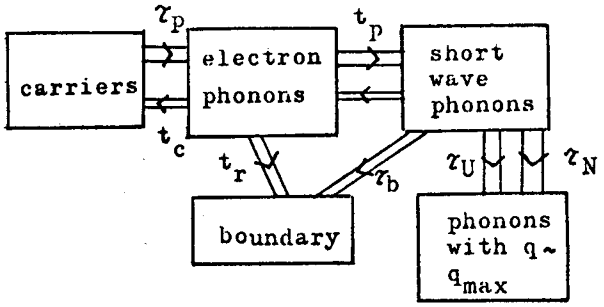

Fig.2 Momentum relaxation processes in carrier- and phonon-systems.

they do not explicitly participate in the kinetic equation. However, with decreasing temperatures the short wave phonons deviate from the thermal equilibrium because the Umklapprocess (U-process) becomes inactive as compared with the Normal process(N-process). Accordingly, the short wave phonons can drag carriers via the electron phonons. This two-stage drag induces the extra anomaly of $\beta_{xx}(0)$ in Fig.1.

By solving the coupled Boltzmann equation of carriers and phonons, an expression of the two-stage drag effect is given in §2.

§2. Two-stage drag effect in graphite

Main assumptions made in our calculation are as follows:

1) The Fermi surface is approximated by the ellipsoid model. (6~ 9)

2) Electron-phonon interaction is limited to the coupling with the in-plane vibration. (6~ 9)

3) As we consider a case of $\tau_U \gg \tau_N$, where τ_U and τ_N correspond to relaxation times of the short wave phonons and U and N indicate the U- and N-processes, their distribution functions are assumed to be

$$F_q \simeq \left[\exp \beta(\hbar\omega_q - \hbar\underline{u}\cdot\underline{q}) - 1\right]^{-1}. \qquad (2.1)$$

$\underline{u}$ is a quantity to be determined by use of the coupled Boltzmann equation.

To get β, it is more convenient to calculate the heat flux $\underline{w}$ subjected to an electric field $\underline{F}$ and without temperature gradient $\underline{\nabla}T$. In this case we have

$$\underline{w} = \underline{\chi}\,\underline{F}, \quad T\beta_{ij}(H) = \chi_{ji}(-H). \qquad (2.2)$$

Along the similar line to the procedure

of Kozlov and Kozlov et al (10 ~ 12), we get an expression of w due to the two-stage drag effect as follows:

$$\underline{w} = \sum_q \hbar \omega_q \underline{v}_s \left(\frac{\tau_U}{t_p(q)}\right) (\delta N_q)_{\text{normal drag}}. \quad (2.3)$$

v_s: phonon velocity,
$t_p(q)$: relaxation time of the electron phonon q related to the scattering by the short wave phonons (see Fig.2),
$(\delta N_q)_{\text{normal drag}}$: electron phonon deviation in the normal phonon drag process.

According to the theory of the normal phonon drag effect in graphite (6,8,9), $(\delta N_q)_{\text{normal drag}}$ takes the form:

$$(\delta N_q)_{\text{normal drag}} = - \varphi_q \frac{\partial N_q^0}{\partial \hbar \omega_q},$$

$$\varphi_q \cong \sum_{\lambda,\mu} R_{\lambda\mu}(q)(\underline{v}^{(\mu)} \cdot \hbar \underline{q}), \quad (2.4)$$

$R_{\lambda\mu}(q) = t(q)/t_{\lambda\mu}(q)$,
$t(q)$: total relaxation time of the electron phonon q,
$t_{\lambda\mu}(q)$: relaxation time of the electron phonon q in the scattering process by carriers,
λ , μ: indicies specifying carriers,
$\underline{v}^{(\mu)}$: drift velocity of μ-th carrier.

Inserting (2.4) into (2.3), we get

$$\underline{w} = \beta \sum_q \hbar \omega_q (\underline{v}_s \cdot \underline{q}) \left(\frac{\tau_U}{t_p(q)}\right) \Big\{ \left[R_{ee}(q) + 2R_{eh}(q)\right]$$

$$\times \underline{v}^{(e)} + 2 \left[R_{hh}(q) + R_{eh}(q) + R_{hh'}(q)\right] \underline{v}^{(h)} \Big\}$$

$$\times N_q^0(1 + N_q^0), \ \beta = 1/k_0 T. \quad (2.5)$$

In (2.5) contributions of electron and hole cancel each other.

At low temperatures τ_U increases rapidly as $\exp(\alpha \Theta / T)$ ($\alpha \sim 1$). With further decrease of temperatures boundary scattering plays an important role in the relaxation process of the short wave phonons. Then, we should replace τ by

$$\tau_U^* = \tau_U / (1 + \tau_U/\tau_b) . \quad (2.6)$$

(see Fig.2)

If a condition of $t_p \gg \tau_b$, $\tau_U \gg \tau_b$ is satisfied, two-stage drag effect becomes negligible. This explains the feature of Fig.1 qualitatively. In the presence of a magnetic field ρ_{xx} decreases due to the cyclotron motion of carriers. (see Fig.1)

Clear indication of the two-stage drag effect was observed in good samples of bismuth at helium temperatures. (13)

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