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Phonon-Drag Thermoelectric Power in High Magnetic Fields in Heterojunctions

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S. K. Lyo
Sandia National Laboratories, Albuquerque, N.M. 87185

A theory is presented for the low-temperature (T) phonon-drag thermopower S_{xx} in a semiconductor heterojunction in a strong magnetic field. Gigantic quantum oscillations (much larger than electron-diffusion contributions) are obtained. When the Landau-level width is larger than $k_B T$, the one-phonon intra-Landau-level absorption and emission processes are dominant. In the opposite limit, the two-phonon Raman processes give major contributions. The temperature and field dependences of S_{xx} agree reasonably with recent data in GaAs/$Al_xGa_{1-x}As$ heterojunctions. Effects of localized states on S_{xx} are discussed.

In a strong magnetic field, the thermoelectric power (TEP) S_{xx} equals the heat carried by the Hall current per unit charge and unit temperature. Quantization of two-dimensional degenerate electron gases in high magnetic fields yields striking effects such as integer and fractional quantum Hall effects (QHE). How much these effects are reflected in S_{xx} is an interesting question and the TEP in heterostructures has received increasing attention.[1-7] To the author's knowledge, theoretical studies have examined only the electron-diffusion TEP (EDTEP) and yielded approximately $-S_{xx}$ =

60/p μV/K at the maxima which occur at half odd integer values of the filling factor p.[6,7] Early data[1-4] in GaAs/Al_xGa_{1-x}As heterojunctions with mobilities of 0.5 - 50 m^2/Vsec show $-S_{xx} \leq 60/p$ μV/K and have been analyzed in terms of EDTEP. More recently, Fletcher et al.[5] reported S_{xx} data with peak values of 1 - 6 mV/K for samples with mobilities of 4.2 - 37.7 m^2/Vsec. They also found surface polishing to enhance S_{xx} and suggested that the phonon-drag TEP (PDTEP) may yield such large TEP.[5] We develop a theory of the PDTEP. Our results agree reasonably with the data of Fletcher et al.[5]

The TEP S_{xx} is given by the ratio of the transverse heat and charge (i.e., Hall) current densities per temperature in the QHE configuration in the high field (perpendicular to the x-y quantum-well plane) limit.[7] The electron heat current density (HCD) yields the EDTEP, while the phonon HCD induced by the electron-phonon interaction (EPI) yields the PDTEP. The electrons are in the ground sublevel and are scattered elastically. The phonons are scattered mainly by the boundaries. The phonon HCD induced by $E \rightarrow 0$ is calculated in the following way. First, we set up a relationship between the phonon and electron distribution functions n_{qs} and f_n through the steady-state Boltzmann equation[8] by equating the rate of destruction of phonons of wave vector q and polarization s through boundary scattering ($\tau_{qs}^{ph\ -1}$) to the rate of creation through the EPI. The latter occurs through intra-Landau level (LL) one-phonon emission and absorption as well as two-phonon Raman processes. The deviation of n_{qs} from the equilibrium boson function n^o_{qs} is then obtained in terms of the deviations ($\propto$ E) of f_n's from their equilibrium Fermi functions f^o_n's. The lattice HCD is then obtained by summing $\hbar\omega_{qs}\partial\omega_{qs}/\partial q_y n_{qs}$ over qs (ω_{qs} is the angular frequency), yielding

$$S_{xx} = - (S_{1p} + S_{2p}), \tag{1a}$$

$$S_{1p} = \frac{(k_B/e)}{p(k_BT)^2} \sum_{qs} \tau^{ph}_{qs} \hbar\omega_{qs} q_y (\frac{\partial}{\partial q_y} \hbar\omega_{qs}) \sum_n P_n(q,s), \tag{1b}$$

$$S_{2p} = \frac{(k_B/e)}{p(k_BT)^2} \sum_{qs} \sum_{q's'} \tau^{ph}_{qs} \hbar\omega_{qs} (q_y - q_y') (\frac{\partial}{\partial q_y} \hbar\omega_{qs}) \sum_n P_n(qs,q's'), \tag{1c}$$

where the subscript 1p (2p) denotes one (two)- phonon processes and

$$P_n(q,s) = \frac{2\pi}{\hbar}|V_{qs}|^2 \Delta_z(q_z)\Delta_n(q_{||}) \int d\epsilon \int d\epsilon' \rho_n(\epsilon)\rho_n(\epsilon')$$
$$\times n^o_{qs} f^o(\epsilon)[1 - f^o(\epsilon')]\delta(\epsilon + \hbar\omega_{qs} - \epsilon'), \tag{2a}$$

$$P_n(qs,q's') = \frac{2\pi}{\hbar}|V_{qs}V_{q's'}/\hbar\omega_{qs}|^2 \Delta_z(q_z)\Delta_n(q_{||})\Delta_z(q_z')\Delta_n(q_{||}')$$
$$\times 2[1-\cos\{q_{||}q_{||}'\ell_H^2\sin(\phi'-\phi)\}] n^o_{qs}(n^o_{q's'}+1) f^o_n(1-f^o_n)\delta(\hbar\omega_{qs}-\hbar\omega_{q's'}). \tag{2b}$$

Here ϕ (ϕ') is the azimuthal angle of $q_{||}$ ($q_{||}'$), $\Delta_z(q_z) = [b^2/(b^2+q_z^2)]^3$ and $\Delta_n(q_{||}) = \exp(-\chi)\{L_n(\chi)\}^2$, where $q_{||}^2 = q_x^2 + q_y^2$, $\chi = (q_{||}\ell_H)^2/2$, ℓ_H is the classical magnetic length ($= [\hbar c/(eH)]^{1/2}$), and $L_n(\chi)$ the Laguerre polynomial.[9,10] b is the parameter in the variational confinement wave function:[11] $b/k_F = [33e^2k_F/(64\kappa_s\epsilon_F)]^{1/3}$, $\kappa_s = 12.9$ the bulk dielectric constant and k_F (ϵ_F) the Fermi wave number (energy) at H = 0. Spin splitting is ignored in (1).

In (2), $|V_{q\ell}|^2$ and $|V_{qt}|^2$ (defined in Ref.9) are the square of the screened EPI for longitudinal (ℓ) and transverse (t) modes respectively. The former (latter) includes both the deformation potential and piezoelectric EPI (the piezoelectric EPI). For the static dielectric screening the result of Ref.12 is used. The spectral density of states (DOS) at the nth LL $\rho_n(\epsilon)$ is given by the imaginary part of the dressed electron Green's function of the nth LL slightly below the real axis i.e., $\rho_n(\epsilon) = \frac{1}{\pi} \mathrm{Im}\, S_n(\epsilon - i0)$. This quantity is proportional to the DOS for narrow LL's where the impurity-induced transfer of states between the LL's is small. For applications we assume a gaussian form for $\rho_n(\epsilon)$ centered at the nth LL energy $\epsilon_n = (n+1/2)\hbar eH/m^*c$ with root-mean-square full width Γ.[13] Only the LL's adjacent to the Fermi level give contributions to S.

We now evaluate (1) and compare the result with the data from Ref.5. The following parameters are used:[9] the effective mass $m^* = 0.07m_o$, the sound velocities $c_\ell = 5.14\times10^5$ cm/sec, $c_t = 3.04\times10^5$ cm/sec, the mass density $\rho = 5.3$ g/cm^3, the piezoelectric constant $h_{14} = 1.2\times10^7$ V/cm, the deformation potential coefficient D = -9.3 eV, and the carrier density[5] N = 6.24×10^{11} cm^{-2}. The TEP S_{xx} is proportional to the phonon mean free path Λ ($= c_s\tau_{qs}^{ph}$). Λ is independent of the temperature and is determined by the boundary scattering at low temperatures.[5] Thermal conductivity data yields $\Lambda \approx 2$ mm for the polished sample (BP4).[5] The width Γ is estimated from the mobility and specific heat data to be $\Gamma \approx 1 - 2$ meV.[14] Λ and Γ are treated as adjustable parameters.

The calculated $S = |S_{xx}|$ (solid curves) is compared with the data[5] (dashed curves) in Fig.1 for $\Lambda = 1.3$ mm and $\Gamma = 1$ meV. The double maxima shown both by the data and the theory at 1.61 K near 5.15 T is due to the fact that the screening ($\propto$ DOS) reduces the EPI at the peak of the DOS. The T-dependence of S in (1) (dashed curve) is compared with the data[5] (empty circles) in Fig.2 for the same parameters at h = 2.85 T (p = 4.5). The EDTEP is less than 2% of the data and is ignored. Major contributions to the TEP arise from S_{1p}. For smaller values of Γ, S increases much more slowly, reaches a maximum, and decreases with increasing temperature as is shown by a dotted curve in Fig.2 for $\Gamma = 0.5$ meV. For a very narrow width Γ, S_{2p} is dominant, yielding S comparable to EDTEP: The T-dependence of S in (1) is displayed in Fig.3 for $\Gamma = 0.05$ meV and $\Lambda = 2$ mm. In this case, a high-temperature RPA screening formula is used. The steep theoretical S-minima valleys in Fig.1 are the result of ignoring the localized states. Our preliminary result shows that a much better fit (with flat S-minima valleys) is obtained for both the H- and T-dependences, if we assume sharp mobility edges 0.75 meV from the center of the LL with $\Gamma = 1.6$ meV and with $\Lambda = 2.5$ mm. The T-dependence is shown for this case (solid curve) in Fig.2.

In summary we presented a theory of the low-temperature phonon-drag magneto-thermopower in a heterojunction. Large quantum oscillations are obtained. The temperature and field dependences agree reasonably well with recent data. The role of the localized states was discussed.

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Figure Captions

Fig.1 Comparison of the calculated S (solid curves) with the data[5] (dashed curves). No localized states are assumed. The parameters used are given in the text.

Fig.2 The temperature dependence of the calculated S with (solid curve) and without (dashed, dotted curves) localized states at $h = 2.85$ T. The parameters used are given in the text. The empty circles denote the data.[5]

Fig.3 The theoretical temperature dependence of S for $\Gamma = 0.05$ meV at $h = 2.85$ T. Other parameters used are given in the text.

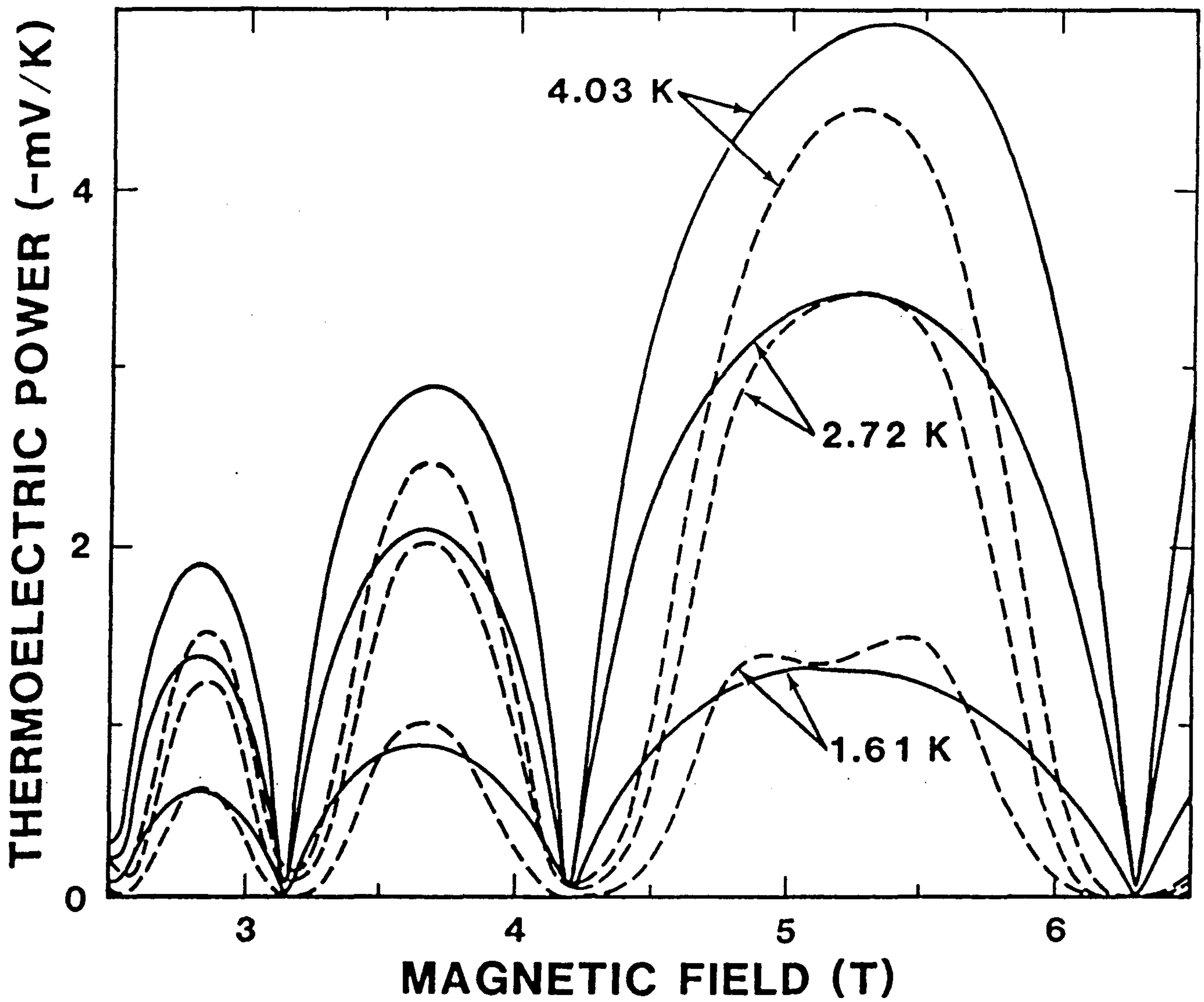
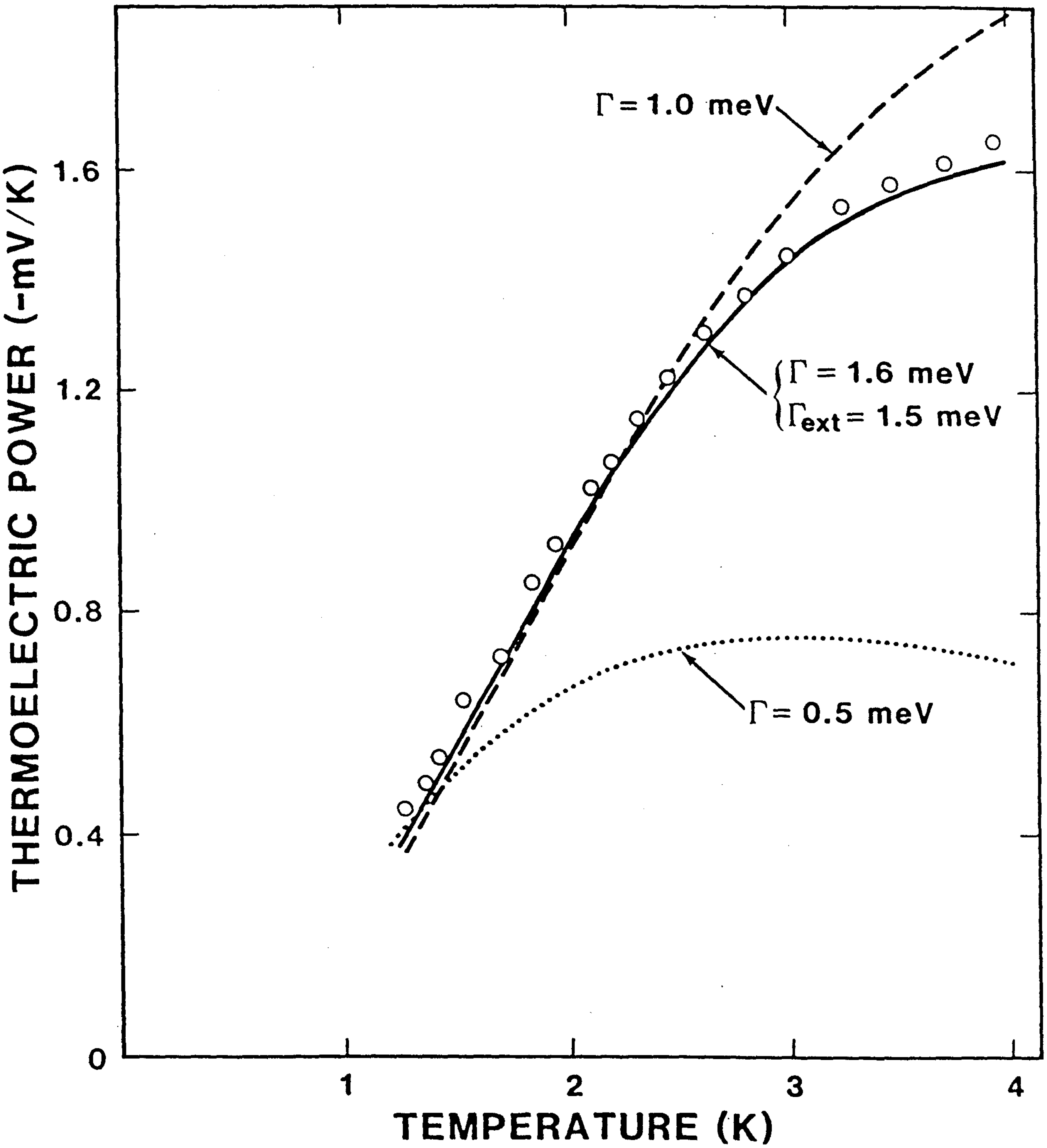

4.03 K
2.72 K
1.61 K
THERMOELECTRIC POWER (-mV/K)
0
2
4
3
4
5
6
MAGNETIC FIELD (T)

Fig. 1



THERMOELECTRIC POWER (-mV/K)
TEMPERATURE (K)
0
0.4
0.8
1.2
1.6
1
2
3
4
Γ = 1.0 meV
Γ = 1.6 meV
Γext = 1.5 meV
Γ = 0.5 meV

Fig. 2

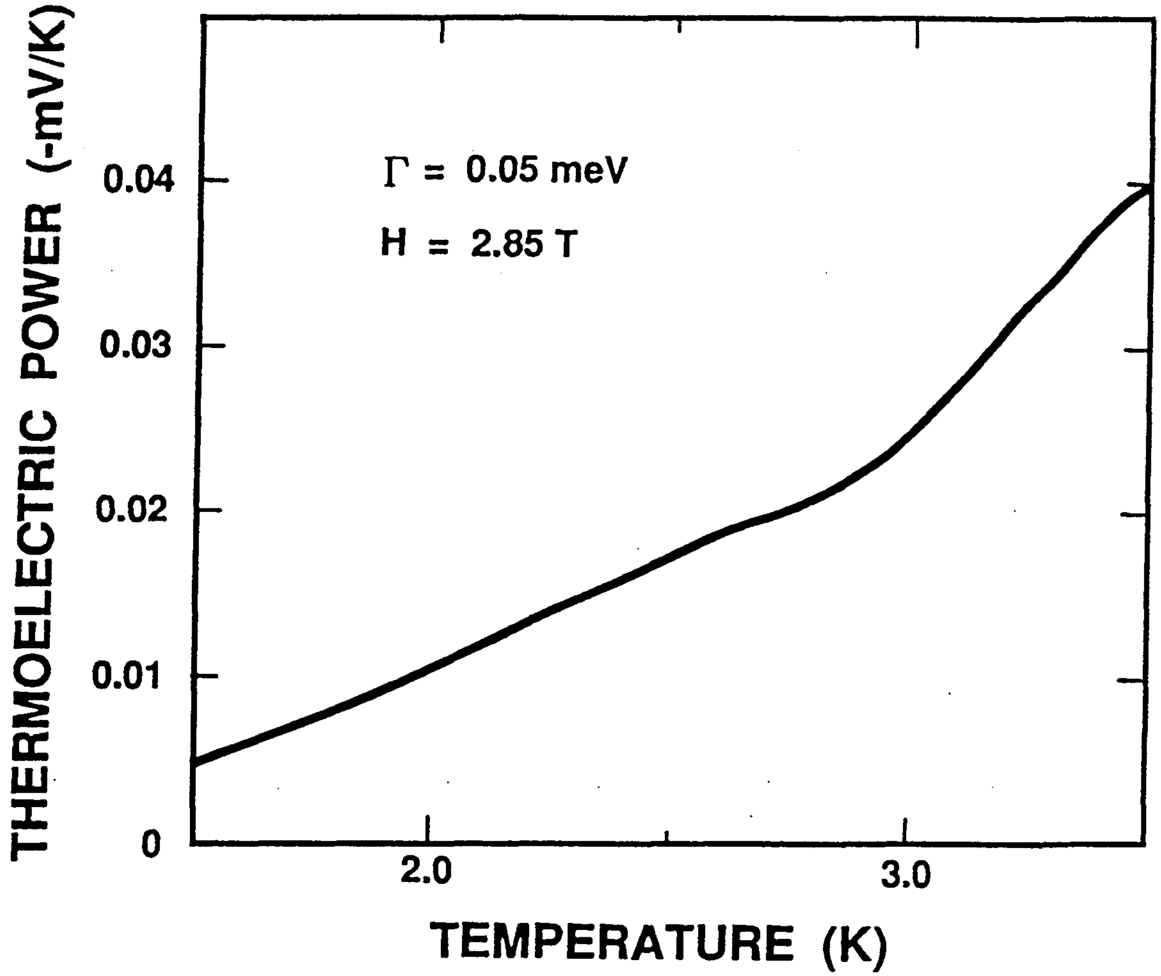


Fig. 3

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