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Effective mass and bandstructure of n-InAs from magnetophonon resonance and Raman scattering at temperatures between $T = 64$ and 360 K [1]

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Abstract

We investigate properties of electrons and phonons in n-InAs and their interaction by the magnetophonon resonance (MPR) at temperatures between $T = 64$ K and for the first time to above room temperature. Raman scattering experiments were performed to determine the frequency of longitudinal optic phonons, also for the first time over the whole range from $T = 77$ to 400 K. The transversal magnetoresistance was measured at more than fifty different temperatures between $T = 64$ and 360 K. We observed MP oscillations and extract the fundamental resonance field $B_0(T)$ for the first time for InAs by a full curve fit of the formula for MPR, derived by Barker. We deduce the effective bandedge mass of electrons $m_0^*(T)$, consider nonparabolicity as well as polaron effect and compare it to three and five band kp-calculations.

Keywords: InAs; Effective electron mass; LO-phonon frequency; Raman scattering; Magnetophonon resonance

1. Introduction

The III/V-compound semiconductor indium arsenide (InAs) has attracted interest recently (see e.g. [1]) for application in semiconductor hetero- and nanostructures because of its small energy gap and high electron mobility. InAs is also used as a component for "bandgap engineering" by growing mixed crystals. Detailed knowledge of its electron effective mass, bandstructure and phonon frequencies at room temperature is important. Due to the nonparabolicity of the conduction band Γ_6^c, the "bare" effective mass m_0^* of electrons at the band edge depends on temperature T. This has been deduced for InAs at $110 \leqslant T \leqslant 290$ K and $150 \leqslant T \leqslant 250$ K experimentally from magnetophonon resonance (MPR) by Stradling and Wood [2] and Takayama et al. [3], respectively. A review on MPR in InAs is given by Firsov et al. [4]. Those early results for $m_0^*(T)$ deviate from each other as well as from kp-band calculations and were deduced without detailed knowledge of the involved longitudinal optical (LO) phonon frequency $\omega_{\mathrm{LO}}(T)$ over the whole temperature range. We investigate n-InAs by a procedure similar to the one used in the latest MPR investigations of n-InP [5] and n-GaAs [6]. The evaluated $m_0^*(T)$ is compared to three [7] and five band [8] kp-calculations.

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2. Experimental

We investigated bulk samples from a 0.5 mm thick n-InAs wafer (No.62), perpendicular to [1 0 0] of an undoped single crystal (No. R4/IA/663/UN), produced by Wafer Technology Ltd., UK. For magnetoresistance investigations, the sample 62 M was cleaved with 7×2 mm^2 and for Raman experiments the sample 62 R with 5×5 mm^2 in surface area.

The Raman scattering experiments were performed in the conventional back-scattering geometry by employing the 514.5 nm wavelength of an argon-ion laser at temperatures between 77 and 400 K. A good spectral resolution was obtained by reducing the slit width and making correction for the slit function.

Transversal magnetoresistance and the Hall effect measurements were taken between $T = 64$ and 360 K at more than 50 different temperatures. Below 300 K the sample located in a superconducting magnet system (SPECTROMAG 2000, Oxford Instruments). Above 300 K a He-gas cryostat has been used, surrounded by a Bitter magnet, as described in Ref. [5] together with sample preparation and the experimental set-up. Magnetic field was applied perpendicular to the sample axis located in the (1 0 0) plane. Detection of MP oscillations as small as 10^{-4} compared to the whole magnetoresistance change $\Delta\rho/\rho_0 \equiv [\rho(B) - \rho(B=0)]/\rho(B=0)$ was possible.

3. Results and discussion

Anharmonicity in the vibrational potential leads to the decay of an optical phonon into low energy phonons [9–11] giving rise to a temperature dependent shift in LO phonon in Raman spectra. At temperatures above the Debye temperature of the sample (≈250 K), it becomes important to consider the decay processes where LO phonon decays into two and three low energy phonons [9,10]. Assuming that the LO phonon decays into two and three phonons of equal energy, the theoretical expressions for the temperature dependence of the frequency of the LO phonon can be given by [9,10]

$$\omega(T) = C\left[1 + \frac{2}{e^x - 1}\right] + D\left[1 + \frac{3}{e^y - 1} + \frac{3}{(e^y - 1)^2}\right], \quad (1)$$

where $x = \hbar\omega_0/2k_BT$ and $y = \hbar\omega_0/3k_BT$, k_B is the Boltzmann constant. ω_0 is the intrinsic frequency of the LO phonon and C and D represent the anharmonic constants of the sample. The experimental values of the LO phonon frequency at various temperatures are presented in Fig. 1. Eq. (1) was used to fit these data by suitably choosing the constants ω_0, C and D. The resultant curve is also shown in Fig. 1. Fig. 1 shows a good agreement between the experimental results and the calculated curve for $\omega_0 = 242.74$ cm^{-1}, $C = -1.561$ cm^{-1} and $D = -0.036$ cm^{-1}.

Carrier concentration n and the Hall mobility μ of sample 62 M were determined between $T = 77$ and 300 K to increase from $n = 2.3$ to 4.6×10^{16} cm^{-3} and to decrease from $\mu = 9.5$ to 4.0×10^4 cm^2/V$_s$ respectively. The magnetoresistance $\Delta\rho/\rho$ is modulated by very small MP oscillations between quantum number $N = 1$ and 4. The MP oscillations are periodic with $1/B$. The effective mass m^* of conduction electrons is related to the period $1/B_0$ by $1/B_0 = em^*/\omega_{LO}$. B_0 is the so-called fundamental field [4]. Different corrections must be applied to evaluate the bare mass m_0^* from the

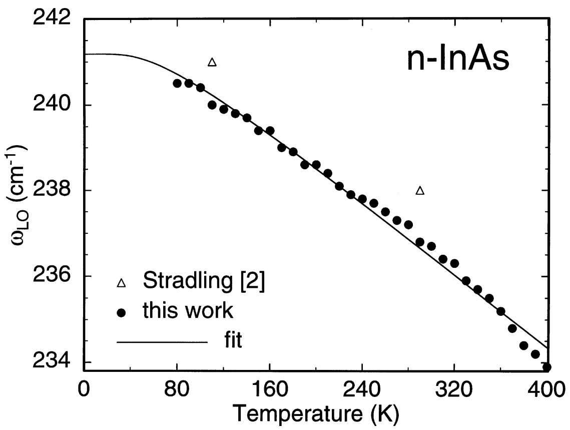

Fig. 1. LO phonon frequency ω_{LO} in dependence on temperature as measured with n-InAs and fit of Eq. (1), compared to values taken by Ref. [2] for MPR interpretation.

recordings as summarized in Ref. [5]. However we extracted the MP oscillations directly as an additive part of the transverse magnetoresistance $\rho(B)=\rho_{\text{mon}}(B)+\rho_{\text{osc}}(B)$ without application of differential methods. We fit the first two terms of Barker's formula [12] to the observed MP oscillations. To get good convergence we have to restrict the magnetic field range somewhat below $N=1$. Fig. 2 shows the fit matches the experimental points at best. Our result of the fit for the fundamental field $B_0(T)$ is displayed in Fig. 3, upper part. The next step is the correction for the nonparabolicity. The procedure, as used with InP [4] and GaAs [5], does not work above 260 K. We assume the reason being the spin split off energy Δ_0, which cannot be neglected relative to the band gap E_g . We follow the procedure of Ref. [3]. The result is an NP corrected effective mass. Those values were taken to calculate the NP corrected fundamental field, plotted in Fig. 3. To get m_0^* we applied the polaron correction, as taken by Ref. [3]. Fig. 4 shows the result compared with earlier work. The change in mass behaves parallel to the results of Ref. [3] and is nearly in accordance with

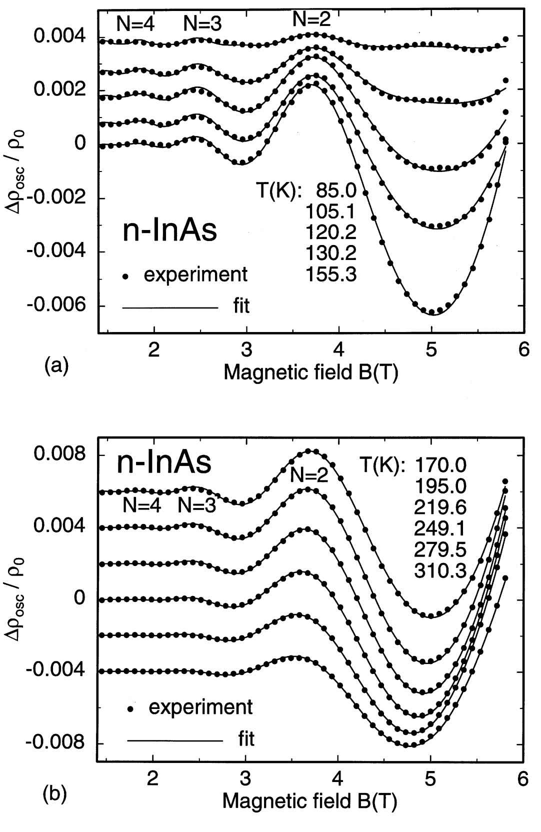

Fig. 2. MP oscillations $\Delta\rho_{\text{osc}}(B)$ for InAs, separated from total magnetoresistance $\rho(B)$ and normalized to the zero field value ρ_0. Only one out of ten measurement points and only eleven out of 53 measured curves at constant temperatures between $T=64$ and 359 K are reproduced, together with the fitted line. Most of the curves are shifted from zero.

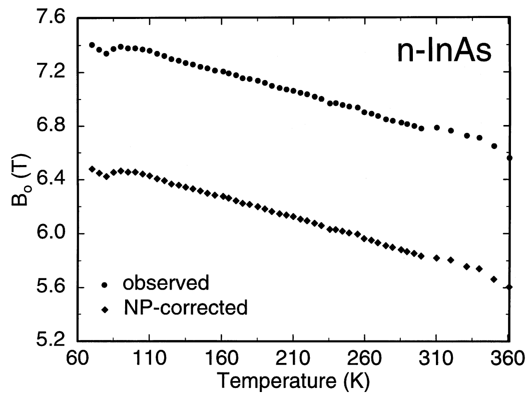

Fig. 3. Fundamental resonance field $B_0(T)$ for MP oscillations in InAs, extracted from the experiment by fit of the relation by Barker [12] (upper part) and after applying nonparabolicity correction (lower part).

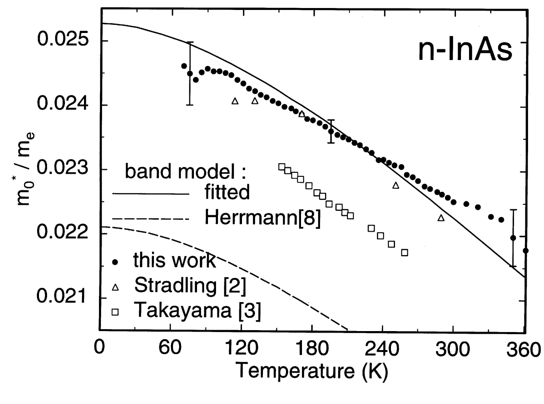

Fig. 4. Temperature dependence of the effective mass m_0^* of the conduction electrons at the band edge Γ_6^C, as deduced from MP magnetoresistance measurements, compared to earlier work [2,3]. Dashed line gives the result of a 5-band calculation after [8] and full line shows our result of the fit with 3-band calculation [7].

Ref. [2]. However in Ref. [2] the measured B_0 as well as the estimated $\omega_{L0}(T)$ values are both higher, which compensate each other, if m_0^* is determined. The curves are calculated from different approximations of the band model, including the change of band gap E_g with temperature. We describe $E_g(T)$ by the Varshni relation $E_g(T) = E_{g0} - \alpha T^2/(\beta + T)$, with parameters ($E_{g0} = 0.41$ eV; $\alpha = 3.35 \times 10^{-4}$ eV/K; $\beta = 248$ K), taken from Ref. [13]. If only the dilational change in energy gap or the optical energy gap is taken into account the change in effective mass becomes too small respectively to large [1,3]. We fitted the Kane kp-model and receive $E_{g0} = 0.41$ eV; $\Delta_0 = 0.39$ eV and $P^2 = 19.6$ eV. If we take $P^2 = 21.0$ eV, this model shows no difference in $m_0^*(T)$ to the 5-band calculation for InAs as worked out by Ref. [10] and shown in Fig. 4 (dashed line) below the experimental findings.

Acknowledgements

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