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# Effective electron mass in GaAs/$Al_xGa_{1-x}As$ heterostructures under hydrostatic pressure

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**Abstract.** We have determined the effective electron mass in a GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure from the temperature dependence of the amplitude of the Shubnikov–de Haas oscillations. The effective mass is expected to increase with increasing electron concentration due to the non-parabolicity of the conduction band. The effective mass will also increase when we apply a hydrostatic pressure. We evaluated the effective mass in our sample at different electron concentrations and different hydrostatic pressures and have shown that the experimental values fit very well with the theoretically predicted values.

## 1. Introduction

The electronic properties of GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructures can be influenced by the application of hydrostatic pressure. This hydrostatic pressure changes all the electronic states in the GaAs and AlGaAs. A consequence of this change of the electronic states is the increase of the bandgap and a decrease of the 2D electron gas concentration with increasing pressure [1]. With the increase of the bandgap the effective electron mass ($m^*$) at the bottom of the $\Gamma$ band also increases. The effective electron mass can be determined from cyclotron resonance measurements or by magnetophotoluminescence experiments as has been done by Zhou *et al* [2] in GaAs/AlGaAs quantum wells. From their measurements they found a much larger pressure dependence of the effective mass, $dm^*/dp$, than theoretically predicted by $\boldsymbol{k}\cdot\boldsymbol{p}$ theory. Chaubet *et al* [3], in contrast, found in a GaAs/AlGaAs heterostructure a slightly smaller $dm^*/dp$ than the calculated value. They explained the discrepancy by assuming the pressure dependence of the electron concentration in their model: the effective mass changes due to the non-parabolicity of the conduction band. Lo *et al* [4] measured the effective electron mass from the temperature dependence of the amplitude of the Shubnikov–de Haas (SdH) oscillations for the lowest two subbands and found almost the same values for both subbands. In this paper we report measurements of the effective mass in a GaAs/AlGaAs heterostructure determined from the temperature dependence of the amplitude of the SdH oscillations. The effective electron mass is determined as a function of both hydrostatic pressure (at a constant electron concentration) and the electron concentration (at zero pressure). The electron concentration was kept constant by making use of the persistent photoconductivity (PPC) effect to compensate for the decrease of the electron concentration with increasing pressure.

## 2. Experiments

The sample we used is a high-carrier-density GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure grown by molecular beam epitaxy (MBE). On top of the [001] semi-insulating GaAs substrate we have grown a 4 $\mu$m undoped GaAs layer, followed by a 100 Å undoped $Al_{0.33}Ga_{0.67}As$ layer, a 500 Å n-doped $Al_{0.33}Ga_{0.67}As$ layer ($3.05 \times 10^{18}$ $cm^{-3}$ Si) and a 170 Å undoped GaAs cap layer. The samples were shaped into Hall-bar geometries using standard lithographic techniques. This resulted in a 2DEG with an electron concentration of $5 \times 10^{11}$ $cm^{-2}$ and a mobility of 96.000 $cm^2\ V^{-1}\ s^{-1}$ in the dark and an electron concentration of $10.8 \times 10^{11}$ $cm^{-2}$ and a mobility of 139.600 $cm^2\ V^{-1}s^{-1}$ after illumination at a temperature of 4.2 K.

The sample was mounted in a liquid pressure cell, suitable for pressures up to 10 kbar at liquid helium temperature. The pressure was always applied at room temperature before cooling down. The electron concentration in the sample will decrease if we increase the applied hydrostatic pressure. To be able to perform measurements at a constant electron concentration we made use of the PPC effect. The measurements at zero

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pressure were performed without illuminating the sample. At higher pressures we illuminated the sample with short pulses of red light, using a LED mounted inside the pressure cell, until the electron concentration reached the zero-pressure value. After each flash we waited a few minutes to let the electron concentration stabilize. When the desired electron concentration was reached, we measured the magnetoresistance at different temperatures in a range from 1.1 K to 10 K. The oscillatory magnetoresistance $\Delta\rho$ for a particular subband ($i$) can be expressed by [5]:

$$\Delta\rho/\rho_0 = \frac{X}{\sinh X}\exp(-\pi/\mu_q B)\cos\left(2\pi\frac{E_F - E_i}{\hbar\omega c_i} - \phi\right) \quad (1)$$

where $\rho_0$ is the zero-field resistivity, $\mu_q$ is the quantum mobility, $B$ the magnetic field, $\hbar\omega_c$ = the energy separation of the Landau levels, $E_i$ is the energy of the $i$th subband, $E_F$ is the Fermi energy with respect to the bottom of the well, $\phi$ is a phase constant and $X = 2\pi kT/\hbar\omega_c$. The factor $X/\sinh X$ in equation (1) describes the temperature dependence of the amplitude of the SdH oscillations. A typical experimental trace of the SdH signal is shown in figure 1. At a fixed magnetic field, $X/\sinh X$ is only dependent on the temperature and the effective mass $m^*$, assuming that the quantum mobility is not temperature dependent. This will be the case because remote impurity scattering is the limiting scattering mechanism in this temperature regime and the Hall mobility is known to be independent of temperature at low temperatures. The mean scattering angle is not likely to change, therefore the quantum mobility will also be temperature independent. At a given magnetic field we can plot the ratio of the amplitudes $A(T)$ of the SdH oscillations at two temperatures ($T$) and fit this with

$$\frac{A(T)}{A(T_0)} = \frac{T\sinh(\beta T_0/B)}{T_0\sinh(\beta T/B)} \quad (2)$$

using $m^*$ as a fitting parameter. The result of such a fitting with amplitudes at eight temperatures is shown in figure 2. This method gives a very accurate value of the

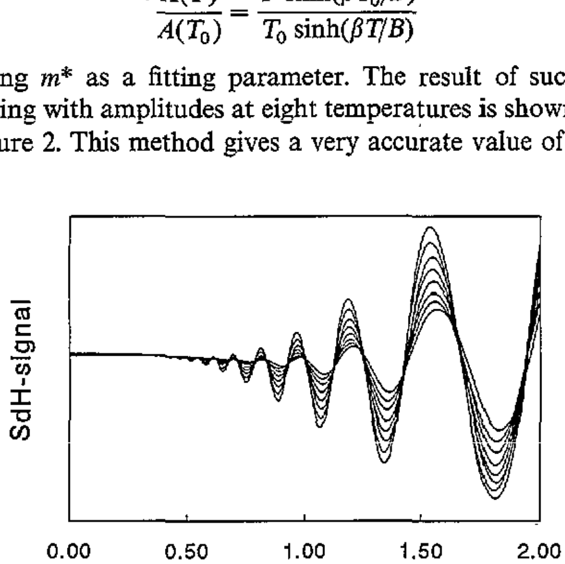


**Figure 1.** Shubnikov–de Haas oscillations at different temperatures. The measurements were performed at a pressure of 7.5 k bar, with an electron concentration of $5 \times 10^{11}$ cm$^{-2}$. The different curves represent measurements carried out at temperatures of 4.2, 3.8, 3.5, 3.0, 2.7, 2.4, 1.7 and 1.1 K.

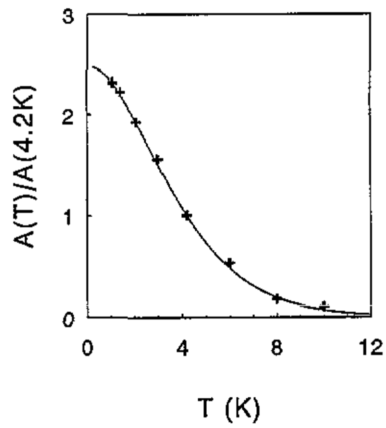


**Figure 2.** Amplitude of the Shubnikov–de Haas oscillations versus the temperature measured at an electron concentration of $5 \times 10^{11}$ cm$^{-2}$ and at zero pressure. The full curve gives the fit with an effective mass of $0.069m_0$.

effective mass. If the two subbands are occupied, which manifests itself by a second period in the SdH oscillations, we use a digital Fourier bandpass filter to remove the second subband oscillations.

## 3. Results and discussion

Figure 3 shows the effective mass without pressure at an electron concentration of $5 \times 10^{11}$ cm$^{-2}$ in the dark and at $10 \times 10^{11}$ cm$^{-2}$ after illumination. The effective mass increases with increasing electron concentration due to the non-parabolicity of the Γ-conduction band. Figure 4 shows the pressure dependence of the effective mass keeping the electron concentration constant. This figure shows clearly the pressure dependence of the effective mass: the effective mass increases with a slope $(dm^*/m)/dP = 4.4 \times 10^{-4}$ kbar$^{-1}$.

The enhancement of the effective mass due to the non-parabolicity can be described theoretically [6] by

$$\frac{\Delta m^*}{m^*} \simeq \left(1 + 4\frac{\langle K_0\rangle + E_F}{E_g}\right)^{1/2} - 1 \quad (3)$$

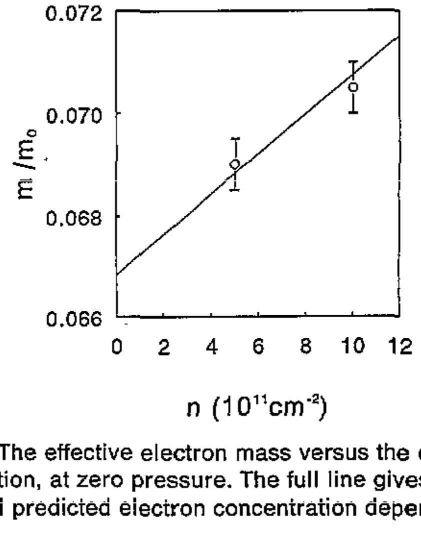


**Figure 3.** The effective electron mass versus the electron concentration, at zero pressure. The full line gives the theoretical predicted electron concentration dependence.

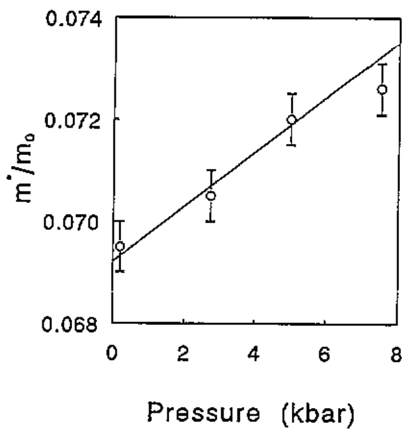


**Figure 4.** The hydrostatic pressure dependence of the effective mass. The full line represents the theoretical predicted pressure dependence ($n = 5 \times 10^{11}$ cm$^{-2}$).

where $\Delta m^*$ is the enhancement of the effective mass, $m^*$ is the effective mass at the bottom of the band, $E_g$ is the bandgap for the $\Gamma$ band ($1.520 + 0.0115p$ eV) and $\langle K_0 \rangle$ the expectation value of the kinetic energy. In a triangular potential the expectation value of the kinetic energy $\langle K_0 \rangle = E_i/3$, where $E_i$ is the energy of the $i$th subband with respect to the bottom of the conduction band. If we use variational wavefunctions the value of $\langle K_i \rangle$ will be smaller than $E_i/3$, and will depend on the depletion charge in the GaAs. In figure 3 the full line gives the calculated effective masses, when we assume a very reasonable depletion charge of $0.6 \times 10^{11}$ cm$^{-2}$. The change of the depletion charge due to the neutralization of the acceptors in the GaAs results in a negligible change in the effective mass ($0.0703\ m_0$ instead of $0.0705\ m_0$ at $n = 10 \times 10^{11}$ cm$^{-2}$ and zero pressure). Experiment and theory match within the accuracy of the measurements.

We also calculated the pressure dependence of the effective mass. Warburton *et al* [7] showed that the relative change of the effective mass is the same as the relative change of the bandgap. This leads, together with equation (3), to

$$m^*(p) = m^*(0)\frac{E_g(p)}{E_g(0)}\left(1 + 4\frac{\alpha E_i + E_F}{E_g}\right)^{1/2} \qquad (4)$$

where $\alpha$ is $\langle K_i \rangle / E_i$. The full line in figure 4 shows the calculated pressure dependence of the effective mass, using variational wavefunctions [8. 9] and a depletion charge of $0.6 \times 10^{-11}$ cm$^{-2}$. This figure shows a good agreement between experiment and theory.

## 4. Conclusions

The effective electron mass in GaAs/$Al_xGa_{1-x}As$ heterostructures has been determined from the temperature dependence of the SdH oscillations. The observed increase of the effective mass with increasing hydrostatic pressure at a fixed electron concentration agrees very well with theory. We also showed experimentally the influence of the electron concentration on the effective mass.

## Acknowledgment

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**Note.** A recent publication [7], appearing after this work was completed, deals with the same subject, i.e. the pressure dependence of the effective electron mass, determined from cyclotron resonance experiments, whereas our experimental results are obtained from Shubnikov–de Haas studies. Our results, as far as the pressure dependence of the effective electron mass are concerned are perfectly in agreement with those of Warburton *et al.*

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