Solid State Communications, Vol. 79, No. 12, pp. 1039-1042, 1991.
Printed in Great Britain.

0038-1098/91$3.00+.00
Pergamon Press plc

HIGH FIELD CYCLOTRON RESONANCE AND THE ELECTRON EFFECTIVE MASSES IN AlAs

N. Miura, H. Yokoi, J. Kono and S. Sasaki

Institute for Solid State Physics, University of Tokyo,
Roppongi, Minato-ku, Tokyo 106, Japan

(Received on 30 July 1991 by H. Kamimura)

Abstract

We have measured far-infrared cyclotron resonance in n-type AlAs in pulsed high magnetic fields up to 150T. At a wavelength of 119μm, a prominent resonance peak was observed at 42T corresponding to the heavy effective mass of $\sqrt{m_t^* m_l^*} = 0.47 \pm 0.01 m_0$ on the ellipsoidal equienergy surface at the X-point. Also observed a shoulder-like structure centered at 22T. Assigning it to the light effective mass m_t^*, the effective masses were determined as $m_t^*=0.25\pm0.01m_0$ and $m_l^*=0.88\pm0.06m_0$.

The importance of AlAs has been increasing as an electronic material for barrier layers in quantum wells, superlattices and heterostructures incorporated with GaAs. It is well known that AlAs is an indirect semiconductor which has conduction band minima near the X-points[1]. However, neither its band parameters nor the carrier effective masses have been accurately determined, because of the difficulty in growing good quality single crystals and of the low carrier mobility. Due to the lack of accurate data of the effective masses, only theoretical values [2] or the values obtained from an indirect method such as the Faraday rotation[3] have been employed for the effective masses in analyses of the GaAs-AlAs or GaAs-AlGaAs 2-dimensional electron systems.

In III-V compounds, there is a possibility that the conduction band minina may have a "camel's back struture" due to the lack of inversion symmetry[4]. The camel's back structure has been actually observed in the conduction band minima near the X-point in GaP[5]. Bimberg *et al.* have reported that their experimental results of the luminescence spectra in $Ga_{0.08}Al_{0.92}As$ can be explained only by taking account of the camel's back structure[6]. In case of the camel's back structure, the effective mass should exhibit an unusual nonparabolicity[4,5]. Detailed investigation of the conduction band in AlAs is of interest also from such a viewpoint.

The recent development of the techniques for producing ultra-high magnetic fields has opened up many new possibilities in solid state physics[7]. Particularly in the viewpoint of cyclotron resonance, it has extended the range of low mobility materials on which we can study by means of cyclotron resonance, because the condition $\omega_c\tau > 1$ can easily be satisfied. By using the single-turn coil technique, we can apply very high magnetic fields up to a few megagauss to samples without destroying them[8]. In this paper, we report the first observation of the cyclotron resonance in the conduction band of n-type AlAs in ultra-high magnetic fields up to 150T produced by the single-turn coil technique.

An epitaxial AlAs thin single crystal was grown on semi-insulating GaAs substrates with < 100 > surfaces by Horikoshi's group of NTT using the MBE technique. The thickness of the epitaxial layer was 5μm. Si was doped to the concentration of 5.0×10^{16}cm^{-3}. On top of the AlAs layer, an undoped GaAs cap layer of 15nm thick was grown for protecting the deliquescent AlAs layer.

The block-diagram of the experimental apparatus is shown in Fig. 1. Pulsed high magnetic fields up to 150T were produced by the single-turn coil technique. The fields were produced by supplying short large current pulses of about 2.5MA to thin single turn coils from a fast capacitor bank with a storing energy of 100kJ at 40kV. The pulse duration was about 7μs. The single-turn coils were made from copper plates with a thickness of 3mm. Both the bore diameter and the length of the coils were 10mm. The magnetic field was measured by a pick-up coil wound on the samples. The error of the field measurement was less than 3% [9]. The cyclotron reso-

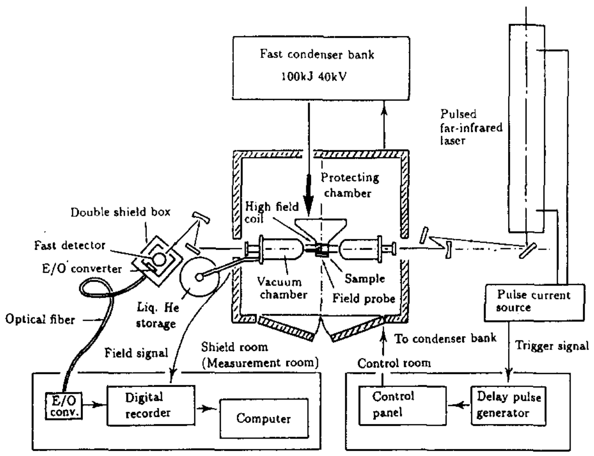

Fig.1 Block-diagram of the experimental set-up for measuring cyclotron resonance in ultra-high magnetic fields in the megagauss range using the single-turn coil technique.

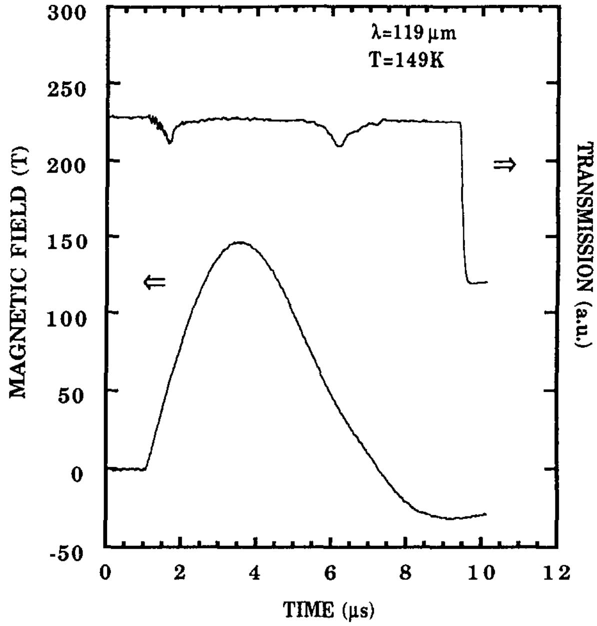

Fig.2 Recorder traces of the magnetic field pulse and the transmitted radiation by the sample. The temperature was 149K.

nance was measured by using a pulsed H_2O laser with a wavelength of 119μm, synchronized with the magnetic field pulse. The pulse duration of the laser was about 100μs. The intensity of the radiation was almost constant during the magnetic field pulse. As a far-infrared detector, we used the extrinsic photoconductivity of Ga-doped Ge cooled to liquid He temperatures. The response time of the detector was fast enough to detect the cyclotron resonance even in the short pulse fields. The magnetic field pulse and the signal from the detector were recorded by digital recorders[10]. By using a liquid flow-type cryostat, temperature of the samples was varied in the range between about 4K and room temperature.

Figure 2 shows an example of the recorder traces of the field pulse and the transmitted radiation from the sample. The resonance absorptions are observed twice in one pulse in the rising and falling slopes of the magnetic field. The coincidence of the two traces ensured a sufficiently fast response of the detector system and the accuracy of the measurement. In Fig. 3, the cyclotron resonance spectra at various temperatures for different polarizations of the incident radiation.

A broad but prominent absorption peak of cyclotron resonance was observed at 42T for the electron active circular polarization σ_e or linear polarization L. A very small absorption was observed for the opposite circular polarization σ_h at the same position. From the resonance field position, the effective mass was obtained as 0.47±0.01m$_0$. A shoulder-like structure was also observed at around 22T in the low field side of the most prominent peak. A small abosorption peak at about 6T is ascribed to the cyclotron resonance of the GaAs cap layer. The position of the resonance peak at 42T did not show descernible temperature dependence, but the peak intensity had a maximum at about 150K. At room temperature, the peak becomes very broad due to the decrease of the mobility, whilst at temperatures below about 30K, the resonance becomes very weak due to the carrier freeze-out.

The value of $\omega_c\tau$ was estimated as 3.1 at 145K, leading to a mobility of 7.3×10^2cm^2/Vs. When we tilted the

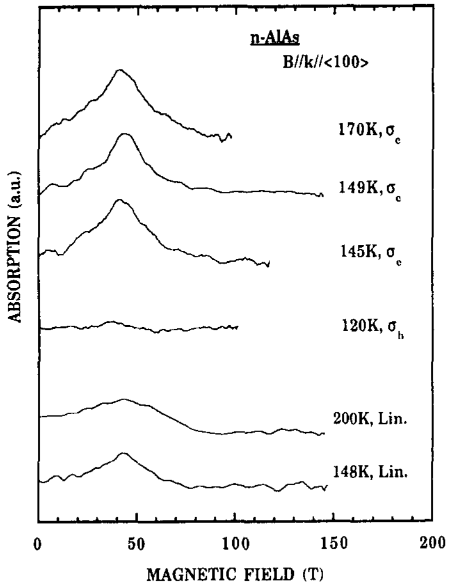

Fig.3 Cyclotron resonance absorption spectra in AlAs at various temperatures and different incident radiation polarizations. The wavelength of the radiation was 119μm.

angle between the magnetic field and the normal of the sample by several degrees, the peak position shifted to a lower field. This suggests that the observed peak is due to the cyclotron resonance corresponding to the heavier mass $\sqrt{m_t^* m_l^*}$ of the ellipsoidal equienergy surface at the X-minima. In order to obtain m_t^* and m_l^* separately, we need to know the value of m_t^*. Resosnance peaks corresponding to the lighter mass m_t^* have not been observed as a separate peak. However, the shoulder-like structure on the lower field side of the main peak is considered to be due to the cyclotron resonance corresponding to the lighter mass m_t^*. In order to separate the peaks, we decomposed the absorption spectra for the σ_e polarization to a sum of Lorentzian curves as shown in Fig. 4.

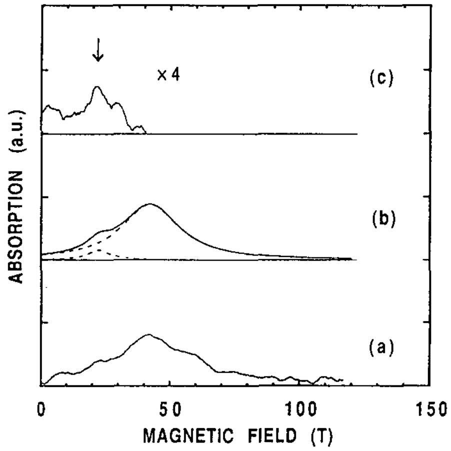

Fig.4 Decomposition of the cylotron resonance absorption spectra for σ_e polarization into two Lorentzian resonance curves. (a) Experimental curve at 145K. (b) Two Lorentzian resonance curves for light and heavy effective masses, m_t^* and $\sqrt{m_t^* m_l^*}$ (dashed curves), and their sum (solid curve). The assumed parameters are m_t^*=0.25m$_0$, $\sqrt{m_t^* m_l^*}$=0.47m$_0$, $\omega_c\tau(m_t^*) = 4.2$, and $\omega_c\tau(\sqrt{m_t^* m_l^*}) = 3.1$. (c) The experimental curve after subtracting the theoretical curve of the resonance for $\sqrt{m_t^* m_l^*}$.

Subtraction of the resonance curve for $\sqrt{m_t^* m_l^*}$ yields a well-defined peak at around 22T as demonstrated in Fig. 4(c). On the other hand, the sum of the two Lorentzian curves (b) reproduces the experimental curve (a), their agreement being excellent. By such an analysis the effective mass m_t^* was obtained as 0.25±0.01m$_0$.

From these values, the electron effective masses of AlAs are determined as $m_t^* = 0.25 \pm 0.01$m$_0$, and m_l^*= 0.88±0.07m$_0$. The effective masses of the electrons reported in previous papers are listed in Table 1, together with the present results. The value of the effective mass $\sqrt{m_t^* m_l^*}$ = 0.47m$_0$ obtained in the present work is considerably smaller than the value $\sqrt{m_t^* m_l^*}$ = 0.55m$_0$ reported by Maezawa *et al.*[11] from the temperature dependence of the Shubnikov-de Haas effect, but is cole to the value $\sqrt{m_t^* m_l^*}$ = 0.46m$_0$ reported by Rheinländer *et al.* from the Faraday rotation experiment[3].

It should be noted that the anisotropy factor $K = m_l^*/m_t^*$ of AlAs obtained in the present study is significantly smaller than for GaP[5] which has also conduction band minima near the X-point. This suggests that the effect arising from the camel's back structure is small. However, more experiments with different photon energies are required to clarify the more details of the conduction band structure, including the problem whether the camel's back sturucture really exists in AlAs or not. The photon energy used in the present experiment 10.4meV is considerably smaller than the LO phonon energy in AlAs 50.2meV[12]. Therefore, the polaron pinning effect should be small.

The present results provide the first data of the direct measurement of the effective masses and will increase the accuracy of various arguments concerning the quantum wells and superlattices based on the GaAs-AlAs system.

Acknowledgment

The authors are obliged to Dr. Y. Horikoshi and Dr. Saku of NTT Musashino Electrical Communication Laboratories for providing them with the high quality AlAs crystals.

Table 1 Effective masses in the conduction band of AlAs so far reported (in units of m$_0$)

Reference	m_t^*	m_l^*	$\sqrt{m_t^* m_l^*}$	$K = m_l^*/m_t^*$	Method
Rheinländer *et al.*[3]	0.19	1.1	0.46	5.8	Faraday rotation
Maezawa *et al.*[11]			0.55±0.05		Shubnikov-de Haas effect
Hess *et al.*[2]	0.24	1.48	0.60	6.2	Theory
Present results	0.25±0.01	0.88±0.07	0.47 ± 0.01	3.5±0.4	Cyclotron resonance

References

1. D. J. Stukel and R. N. Euwena, Phys. Rev. **188**, 1193 (1969).
2. E. Hess, I. Topol, K. R. Schulze, H. Neumann and K. Unger, Phys. Status Solidi (b) **55**, 187 (1973).
3. B. Rheinländer, H. Neumann, P. Fischer and G. Kühn, Phys. Stat. Sol. (b) **49** K167 (1972).
4. P. Lawaetz, Solid State Commun. **16** 65 (1971).
5. N. Miura, G. Kido, M. Suekane and S. Chikazumi, J. Phys. Soc. Jpn. **52**, 2838 (1983).
6. D. Bimberg, W. Bludau, R. Linnebach and E. Bauser, Solid State Commun. **37**, 987 (1981).
7. N. Miura, T. Goto, K. Nakao, S. Takeyama, T. Sakakibara, T. Haruyama and T. Kikuchi, Physica B **155**, 23 (1989).
8. K. Nakao, F. Herlach, T. Goto, S. Takeyama, T. Sakakibara, and N. Miura, J. Phys. E Sci. Inst. **18**, 1018 (1985).
9. G. Kido, N. Miura, K. Kawauchi, I. Oguro and S. Chikazumi, J. Phys. E Sci. Instrum. **9**, 587 (1976).
10. H. Yokoi, S. Takeyama, N. Miura and G. Bauer, *Proc. 20th Int. Conf. Phys. Semiconductors*, eds. E. M. Anastassakis and J. D. Joannopoulos (World Sci. Pub., 1990) p.1779.
11. K. Maezawa, T. Mizutani and S. Yamada, *Institute of Physics Conference Series, No. 112*, p.515 (1990).
12. A. Onton, *Proc. 10th Int. Conf. Phys. Semiconductors*, eds. S. P. Keller, J. C. Hensel and F. Stern, (US Atomic Energy Commission, 1970), p.107.