RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 32, NUMBER 12 15 DECEMBER 1985

Optically detected cyclotron resonance in a $GaAs/Ga_{0.67}Al_{0.33}As$ superlattice

B. C. Cavenett* and E. J. Pakulis

IBM Thomas J. Watson Research Center, P. O. Box 218, Yorktown Heights, New York 10598

(Received 9 October 1985)

Cyclotron resonance has been optically detected in a $GaAs/Ga_{0.67}Al_{0.33}As$ superlattice with the wells doped with Si to 6×10^{16} cm^{-3}. The sign and magnitude of the signal depend on the emission monitored, and an effective mass of $0.062m_0$ was obtained for the electrons. Because of the low magnetic field needed at 22 GHz for cyclotron resonance, the confinement of the orbits is readily observed.

The optical detection of cyclotron resonance (ODCR) was first observed in Ge by Baranov *et al.*[1] and then by Romestain and Weisbuch[2] in GaAs and CdTe. This indirect method for observing cyclotron resonance involves the monitoring of microwave-induced changes in the luminescence intensity in analogy with optically detected magnetic resonance (ODMR).[3] In fact, the interaction of the carriers with the microwave electric field can contribute to very broad nonresonant signals which are often observed in ODMR experiments and referred to as background signals, but no detailed investigation of the mechanisms has been carried out. ODCR is of particular interest in the case of semiconductor multilayers as a means of characterizing the carriers localized in the quantum wells of a superlattice, and Romestain and Weisbuch[2] have pointed out the importance of the optical technique at the low magnetic field limit of resonance since the condition $\omega_c\tau > 1$ is more easily obtained because of light-induced impurity neutralization. In the case of superlattices, the low-frequency measurements are of considerable interest, since the cyclotron orbits can be much larger than the well dimensions. In fact, in the present paper we report the first observation of ODCR in a superlattice, and the confinement of the cyclotron orbits is observed as the magnetic field is rotated away from the normal to the multilayers.

The ODCR was carried out at 22 GHz using an Oxford Instruments split coil magnet system. The sample was placed in a TE_{011} cylindrical microwave cavity, and luminescence was excited with a He-Ne laser. The signals were monitored with a cooled Ge detector and analyzed with a 0.25-m monochromator. The signals could be observed either with cw or chopped microwaves. The sample was grown by molecular beam epitaxy and consisted of 16 180-Å-thick GaAs wells separated by 230-Å $Ga_{0.67}Al_{0.33}As$ barriers. The GaAs layers were doped with 6×10^{16}-cm^{-3} Si donors, and the sample showed an intense recombination emission, consisting of at least two components, at 1.524 eV and many transitions at longer wavelengths, as shown in Fig. 1(a). The nonresonant microwave-induced change, ΔI_{nr}, in the luminescence appears in Fig. 1(b), and it can clearly be seen that the sign of the signal depends on the emission being monitored. At the main luminescence peak the nonresonant microwave-induced change amounts to a 13% decrease of the luminescence intensity, for 100 mW of microwave power incident on the cavity.

The ODCR signal for the magnetic field B normal to the layers of the multiple-quantum-well (MQW) structure is the curve labeled 0° in Fig. 2. This signal was obtained for the 1.524-eV emission, which corresponds to monitoring the minimum of the curve in Fig. 1(b) (see arrow). The cyclotron resonance induces a resonant increase in this luminescence. A similar cyclotron resonance signal can also be observed for the 1.528-eV emission, corresponding to monitoring the maximum of the curve in Fig. 1(b), but there the cyclotron resonance induces a resonant decrease in the luminescence. The resonant change amounts to 19% of the nonresonant microwave-induced signal, or 2.5% of the luminescence intensity. From the position of the resonance we can deduce an effective mass for the electrons in the wells of $(0.062\pm0.007)m_0$, which is comparable to the bulk effective mass of $0.067m_0$. Our result for the effective mass is in agreement with infrared cyclotron resonance measurements on thick quantum wells.[4] Due to the thickness of the wells, we do not observe any increase in the effective mass caused by nonparabolicity of the conduction band, as reported in Ref. 5.

The confinement of the cyclotron orbits to the plane of the GaAs layer is also illustrated in Fig. 2 by the shift in the ODCR signal as the angle θ between the normal to the

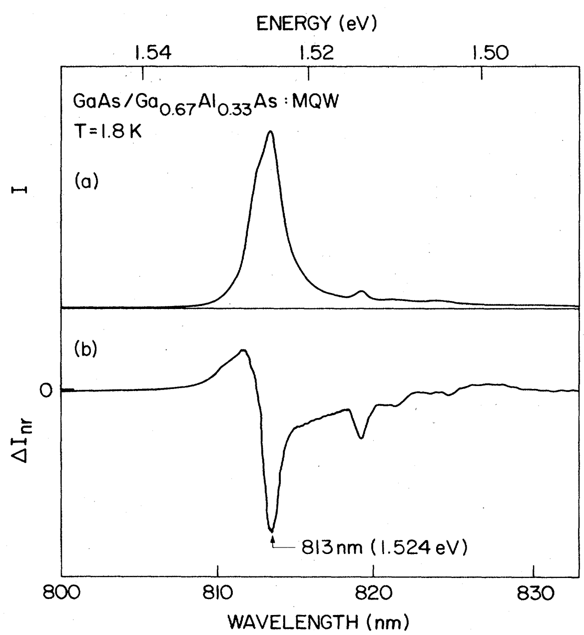

FIG. 1. (a) Luminescence intensity as a function of wavelength. (b) Nonresonant microwave-induced change in luminescence with no applied magnetic field.

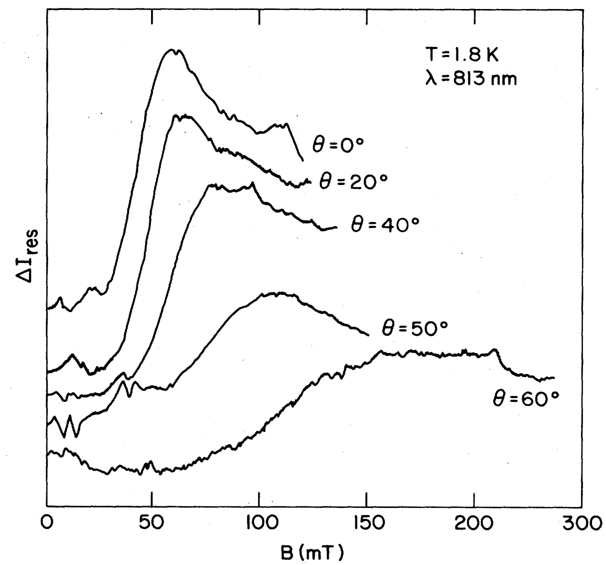

FIG. 2. ODCR for different angles θ between the magnetic field and the normal to the MQW layers.

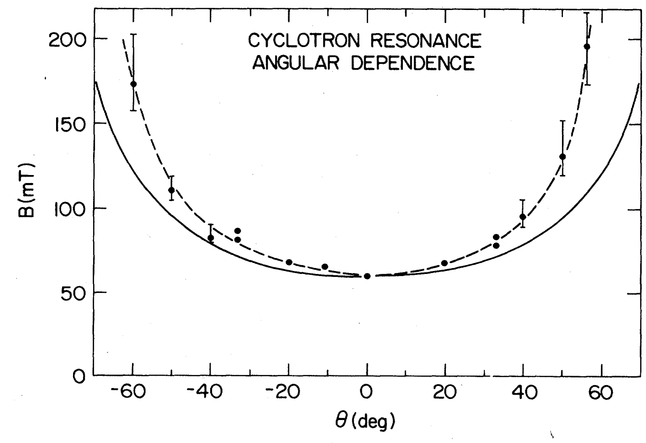

FIG. 3. Angular dependence of the cyclotron resonance peak position. Solid curve is calculated based on a cosθ dependence.

MQW structure and the magnetic field direction is varied. This dependence cannot be followed beyond $\theta = 60°$, since already at that angle the resonance has broadened considerably. The peak positions have been plotted as a function of θ (dashed curve) in Fig. 3, where the solid curve follows the cosθ dependence which would be expected if the cyclotron orbits sampled only the component of B normal to the MQW layers. The deviation in Fig. 3 of the data from the cosθ dependence appears to be larger than the estimated uncertainty in the data points indicated by the error bars, so this result merits further investigation. One possible explanation is an effective mass which increases with tilt angle.

To our knowledge, all previous measurements of cyclotron resonance in $GaAs/Ga_xAl_{1-x}As$ heterostructures have been carried out in the far-infrared spectral region (~ 100–200 μm),[4,5] where the cyclotron orbit is typically smaller than the width of the quantum wells. However, the observation at 22 GHz reported in this paper corresponds to the resonance of carriers in cyclotron orbits of radius $\geqslant 1100$ Å, which is six times larger than the well width. This means that the ODCR signal is very dependent on the angle θ as shown in Fig. 3, and so the results are analogous to Shubnikov–de Haas oscillation measurements which also show this dependence.

The occurrence of ODCR in semiconductors has been attributed by Romestain and Weisbuch[2] to microwave heating of the carriers. In the present investigation we must consider first the nonresonant effect of the microwaves on the luminescence [Fig. 1(b)], and then the effect of cyclotron resonance. Extrinsic recombination processes in MQW's have been investigated in detail by numerous authors,[4,6–8] and it is generally agreed that the emission consists of free-exciton transitions at the highest energy and donor-bound-exciton emissions a few meV lower in energy. Two transitions are partially resolved in the present measurement of the luminescence [Fig. 1(a)], and can also be distinguished in Fig. 1(b), because of the different effect of the microwaves on each transition. In the latter case, because of the position and shape of the higher-energy band, we suggest that it includes not only the free-exciton emission (electron→ heavy holes) but also one or more unresolved nearby transitions (for example, transitions involving light holes rather than heavy holes). The lower energy emission at 1.524 eV we attribute to the donor bound exciton. The fact that the microwaves increase the free-exciton emission at the expense of the bound exciton is consistent with microwave ionization of the donor bound exciton. Cyclotron resonance absorption of microwaves by the electrons then reduces the microwave field available for the ionization of the bound excitons, thus decreasing the free-exciton emission and increasing the bound-exciton emission. This is exactly opposite what would be expected for a microwave-heating ODCR effect. Resonant heating would result in a further increase in the signal of Fig. 1(b), and the cyclotron resonance signals would be an increase of the free-exciton emission and a decrease of the bound-exciton emission, contrary to the observed results.

In summary, we have observed cyclotron resonance in a $GaAs/Ga_{0.67}Al_{0.33}As$ MQW using optical detection. The doping of the GaAs wells results in both free- and bound-exciton emission, and the different sign of the microwave effect on each distinguishes these transitions. Cyclotron resonance at microwave frequencies has allowed us to examine the case where the cyclotron orbit is much larger than the well width, and deviations from the expected angular dependence were found. The optical method for detecting cyclotron resonance should also be a sensitive method for investigating intrinsic MQW's.

The authors are grateful to M. Heiblum for growing the MQW structure. B.C.C. wishes to thank M. Brodsky and F. Fang for support and encouragement while visiting IBM.

*Permanent address: Department of Physics, University of Hull, Hull, North Humberside, United Kingdom.

[1]P. G. Baranov, Yu. P. Veshchunov, R. A. Zhitnikov, N. G. Romanov, and Yu. G. Shreter, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 369 (1977) [JETP Lett. **26**, 249 (1977)].

[2]R. Romestain and C. Weisbuch, Phys. Rev. Lett. **45**, 2067 (1980).

[3]B. C. Cavenett, Adv. Phys. **30**, 475 (1981).

[4]B. V. Shanabrook, *Proceedings of the Thirteenth Yamada Conference on Electronic Properties of Two-Dimensional Systems, Kyoto, Japan, 1985* [Surf. Sci. (to be published)].

[5]H. L. Stormer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. **29**, 705 (1979).

[6]R. C. Miller, A. C. Gossard, W. T. Tsang, and O. Munteanu, Phys. Rev. B **25**, 3871 (1982).

[7]B. Lambert, B. Deveaud, A. Regreny, and G. Talalaeff, Solid State Commun. **43**, 443 (1982).

[8]D. C. Reynolds, K. K. Bajaj, C. W. Litton, P. W. Yu, W. T. Masselink, R. Fischer, and H. Morkoc, Phys. Rev. B **29**, 7038 (1984).