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Microwave and far-infrared induced optically detected cyclotron resonance in epitaxial InP and GaAs

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A comparative study of optically detected cyclotron resonance in the microwave and far-infrared frequency range in epitaxial InP and GaAs is presented. The electron cyclotron resonances and the inter-impurity $1s$-to-$2p^+$ transitions are observed in both high-mobility layers. Cyclotron-resonance-induced impact ionization of shallow donors and bound excitons is the basic mechanism for the observation by photoluminescence.

As one variety of optically detected magnetic resonance, optically detected cyclotron resonance (ODCR) using microwaves has become a powerful analytical technique in recent years.[1–5] In addition to determining band masses of electrons and of light and heavy holes in one experiment, ODCR provides the ability to determine scattering times and, thus, the mechanism of scattering processes at low temperatures in ternary and quaternary alloys. In a recent experiment using 9-GHz microwaves Wang, Monemar, and Ahlström[6] studied the influence of microwave modulation on the photoluminescence (PL) properties of epitaxial GaAs. They concluded that impact ionization gives rise to selective quenching and enhancement of the different radiative contributions in PL allowing for the detection of cyclotron resonance (CR). To observe the ODCR signal, $\omega\tau$ must be greater than 1, where ω is the frequency and τ the scattering time. This condition is usually not fulfilled in the microwave region below 30 GHz. By extending the experiments to far-infrared radiation (FIR) instead of microwaves, the resolution of ODCR can be greatly enhanced (i.e., $\omega\tau$ scaled by a factor of about 200). Quite recently, Wright *et al.*[7] observed ODCR in GaAs using the FIR technique, but stated that the detection mechanism is far from clear. One motivation for this investigation is, therefore, to gain further insight into the detection mechanism by studying ODCR on epitaxial GaAs and InP in the microwave and FIR range.

In this paper we report the observation of optically detected electron cyclotron resonance and interimpurity cyclotron absorption ($1s$-$2p^+$) in high-mobility InP using far-infrared detection. By a comparison with experiments performed at microwave frequencies we conclude that cyclotron-resonance impact ionization of shallow donors and bound excitons is the basic mechanism to generate the ODCR signals. Our experiments are in close agreement with impact-ionization studies using dc electrical fields.[8,9]

PL spectrally dispersed by a SPEX single monochromator was detected by a North Coast Ge detector when the sample was excited with the 526-nm line of a Kr^+ ion laser (100 mW, $T=1.7$ K). For the ODCR experiments a sample was placed in the center of a cylindrical open-microwave resonator (TE_{011} mode) working at 12 GHz with maximum microwave power of 500 mW. Usually the power was reduced below 30 mW and amplitude modulated by a *p-i-n* modulator at 1 kHz to avoid bolometric effects. The resonator was placed in the center of a superconducting split coil magnet generating fields up to 7 T. To observe the microwave-induced changes in the PL (induced by the microwave's electrical field), the resonator could be detuned to allow the electric field to have maximum influence.[9]

For the ODCR-FIR experiments, the detection system is mainly the same with slightly less resolution for the PL, but the sample here is placed in the center of a solenoid magnet (0–12 T) and the exciting and emitted light is guided in a single optical fiber to the sample. The epilayer is excited with a He-Ne laser (3 mW) in Faraday configuration. The FIR light (118.8 μm) with a maximum power of 35 mW (cw) is obtained from a CO_2 (20 W) pumped Edinburgh Instruments FIR laser, which irradiates the sample through the semi-insulating (si) substrate. The FIR laser is amplitude modulated by a mechanical chopper. The samples we used in the study were MBE grown GaAs on si GaAs substrate with a net carrier concentration in the middle of the 10^{14} cm^{-3} range and a Hall mobility at 77 K of 91 000 cm^2/V s and a metal-organic vapor-phase epitaxy (MOVPE)-grown epitaxial InP on a si InP:Fe substrate with a carrier concentration of 3×10^{14} cm^{-3} and a mobility of 100000 cm^2/V s (77 K).

We first discuss the PL and the microwave-induced change in PL in InP [in accordance with previous research[6] called optically detected impact ionization (ODII)]. The PL spectrum shown in Fig. 1(a) is dominated by the impurity bound exciton spectrum close to the band gap of InP ($E_g=1.4237$ at 4.2 K) and an impurity related band at 1.4 eV. One of the major advantages of the ODII technique is its ability to obtain enhanced

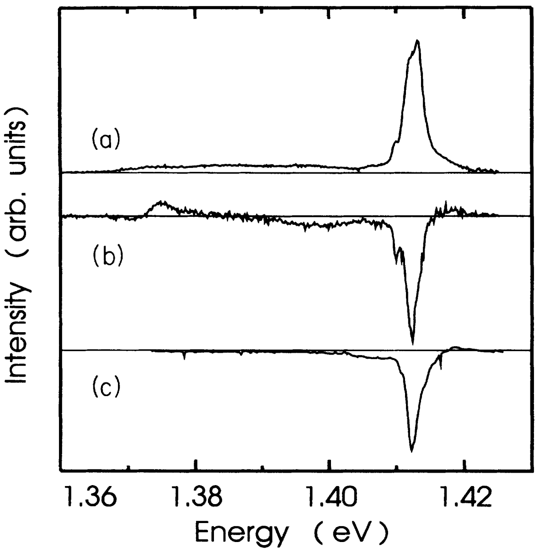

FIG. 1. (a) Photoluminescence spectrum of epitaxial InP. Optically detected impact-ionization spectra under (b) microwave irradiation and (c) under resonant ($B=7.25$ T) far-infrared irradiation (118.8 μm).

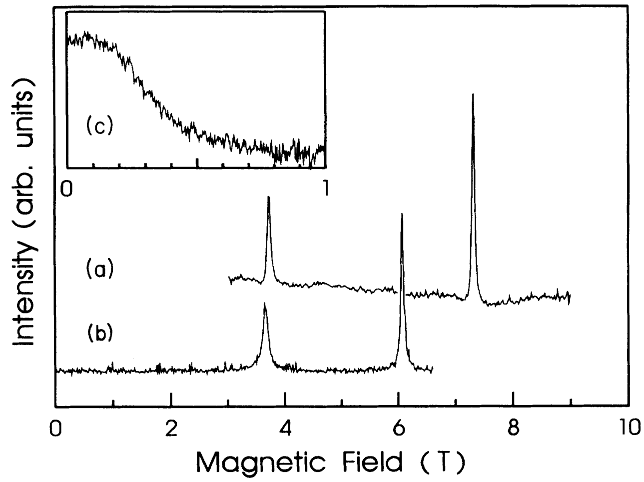

FIG. 2. Optically detected interimpurity resonance ($1s$ to $2p^+$) (low-field lines) and the electron cyclotron resonances in (a) InP and (b) GaAs, 118.8 μm. (c) The electron cyclotron resonance observed with 12 GHz. In all cases, donor bound exciton transitions were monitored.

resolution due to the derivativelike spectral shapes as demonstrated in Fig. 1(b). In the ODII spectrum (12 GHz, $B=0$ T, $T=1.7$ K) we observe a positive increase at the highest energy followed by a steep decrease. We attribute this to microwave-induced impact ionization, i.e., free carriers accelerated by the electrical-field impact on donor bound excitons and neutral donors. The excitons and electrons split off, resulting in a quenching of the bound exciton transition and in an enhancement of the free exciton decay. Notable are two further transitions at 1.398 and 1.376 eV. The quenching at 1.398 eV is consistent with a donor-acceptor (D^0A^0) transition. Its position and behavior is in excellent agreement with impact-ionization studies using dc electric fields.[8] Enhancement and quenching at 1.375 and 1.37 eV are explainable with free-electron–to–acceptor (e^0A^0) and D^0A^0 transitions involving C or Zn as the acceptor impurity. Again by impact ionization electrons are liberated from the neutral donors and an increase in the intensity of the free-to-bound transition occurs. The absence of a e^0A^0 transition at 1.398 eV (an acceptor of unknown origin[8]), as observed in the ODII spectrum, was already observed in Ref. 8. A direct correlation with the dc electric-field measurements using microwaves and FIR radiation (see below) is thus established.

The FIR induced CR monitored at the position of the bound exciton recombination is shown in Fig. 2(a). The output power of 10 mW was modulated at 120 Hz, and the magnetic field was swept ($T=6$ K). At 7.23 T we observe the electron cyclotron resonance as a 3% change in the PL intensity, with a half width of 55 mT and an $\omega\tau$ value of 162 for a scattering time of 10.2 ps. The electron mass was evaluated as $m^*=0.080m_0$, in good agreement with the value known in the literature.[10] The deduced mobility was 220000 $cm^2/V\,s$, and the enhancement by a factor of 2 compared to the Hall mobility at 77 K was expected because of the photoneutralization mechanism.[1] At the field position of 3.7 T one observes with nearly equal amplitude as the cyclotron-resonance signal, the interimpurity transition of the residual donor, the $1s$-to-$2p^+$ transition.[11] The FIR-CR-induced changes of the PL intensity, as observed at the CR magnetic-field position, are shown in Fig. 1(c), and reproduce the details already seen in the microwave experiments (the lines are slightly broader due to the limited resolution of the single monochromator). The absence of the e^0A^0 and D^0A^0 transitions at 1.37 eV can be caused by the lower excitation density (3 mW compared to 100 mW) and the difference in temperatures (6 K compared to 1.7 K) in the FIR experiment.

The situation in GaAs is demonstrated in Fig. 3. The PL spectrum shows the impurity bound exciton and D-A bands (probably involving Zn). The chopped microwaves induce quenching up to 50% in the respective PL transitions [see Fig. 3(b)]. The same effect (with 10% changes) is seen by the FIR-CR technique [Fig. 3(c)]. Again the electron cyclotron resonance at 6.2 T and the $1s$-to-$2p^+$ transition at 3.7 T are observed, and the mobility calculated from $\omega\tau=160$ is also higher by a factor of 2 compared to the Hall mobility at 77 K. When comparing with Wright *et al.*,[7] we note that polaron shifted transitions, as well as the spin splitting observed in their work, are absent. The reason for their absence is unclear at the moment. Using the $\omega\tau$ value deduced from the FIR experiment ($\lambda=118.8\mu$m) it is clear that $\omega\tau$ at 12 GHz should be approximately 0.8, well below 1. This value results in a broad resonance (see the inset in Fig. 2) centered at 0.035 T. The analysis of the line shape within the framework of the given theoretical explanation[12] taking the electron mass as a fixed parameter results in the same $\omega\tau$ value of 0.8 as expected from the frequency scaling. This clearly demonstrates the possibility of using ODCR experiments in the microwave frequency range to measure mobilities

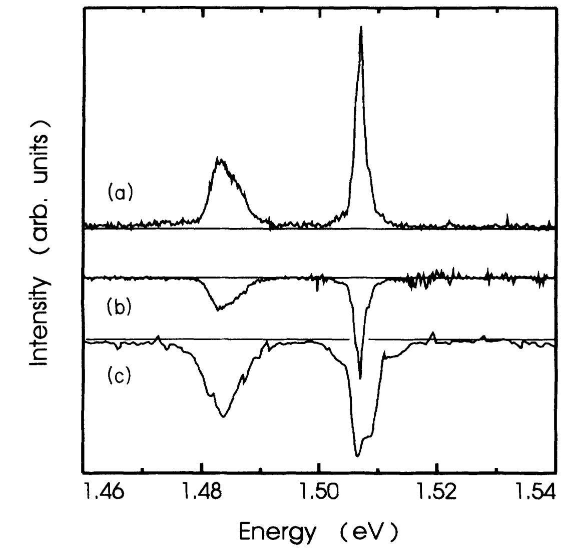

FIG. 3. (a) Photoluminescence spectrum of epitaxial GaAs. Optically detected impact-ionization spectra under (b) microwave irradiation and (c) resonant (B =6.2 T) far-infrared irradiation (118.8 μm).

and scattering times in ternary and quaternary alloys, e.g., Ga-In-As and Ga-In-As-P and obtain more information about the dominating scattering mechanism (ionized impurity versus alloy scattering) at low temperatures. The electron masses in the alloys are often known very precisely.[13]

From a comparison of the FIR and microwave-induced cyclotron-resonance changes in the PL (impact ionization) it is clear that the mechanism for both is the same. When using 118.8-μm irradiation, we observe no nonresonant contribution when the magnetic field is outside resonance. We therefore conclude that the generic mechanism behind optically detected impact ionization is not acceleration of hot carriers by the electrical field, as might be concluded from the investigations using microwaves. It is the resonant excitation which give the carriers energy to impact ionize the bound excitons and neutral donors. The situation in the microwave range is sometimes misleading. We note from Fig. 2(c) that the broadened cyclotron resonance is not zero at zero magnetic field, but goes to zero at magnetic fields above 0.7 T. For the field above 0.7 T, no nonresonant contributions occur. The mechanism for observing impact ionization at zero field stems from the experimental conditions of $\omega\tau < 1$ in the microwave frequency range of 12–30 GHz. So at zero magnetic field we still are under quasiresonance conditions. Nonresonant contributions in the PL spectrum, not due to CR-induced impact ionization and at magnetic fields far above the resonance line can originate either from power-broadened cyclotron resonances, clearly demonstrated in Refs. 4 and 6, or heating effects as are seen by thermally modulated PL spectroscopy.[14]

The ODCR method using a FIR laser has also been applied with success in the studies of undoped $Ga_{1-x}In_xAs/InP$ single quantum wells as a function of the quantum-well thickness and will be reported elsewhere.[15]

In conclusion, we demonstrate the mechanism of ODCR using 12-GHz microwaves and FIR 118.8 μm radiation. It is based on the same mechanism, namely, the cyclotron-resonance-induced impact ionization of shallow donors and impurity bound excitons, feeding the respective free exciton and band acceptor transitions. By the FIR-CR technique we have been able to detect the $1s$-to-$2p^+$ interimpurity transition in InP and GaAs with high sensitivity and resolution. A close agreement with dc electric-field impact-ionization studies in InP and GaAs is found.

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