THz Magneto-photoresponse of an InAs-based quantum point contact in the region of cyclotron resonance

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Abstract. We have studied the THz magneto-photoresponse of a 2DEG in an InAs quantum well with an embedded Quantum Point Contact in the frequency/field region where electron cyclotron resonance (CR) dominates the response. The photoresponse near CR is manifested as an envelope of the amplitude of the Shubnikov-de Haas oscillations of the 2DEG with a peak near the CR field. Clear spin-splitting of the quantum oscillations is observed for B > 4 T. Data were simulated by a model of resonant carrier heating, and from the simulations the carrier density, the CR effective mass, scattering times and the g-factor were obtained. We find a significantly enhanced g-factor apparently due to exchange interaction.

1. Introduction

For more than a decade there has been strong worldwide interest in spin effects and the spin-orbit (SO) interaction in semiconductors. Materials with large inherent SO interaction, and narrow gaps are of particular interest because of the possibility of manipulating spins with electric fields. There have been predictions of extremely large SO effects in InAs-based structures lacking inversion symmetry (the Rashba effect) including the possibility of exciting electron spin resonance via the electric field of an EM wave (Electric Dipole Spin Resonance) and the concomitant promise of efficient spin manipulation [1]. Our previous photoresponse (PR) results [2], which show complex multiple-line structure in the field region of the expected THz ESR that we have interpreted in terms of Rashba effective fields in quantum Hall edge channels, have led us to explore the effects of the Rashba SO interaction, the g-factor of electrons, and the possibility of observing and studying electron spin resonance in quasi-1D structures. The present experiments focus on understanding in detail the PR itself, and effects of a quantum point contact embedded in a 2DEG in an InAs quantum well. We explore PR in the region of cyclotron resonance at two THz laser frequencies, and we examine how the voltages on two lateral gates of the QPC affect the PR signals. We have also determined the electron g-factor from model fits at high fields.

2. Experimental Details

The samples for these studies contained a 3.5 nm InAs QW sandwiched between 10 nm $In_{0.53}Ga_{0.47}As$ neighboring barriers and $In_{0.52}Al_{0.48}As$ outer barriers. These structures were symmetrized vertically by doping with donors in the $In_{0.52}Al_{0.48}As$ barriers "below" the quantum well. The 2DEG has low temperature mobility ≈ 50,000 cm^2/V-sec, and carrier density $n_e \approx 10^{12}$ cm^{-2}. The samples investigated were lithographically fabricated rectangular Hall bars. A Quantum Point Contact (QPC) fabricated by e-beam lithography and chemical etching of isolation trenches was embedded in the 2DEG in the center of the Hall bar (see inset to figure 1c). The minimum physical separation between the trenches was ≈ 280 nm. Contacts to the 2DEG outside the trenches (G in the inset) provide lateral gates to change the electrostatic width of the constriction in a symmetric or asymmetric manner and to pinch off the channel [3].

We have measured both magnetotransport and PR of several samples including a reference Hall bar without the QPC. An Edinburgh Instruments FIR L100 optically pumped THz laser was used as a source of strong (tens to 100 mW), monochromatic CW radiation for the PR measurements. Samples were placed in the Faraday geometry at pumped liquid helium temperature in an Oxford Instruments optical-access, 10 T superconducting magnetic system with a variable temperature insert. The THz beam was focused on the sample by an-off axis parabola. Measurements of the longitudinal (R_{xx}) and transverse (R_{xy}) resistances were made with both ac current and lock-in detection at low audio frequencies (I = 50 nA to 1 μA), or with standard dc methods (I ≈ 1 μA). The photoresponse, ΔR_{xx}, was detected synchronously with the chopped laser beam either with an ac current and a double modulation technique (multiple lock-in amplifiers), or with a dc current and a single lock-in amplifier

3. Results and Discussion

The PR signal at two laser frequencies (1.4 and 2.52 THz) was measured for several gate voltages and two polarizations (parallel or perpendicular to the current shown in the inset to figure 1c)) and

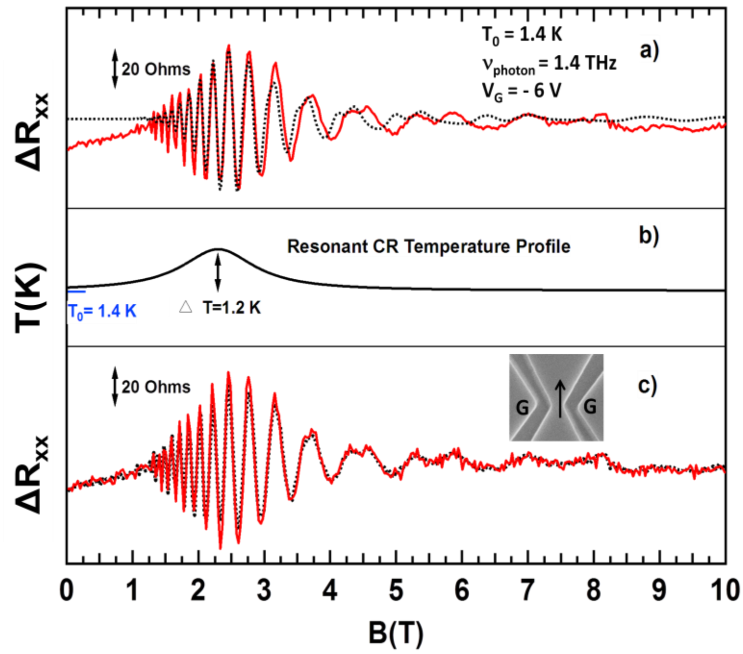

Figure 1. Photoresponse (ΔR_{xx}) and assumed carrier temperature vs magnetic field. a) Experiment and simulation. Solid line – experiment; dashed line – model. b) Carrier temperature profile. c) PR at V_G = -6 V (solid line) and 0 (dashed line). Inset: QPC; arrow - current direction; G - lateral gates.

modeled by assuming that the 2DEG is resonantly heated by cyclotron resonance absorption of the laser light, which creates a Lorentzian temperature profile as shown in figure 1b). The PR signal is the difference in R_{xx} with laser-on and -off. The oscillatory longitudinal magnetoresistance is given by [4]:

$$R_{xx} \propto \sum_{n=1}^{\infty} \frac{(-1)^n}{n^{\frac{1}{2}}} \frac{\left(n\frac{2\pi^2 k_B T}{\hbar\omega_c}\right)}{\sinh\left(n\frac{2\pi^2 k_B T}{\hbar\omega_c}\right)} e^{-n\frac{\pi}{\omega_c \tau_{sdh}}} \cos\left(n\frac{\pi g m^*}{2m_0}\right) \cos\left(n\frac{2\pi\, h n_e}{eB} + \frac{\pi}{4}\right); \quad (1)$$

here, n is the harmonic index, ω_c is the cyclotron angular frequency, τ_{SdH} is a scattering time that describes the Landau level broadening, m* is the effective mass, m_0 is the free electron mass, g is the effective g-factor, n_e is the 2DEG density, and the first cosine term describes the spin splitting of Landau levels. This expression, which does not include the monotonic magnetoresistance, was used to generate ΔR_{xx} by taking the difference at each magnetic field between $R_{xx}(B,T)$ at temperature T with the laser on (e.g., the profile of figure 1b)) and $R_{xx}(B,T_0)$, where T_0 is the bath temperature (laser off).

Figure 1a) shows the photoresponse signal at V_G = -6 V (an asymmetric configuration in which one gate is connected to the drain contact, and the other is biased negatively), and a fit to these data with the model described above. In figure 1c) the PR data at V_g = 0 is compared with the -6 V data; except for small differences in amplitude at the lower fields, the data are in excellent agreement, indicating that over this range of bias voltage the PR is dominated by the 2DEG and the lateral gate bias has little effect. The fit to the – 6V data is generally very good except for the amplitude at low fields and the differences in field position of the peaks above about 4 T. The periodicity of the oscillations determines the sheet carrier density ($n_e = 1.12 \times 10^{12}\ cm^{-2}$), which matches very well the density determined from SdH (R_{xx}) oscillations, as expected. The field at which the maximum of the envelope of the oscillations occurs is determined by the effective mass ($m^* = 0.046 m_0$) through the field position of the peak in CR absorption. The scattering time, τ_{SdH}, strongly affects the onset field for the oscillations and also the resolution of the spin split Landau levels at high B; a value of approximately 10^{-13} sec provides a reasonable fit to both. The spin-splitting of the Landau levels is determined by the product $gm^*/2m_0$. To model the spin-split peaks at high fields it was necessary to increase the electron density (see below for further discussion). The fit combined with the measured m* yields $g = -14 \pm 0.5$for the spin-split peaks at about 4.5 T, much larger than expected from single particle non-parabolicity (> -8). Such large g-factor enhancement in InAs-based 2DEGs has recently been predicted theoretically [5] from exchange effects. The present results are consistent with these predictions.

As mentioned above, although the present resonant carrier-heating model fits the data at 1.4 THz reasonably well at fields up to about 4 T, the field positions of the spin-split peaks deviate from the model at higher fields. We have found that the model with a constant density is incapable of fitting the oscillatory data over the entire range of fields. It appears that above 4 T, the low-temperature carrier density increases continuously by approximately 10% up to 10 T. This is presently not understood. The origin of the poorer fit between 1 and 2 T is also uncertain.

Figure 2 shows a comparison of the PR data with the model at a laser frequency of 2.52 THz (note that the laser power $P_{2.52\,THz} \approx 2P_{1.4THz}$). In this case the fit to the PR signal is very poor except for the oscillatory period, which fits well with the same value of n_e obtained at 1.4 THz. In this case there are two distinct regions where the fit deviates greatly from the data: 1) fields between 1 and 3 T, where the CR heating model predicts very small amplitude, and 2) the region between 3 and 4.5 T, where the CR absorption has its maximum. At low fields the experimental oscillations begin to be observable for B slightly above 1 T, and rapidly increase in amplitude with field. The model with only CR absorption included cannot reproduce this behavior. We have also determined that the large amplitude low-field oscillations with onset just above 1 T cannot be reproduced by any reasonable constant background absorption, which fails to yield a significant increase in onset and greatly increases the oscillatory amplitude at high fields, in contrast to the data. We have also attempted to model this behavior by introducing an additional strong resonant absorption around 1 T; this increases the amplitude significantly above 1.5 T, but does not reproduce the observed onset, which seems to require a

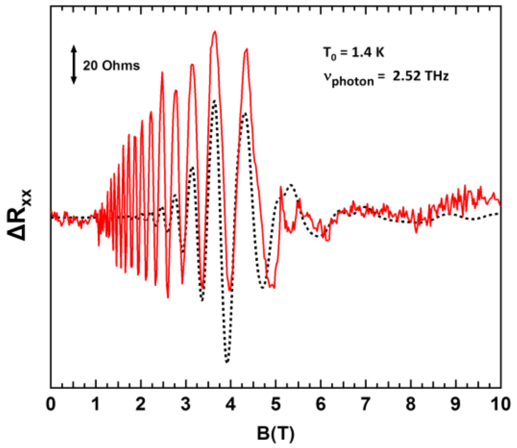

Figure 2. Comparison of experimental PR (solid line) with the model (dashed line) for ν_{Laser}=2.52 THz and $V_G = 0$ V.

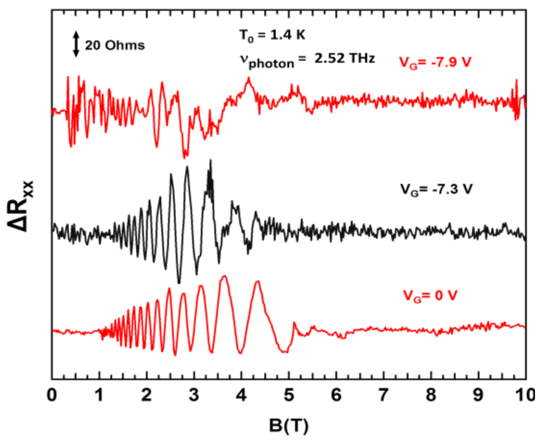

Figure 3. Photoresponse signal vs. B for ν_{photon} = 2.52 THz at three gate voltages; the upper two curves are very close to pinch-off of the QPC channel for asymmetric gate voltages (see text).

significantly longer scattering time. In the field region around CR the amplitude of the oscillations in the data is very asymmetric (the maxima of the oscillations are about a factor of two larger than the minima relative to the reference background signal at 1 T). We have adjusted the resonant CR temperature profile in the model to reproduce the peak-to-peak amplitude of the oscillations at the maximum of the envelope ($\Delta R_{xx}^{pk-pk} \approx 90\,\Omega$) and the variation of the positive-going peaks with magnetic field; this yields an effective mass, m* = 0.042m_0, with considerable systematic uncertainty. We have not attempted to account for resonant changes in the non-oscillatory part of R_{xx}, which we believe is the origin of the large asymmetry, as it could yield a background that peaks at the CR field, but has been ignored in the model.

To explore the effect of the QPC on the PR signal we have examined the PR near pinch-off of the channel by applying appropriate asymmetric gate voltages. When the channel is completely pinched off the resistance becomes very large and no PR signal is expected. The PR signals at two gate bias voltages slightly before pinch-off are compared with the PR signal with no gate bias in figure 3. At –7.3 V the PR signal is clearly affected with more noise appearing and a change in the period of the oscillation. At -7.9 V the PR signal is dramatically changed with some residual evidence of 2DEG oscillations but apparent strong beating and other behavior between 3 and 5 T. We are unable to interpret these data at present, but there are clearly strong effects of the QPC constriction near pinch-off.

4. Summary and Conclusions

We have investigated the THz magneto-photoresponse of InAs-based quasi-2DEGs with an embedded QPC, focusing on the region of frequency and fields corresponding to CR. The observed PR signal in the vicinity of CR has the form of quantum oscillations, the amplitude envelope of which is peaked slightly above the CR field. We have modeled this behavior assuming that the CR power absorbed leads to a corresponding resonant increase in the carrier temperature and find good agreement for a photon frequency of 1.4 THz. We have shown that the PR signal, which is effectively a differential of R_{xx}(B,T) with temperature enhances the low field oscillations and is very sensitive to the spin splitting of the LLs at high fields. We have used detailed fits to determine the carrier density, the cyclotron effective mass and the g-factor (at fields above about 5T). We find g ≈ - 14 at 4.5 T, much larger in magnitude than is predicted by single particle band theory at the Fermi energy. This is apparently a result of many body exchange corrections, which have recently been shown to have a large effect in InAs [5]. Over a range of QPC gate voltages (0 to -6 V), the PR is dominated by the response of the

2DEG; however near pinch-off the behavior changes dramatically, but as yet, we have not been able to interpret details of these data.

These studies have shown that the magneto-PR method is promising for studying the g-factor and effects of many electrons, and that with a suitable enhancement of the EM wave coupling via antennas, it should be possible to study the Rashba effect and electron spin resonance in quasi-1D channels.

5. Acknowledgements
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6. References

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