Influence of a Parallel Magnetic Field on Microwave Photoconductivity in a High-Mobility 2D Electron System

C. L. Yang and R. R. Du
Department of Physics, University of Utah, Salt Lake City, Utah 84112 and Department of Physics and Astronomy, Rice University, Houston, Texas 77005

L. N. Pfeiffer and K. W. West
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

We have studied experimentally the influence of a parallel magnetic field \((B_{//})\) on microwave-induced resistance oscillations (MIRO) and zero-resistance states (ZRS) previously discovered in a high-mobility 2D electron system. We have observed a strong suppression of MIRO/ZRS by a modest \(B_{//} \approx 0.5\) T. In Hall bar samples, magnetoplasmon resonance (MPR) has also been observed concurrently with the MIRO/ZRS. In contrast to the suppression of MIRO/ZRS, the MPR peak is found to be enhanced by \(B_{//}\). These findings have not been addressed by current models proposed to explain the microwave-induced effects.

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Microwave induced resistance oscillations (MIRO) \([1]\) and zero-resistance states (ZRS) \([2,3]\), observed in a high mobility two-dimensional electron system (2DES) in GaAs/AlGaAs heterostructures, have been the subject of intense current interest in the condensed matter community \([4]\). It has been theoretically shown \([5]\) that the ZRS can be the consequence of an instability due to absolute negative conductivity (ANC) occurring at the oscillation minima when the MIRO are sufficiently strong. The instability leads to the formation of electric current domains with zero voltage, resulting in a measured zero resistance. In this context, a large number of microscopic mechanisms have been proposed to account for the MIRO and the subsequent ANC, based on microwave-assisted electron scattering \([6]\) or microwave-induced non-equilibrium electron distribution \([7,8]\) and the oscillatory density of states due to Landau quantization. Other interesting mechanisms, such as orbit self-organization \([9]\), or quantum interference effect \([10]\), have been proposed.

Recently, the importance of electrodynamic effects has been emphasized \([11,12,13]\) for the microwave response of a high mobility 2DES. Specifically, the plasmon modes are expected to play a role on the MIRO and ZRS in real samples with finite size. It is well known that, for a 2DES with lateral width \(w\), the (bulk) magnetoplasmon resonance (MPR) occurs at \(\omega = \sqrt{\omega_c^2 + \omega_0^2}\),

\(\omega = 2\pi f\) is the MW frequency, \(\omega_c = eB/m^*\) is the cyclotron frequency, and \(\omega_0 = \sqrt{ne^2\mu/2}\) is the 2D plasma frequency, with an effective dielectric constant \(\epsilon = (1 + \epsilon_{GaAs}) = 6.9\) for GaAs, and a plasma wave vector \(q = \pi/w\). The MPR has been observed, together with MIRO, in microwave photoconductivity of lower-mobility 2DES \((\mu = 3 \times 10^6 \text{ cm}^2/\text{Vs})\) \([1]\). However, so far it has not been reported in ultra-clean samples where ZRS are observed. This has become a issue relevant to the origin of the MIRO and ZRS \([11]\).

In this paper, we report on the influence of a parallel magnetic field on the microwave photoconductivity of ultra-clean 2DES. The MIRO and ZRS, as well as the magneto-plasma resonance, are experimentally studied under a fixed parallel magnetic field \((B_{//})\) and sweeping perpendicular field \((B_z)\), with \(B_z\) and \(B_{//}\) independently provided by a two-axes magnet. Our main finding is that the oscillatory photoconductivity is strongly suppressed by a relatively small \(B_{//}\), of the order of 0.5 T. And we found that the MPR can occur concurrently with the MIRO and ZRS, while its strength is enhanced by \(B_{//}\) in contrast to the suppression of MIRO and ZRS. In addition, employing \(B_{//}\) we were also able to uncover a new, resistively detected resonance which occurs near twice the cyclotron frequency. These new experimental findings in a parallel magnetic field have not been addressed by current theoretical work on the photo-response of high mobility 2DES, and could help to differentiate between competing theories.

Ultra-clean 2DES used in these experiments were provided by \(\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{GaAs}/\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}\) square quantum wells (QW); similar data have been obtained from single-interface \(\text{GaAs/Al}_{0.3}\text{Ga}_{0.7}\text{As}\) heterostructures. Data reported in this paper are from two specimen, sample \(\text{QW30nm (QW25nm)}\), which is a 30-nm (25-nm) width QW, having an electron density of \(n_e = 3.45 \times 10^{11}(3.30 \times 10^{11})\) cm\(^{-2}\) and a mobility of \(\mu = 1.8 \times 10^7(1.9 \times 10^7)\) cm\(^2\)/Vs at 0.35 K. These parameters were obtained after a brief illumination from a red light-emitting diode at 2 K. Both specimen were lithographically defined and wet-etched: the sample \(\text{QW30nm}\) is a 200 \(\mu\)m \(\times\) 400 \(\mu\)m rectangle and the sample \(\text{QW25nm}\) is a 100 \(\mu\)m \(\times\) 2 mm Hall bar. The measurements were performed in a top-loading He-3 cryostat with a base temperature.
oscillations are observed while the onset moves to higher magnetic field with increasing $B_{//}$ (from $B_z \sim 0.08$ T at $B_{//} = 0$ to $B_z \sim 0.12$ T at $B_{//} = 1.0$ T). With MW irradiation, the most salient feature is that the MIRO diminish rapidly with increasing $B_z$: at $B_z = 0.2$ T, the amplitude has already decreased more than 50% as compared to that at $B_z = 0$; and by $B_z = 0.75$ T, the oscillations completely disappear. Initially, for $B_z = 0$, up to four ZRS are observed at the minima of the MIRO. Among them, the strongest first two ZRS (centered around $B_z = 0.10$ T and $B_z = 0.055$ T) persist up to $B_z = 0.2$ T, and then are quickly suppressed at $B_z = 0.3$ T. Before the diminishing of the ZRS, shrinkage of their width is noticed, for instance, at $B_z = 0.2$ T. We note that, with increasing $B_z$, the positions of the oscillation maxima shift towards higher $B_z$ while those of the ZRS and oscillation minima are roughly constant.

By rotating the sample probe 90°, we were able to perform the same measurements with a parallel magnetic field $B_{//}$ which is perpendicular to the excitation current. The observations are qualitatively the same as those of FIG. 1. However, the suppression of MIRO and ZRS by $B_{//}$ is not as strong as that by $B_z$: The ZRS disappear at $B_{//} \lesssim 0.5$ T and the MIRO are complete suppressed at $B_{//} \lesssim 1.5$ T. Despite of these quantitative difference, our main finding is that ZRS is strongly suppressed by a modest parallel magnetic field $B_{//}$.

In order to study the influence of $B_{//}$ on the resistively-detected MPR, we have performed similar experiments on the Hall bar sample of QW25nm. Not surprisingly, we have also observed a strong suppression of MIRO/ZRS in this sample [16]. However, the MPR peak is enhanced (rather than suppressed) by $B_{//}$. Typically, the magneto-plasmon peak is masked by the MIRO at $B_{//} = 0$ but becomes dominant at elevated $B_{//}$. As shown in Fig. 2, at $B_{//} = 0$, with low MW frequency the MPR just slightly modifies the shape of the MIRO and can only be clearly identified when its position moves up into the wide first minimum of the MIRO, with increasing MW frequency. The enhancement of the MPR peak in an increasing $B_{//}$, concurrent with the suppression of the MIRO, is shown in the left panel of FIG. 3, for $f = 120$ GHz as an example. Another important observation is that the peak position of the magneto-plasmon mode is almost independent of $B_{//}$ (within the accuracy of 1%) as indicated by the vertical line $A$ of the left panel of FIG. 3. This means the effective electron mass ($m^*$) is nearly constant within the $B_{//}$ range studied.

The MP modes at various MW frequencies have also been explored, example traces recorded at $B_y = 1.50$ T for selected microwave frequencies are shown in the right panel of FIG. 3. A set of magneto-plasma peak positions, plotted in the inset of FIG. 3 (right panel), were accurately determined by employing appropriate $B_{//}$ to simultaneously enhance the magneto-plasmon mode and suppress the MIRO. The fit to the dispersion relation

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![Figure 1: Microwave-induced resistance oscillations (MIROs) and the zero-resistance states (ZRS) observed on a ultra-high-mobility 2DES (sample QW30nm, see text) subjected to parallel magnetic field $B_z$ (for clarity, traces are vertically shifted by steps of 3 $\Omega$/sq.). For comparison, corresponding traces without microwave irradiation (thin lines) are also shown.](image-url)

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$B_z = 1.00$ T

$\rho_{xx}$ (\(\Omega$/\text{sq.})

$B_z$ (T)

-0.2

-0.1

0

0.1

0.2

0

0.50

0.40

0.30

0.20

0.10

0.00

21

-0.2

-0.1

0

0.1

0.2

0

0.50

0.40

0.30

0.20

0.10

0.00

FIG. 1: Microwave-induced resistance oscillations (MIROs) and the zero-resistance states (ZRS) observed on a ultra-high-mobility 2DES (sample QW30nm, see text) subjected to parallel magnetic field $B_z$ (for clarity, traces are vertically shifted by steps of 3 $\Omega$/sq.). For comparison, corresponding traces without microwave irradiation (thin lines) are also shown.
Eq. (1) is excellent and it yields $m^* = 0.070 \, m_e$, and a $f_0 \equiv \omega_0/2\pi = 87.0 \, \text{GHz}$ which is reasonably close to the calculated value of 93 GHz.

In addition, we observed a small sharp peak (marked by the vertical line $B$ in FIG. 3a) which overlaps with the second maximum of the MIRO; the $B_z$ position of this peak does not change with $B_{//}$ and its strength does not have strong dependence on $B_{//}$. Although the small peak is discernible for certain frequencies at $B_{//} = 0$ (see FIG. 2, for example), it can be recognized as an extra peak only in elevated $B_{//}$. This new peak has been observed in a wide MW frequency range (50-150 GHz) and is not correlated with the magneto-plasmon mode (see the right panel of FIG. 4, the small peak appears at $f = 85$ GHz where the magneto-plasmon mode is absent). Also the extra peak can not be identified as electron-spin resonance (ESR) since its position is not shifted by $B_{//}$, and the ESR should occur at much higher magnetic field (at the order of 10 T) within the MW frequency range we used. Note this peak is distinct from MIRO by its behavior in $B_{//}$. Although the nature of this resistance peak is not clear, such a feature may signal a new resonance taking place near twice the cyclotron frequency, i.e., $\epsilon \equiv \omega/\omega_c \approx 2$ with $\omega_c = eB_z/m^*$. However, the new resonance can not be simply regarded as a cyclotron harmonic because such a sharp feature is absent from the 1st MIRO peak.

Now we comment on possible mechanism leading to the strong suppression of MIRO/ZRS by a $B_{//}$. In a strictly 2DES, a pure $B_{//}$ can only couple to the spins of the electrons through the Zeeman interaction. In a quasi-2DES with finite thickness, the $B_{//}$ can couple to the orbital motion of the electrons, giving rise to a diamagnetic energy shift and a slightly increased effective mass in the direction perpendicular to $B_{//}$, $m^*$ can also couple to the spins through spin-orbit interactions. These effects, however, hardly affect the Landau quantization under a perpendicular magnetic field $B_{//}$, at least within the parameter regime of our experiments; in particular, the Landau levels are still equally spaced and the oscillatory structure of the density of states is essentially
intact. In this single-particle picture, it is not likely that the $B_{//}$ can significantly alter the photon-assisted scattering processes between Landau levels. Therefore, the strong suppression of the MIRO/ZRS by $B_{//}$ may indicate a many-body or collective origin of the microwave-induced oscillations.

In summary, we have observed a strong suppression of the microwave-induced resistance oscillations and the subsequent zero-resistance states by a parallel magnetic field. On the contrary, magnetoplasmon resonance peaks, observed concurrently with MIRO/ZRS, are robust in a parallel magnetic field.

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