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MAGNETORESISTANCE OSCILLATIONS IN DOUBLE QUANTUM WELLS UNDER MICROWAVE IRRADIATION

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We report in detail oscillatory magnetoresistance in double quantum wells under microwave irradiation. The experimental investigation contains measurements of frequency, power and temperature dependence. In theory, the observed interference oscillations are explained in terms of the influence of subband coupling on the frequency-dependent photoinduced part of the electron distribution function. Thus, the magnetoresistance shows the interference of magneto-intersubband and conventional microwave induced resistance oscillations.

Keywords: Double quantum wells; magnetotransport; microwave excitation.

1. Introduction

Experiments in a high mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures exposed to microwave radiation of frequency ω in a perpendicular magnetic field exhibit microwave induced resistance oscillations (MIROs) governed by the ratio ω/ω_c, where ω_c is the cyclotron frequency.[1] It has been shown that these MIROs in a very high mobility sample and for high radiation power evolve into zero-resistance states (ZRS).[2] These magnetotransport properties are currently under investigation in single quantum wells (QWs) with one occupied subband.

In our paper we report and underline the importance of studies in a system with two occupied 2D subbands. QWs with one occupied subband show commonly known Shubnikov-de Haas oscillations (SdHO), whereas double quantum wells (DQWs) indicate new features known as the magneto-intersubband (MIS) oscillations due to periodic modulation of the probability of intersubband transitions in the magnetic field.[3]

2. Experimental Observation

For our investigations, high mobility samples of 10^6 cm^2/V $\cdot$ s and a total sheet density (for the DQWs) of $n_s \simeq 10^{12}$ cm^{-2} have been used. The symmetric balanced DQWs have well widths of 14 nm and different barrier widths of d_b=1.4, 2, and 3 nm.

The samples were mounted in a waveguide with different cross sections in a VTI cryostat. The measurements were performed for parallel and perpendicular orientation of the current with respect to microwave irradiation. No polarization dependence was observed. The microwave sources are carcinotron generators in the range of 35 to 170 GHz. Whereas samples with different barrier widths - which show qualitatively the same features - have been investigated, the paper reports only the results for 1.4 nm barrier samples.

Fig. 1 shows the comparison of a QW with one occupied subband and a DQW under a microwave irradiation of 170 GHz at 1.4 K. The well-known MIROs periodic in ω/ω_c are observed in the QW. Without irradiation, the magnetoresistance of the DQW exhibits large-period MIS oscillations starting from B = 0.1 T and small-period SdHO at higher fields. From the periodicity of the MIS oscillations, we find the subband energy Δ_{12}=3.67 meV. High microwave intensity leads to the expected damping of SdHO due to electron heating. For the DQW, new features are observed: microwave irradiation causes suppression and/or inversion of MIS or even groups of MIS peaks which are continuously enhanced with increasing irradiation.

3. Frequency, Power and Temperature Dependence

In this chapter we present the magnetotransport data on a DQW under microwave irradiation comprising frequency, power, and temperature dependence (see Fig. 2).

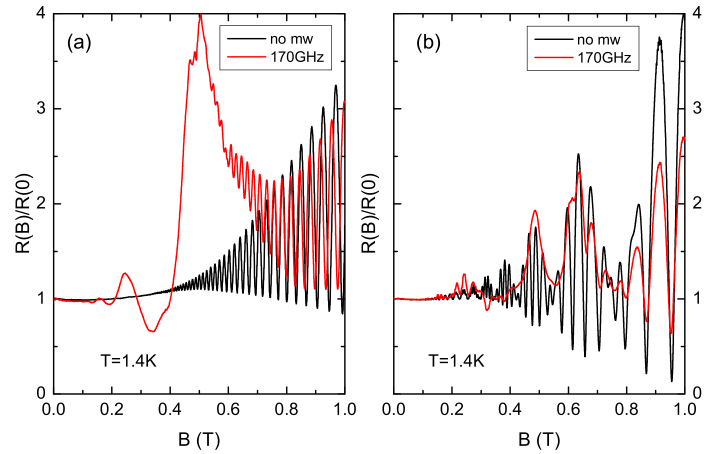

Fig. 1. Normalized magnetoresistance of a single QW (a) and a DQW (b) without (black curve) and under a microwave irratiation of 170 GHz (red curve). The QW with one subband occupied shows MIROs governed by the ratio ω/ω_c. The DQW exhibits suppression and/or inversion of MIS peaks.

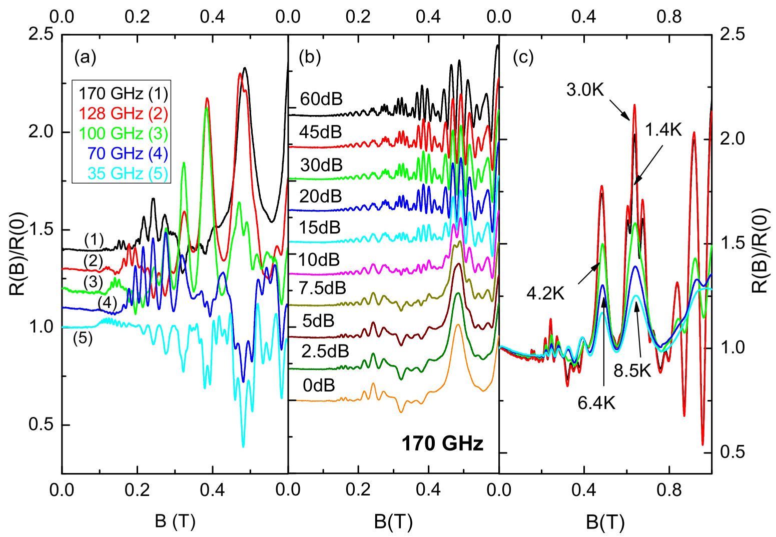

Fig. 2. Frequency dependence (a) with a constant electric field of 2.5 V/cm and power dependence for 170 GHz (b) of a DQW under microwave irradiation at 1.4 K. The temperature dependent magnetoresistance exposed to microwave irradiation of 170 GHz (c) shows a restored picture of MIS oscillations at 6.4 K.

Starting from 170 GHz (see Fig. 2a), all MIS peaks are enhanced for $B < 0.3$ T. Decreasing frequency leads to an enhancement of some MIS peaks, followed by the inversion (flip) of some peaks at high intensity. For 128, 100 and 70 GHz, even some groups of MIS peaks start to flip or enhance their amplitude until, for low frequency

(35 GHz), only the group of MIS peaks at $B = 0.1$ T is enhanced whereas all other MIS oscillations are inverted.

The power dependence at 170 GHz (Fig. 2b) demonstrates the evolution with constantly increasing power of the MIS peaks starting from an attenuation of 60 dB, where the radiation can be neglected, to 0 dB which is the maximal microwave irradiation.

With increasing temperature and without irradiation, the low field SdHO are more and more damped (not shown here) but the MIS oscillations survive at high temperatures. If the sample is exposed to a frequency of 170 GHz (see Fig. 2c), the amplitude of the enhanced MIS oscillations decreases for $T > 3$ K and the inverted peaks go up. For $T = 6.4$ K, the MIS oscillation picture is restored.

4. Theory

Measurements for different frequencies (see Fig. 2a) have confirmed that the peak flips are strongly correlated with the radiation frequency, following the periodicity with ω/ω_c. This allows us to attribute the observed effect to a MIRO-related phenomenon. The theoretical explanation of our data is based on the physical model of Dmitriev *et al.*,[4] generalized to the two-subband case and improved by taking into account electrodynamic effects in the absorption by 2D layers (see Refs. 5–7). The whole calculation and the extended model can be found in Ref. 8. Here we present only the theoretical result on the dc resistivity:

$$\frac{\rho_d}{\rho_0} = 1 - 2D\mathcal{T} \sum_{j=1,2} \cos\left(\frac{2\pi(\varepsilon_F - \varepsilon_j)}{\hbar\omega_c}\right) + D^2(1 - A_\omega)\left[1 + \cos\left(\frac{2\pi\Delta_{12}}{\hbar\omega_c}\right)\right], \quad (1)$$

$$\mathcal{T} = \frac{X}{\sinh X}, \quad X = \frac{2\pi^2 T_e}{\hbar\omega_c}, \qquad A_\omega \simeq \frac{\mathcal{P}_\omega(2\pi\omega/\omega_c)\sin(2\pi\omega/\omega_c)}{1 + \mathcal{P}_\omega \sin^2(\pi\omega/\omega_c)},$$

where $\rho_0 = m/e^2 n_s \tau_{tr}$ is the zero-field resistivity and $\Delta_{12} = \varepsilon_2 - \varepsilon_1$ is the subband separation. The second term, proportional to the Dingle factor $D = \exp(-\pi/\omega_c\tau)$ and temperature damping factor $\mathcal{T}$, describes the SdHO, while the third term, quadratic in D, describes the MIS oscillations and their modification by the radiation. The dimensionless factor $\mathcal{P}_\omega$ is proportional to the radiation intensity and to the ratio of inelastic relaxation time τ_{in} to the transport time τ_{tr}. We have taken into account the heating of electrons by the field and the temperature dependence of the characteristic scattering times. The radiation intensity is estimated by fitting calculated amplitudes of magnetoresistance oscillations to experimental data which is in good agreement with the damping of SdHO amplitudes. An example of the calculation, showing a good agreement with the experiment, is presented in Fig. 3 for three chosen frequencies.

In conclusion, we have presented the frequency, power, and temperature dependence of magnetoresistance in DQWs under microwave irradiation. According to the theory, the induced resistance interference oscillations in DQWs appear because the photoinduced part of the electron distribution function, which oscillates

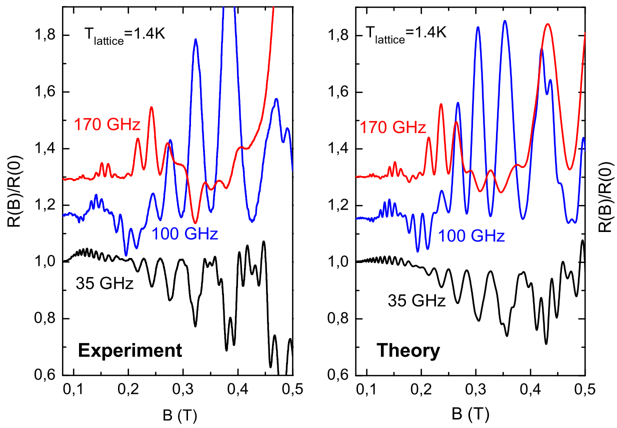

Fig. 3. Measured (a) and calculated (b) magnetoresistance of a DQW at 1.4 K for different frequencies under microwave excitation. The curves for 100 and 170 GHz are shifted up for clarity.

as a function of microwave frequency, is modified owing to subband coupling and becomes also an oscillating function of the subband separation.

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