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Magnetoresistance oscillations in triple quantum wells under microwave irradiation

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ABSTRACT

The interference of magneto-intersubband oscillations and microwave-induced resistance oscillations is studied in high-density triple quantum wells. We give an introduction into magnetotransport in trilayer systems and focus on photoresistance measurements. The power and frequency dependence of the observed magnetoresistance oscillations can be described by the inelastic mechanism of photoresistance, generalized to the three-subband case.

1. Introduction

Two-dimensional (2D) systems exposed to microwave (MW) irradiation in the presence of weak perpendicular magnetic field have attracted much experimental and theoretical interest over the past years. In the systems with one occupied subband, the magnetoresistance shows the microwave-induced resistance oscillations (MIROs), which are governed by the ratio of the radiation frequency ω to the cyclotron frequency ω_c [1] and evolve into "zero-resistance states" for elevated MW intensity and ultrahigh mobility [2]. The phase and periodicity of these oscillations are described by microscopic theories accounting for the displacement mechanism [3,4] and for the inelastic mechanism [5] of photoresistance. The inelastic mechanism dominates at low temperatures T, because its contribution is proportional to the inelastic relaxation time $\tau_{in} \propto T^{-2}$. MIROs can also occur due to the "photovoltaic" mechanism describing combined action of the microwave and dc fields on both temporal and angular harmonics of the distribution function [6]. For high microwave intensity, the resistance has resonant features associated with the fractional ratios $\varepsilon = \omega/\omega_c = n/m$, which have been investigated up to denominator 4 [7] and recently up to denominator 8 in a 2D system with moderate mobility [8]. MIROs have been investigated in systems with two occupied subbands (double quantum wells, DQWs), where the magneto-intersubband (MIS) oscillations [9] are observed in the absence of microwave irradiation. The MIS resonances occur when different Landau levels of the two subbands are sequentially aligned by the magnetic field. The most interesting aspect of two-subband systems is the interference between MIROs and MIS oscillations, which leads to a peculiar magnetoresistance pattern [10] showing inversion of certain groups of MIS peaks, correlated with the radiation frequency. It has been found that the inelastic mechanism also explains magnetoresistance oscillations in a two-subband system [10]. In this paper we present magnetoresistance measurements under microwave irradiation in triple quantum wells (TQWs), where the MIS oscillation picture is more complicated because of the presence of three subbands with energies ε_j ($j = 1, 2, 3$). The periodicity of the MIS oscillations is determined by several subband separation energies $\Delta_{jj'} = |\varepsilon_j - \varepsilon_{j'}|$. Therefore, if such a TQW is exposed to microwave irradiation, MIS oscillations also change its oscillation picture, correlated with the radiation frequency.

2. Basics of a trilayer systems and magnetotransport without MW radiation

We study symmetrically doped GaAs TQWs with a total electron sheet density ($n_s = 9 \times 10^{11}\,\mathrm{cm}^{-2}$) and a mobility of $5 \times 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$. The central well width is 230 Å and both side wells have an equal well width of 100 Å. The barrier thickness is $d_b = 14$ A. The density in the central well is 30% smaller than in the side wells extracted from a simple FFT analysis. Within this FFT analysis of magnetoresistance oscillations at zero MW excitation, we also obtain the corresponding energy gaps $\Delta_{12} = 4.0$ meV and $\Delta_{13} = 5.4$ meV (here and below $\Delta_{jj'} = |\varepsilon_j - \varepsilon_{j'}|$). Fig. 1(a) sketches the TQW system with three occupied 2D

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subbands and the Landau level staircases associated with these subbands. In Fig. 1(b), we present MIS oscillation at a temperature of $T = 1.4$ K. The peaks in Fig. 1(b) occur each time when $\Delta_{jj'}$ is equal to an integer number of cyclotron energies. Note, that for low temperatures, MIS oscillations are superimposed by low-field SdH oscillations. In contrast to Shubnikov–de Haas (SdH) oscillations, the MIS oscillations are not considerably damped with increasing temperature. However, some damping takes place owing to the enhancement of the Landau level broadening by electron–electron scattering, which formally can be described by adding a temperature-dependent ($\propto T^2$) contribution to the inverse quantum lifetime of electrons. This behaviour has been recently investigated in Ref. [9] in a double quantum well (DQW) systems which consist of two quantum wells coupled by tunnelling.

3. Power, temperature and frequency dependence of photoresistance

For photoresistance measurements, the samples are mounted in a VTI cryostat and the microwave radiation is delivered down to the sample by a waveguide. The investigated frequency range is from 35 to 170 GHz. Fig. 2 presents the MIS oscillations for different microwave attenuations at a lattice temperature $T = 1.4$ K. For -60 dB, the microwave intensity is negligible and only MIS oscillations occur. For $B > 0.3$ T we see also the SdH oscillations. A continuous MW irradiation at a frequency of 110 GHz leads to a modification of the MIS oscillation picture. For 0 dB (the highest MW intensity), MIS peaks at 0.37 and 0.43 T are enhanced, whereas the peaks around $B = 0.2$ T are inverted. The amplitude of SdH oscillations is decreased because of MW heating of the 2D electron gas. The MW electric field is estimated to $E \simeq 2.5$ V/cm (the details on estimation of the electric field E can be found in Ref. [10]).

Fig. 3 presents photoresistance at a fixed frequency of 110 GHz when temperature increases from 1.7 to 3 K. In order to compare the MW effect on the 2D electron gas, we have also added the dark magnetoresistance for $T = 4.2$ K. For the constant electric field of $E \simeq 2.5$ V/cm, the photoresistance "approaches" the dark magnetoresistance curve, i.e. the effect of MWs decreases for higher temperatures. While temperature dependence of the dark magnetoresistance is in agreement with the concept of electron–electron scattering (similar to the observation in double quantum wells [9]), the temperature dependence of MW photoresistance appears to be stronger.

We now turn to the frequency dependence shown in Fig. 4. The MIS oscillation picture is strongly frequency dependent. For 170 GHz, the MIS peaks are mostly enhanced. With decreasing ω, we observe for 110 GHz an inversion of MIS peaks around 0.2 T and a strong increase in amplitude at $B = 0.43$ T compared to 170 GHz. For 70 GHz the most enhanced feature occurs at $B = 0.27$ T. For 110, 70, and 35 GHz, the plots show inverted peaks whose positions depend on ω. For 35 GHz the region of inverted peaks extends from 0.2 to 0.45 T.

4. Theoretical model

In Ref. [10] it has been demonstrated that the inelastic mechanism of photoresistance, generalized to the two-subband

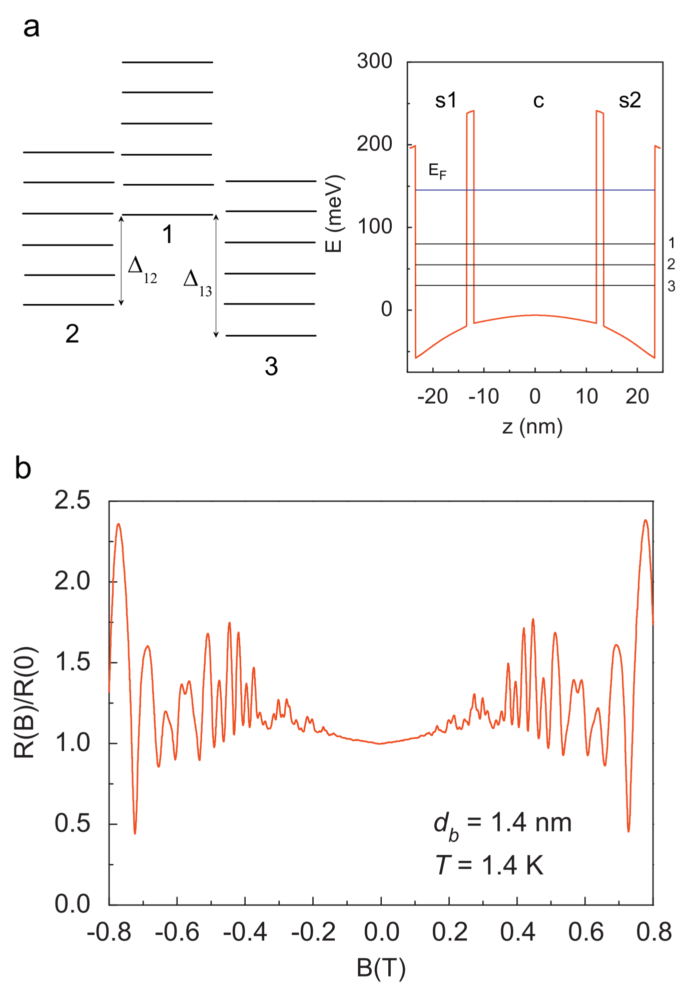

Fig. 1. (a) Staircase of Landau levels for three subbands and a picture of a triple quantum well (sl: left side well, c: central well, sr: right side well) with three subbands (1,2,3) and (b) magnetoresistance at 1.4 K exhibits MIS oscillations superimposed by SdH oscillations for low temperatures.

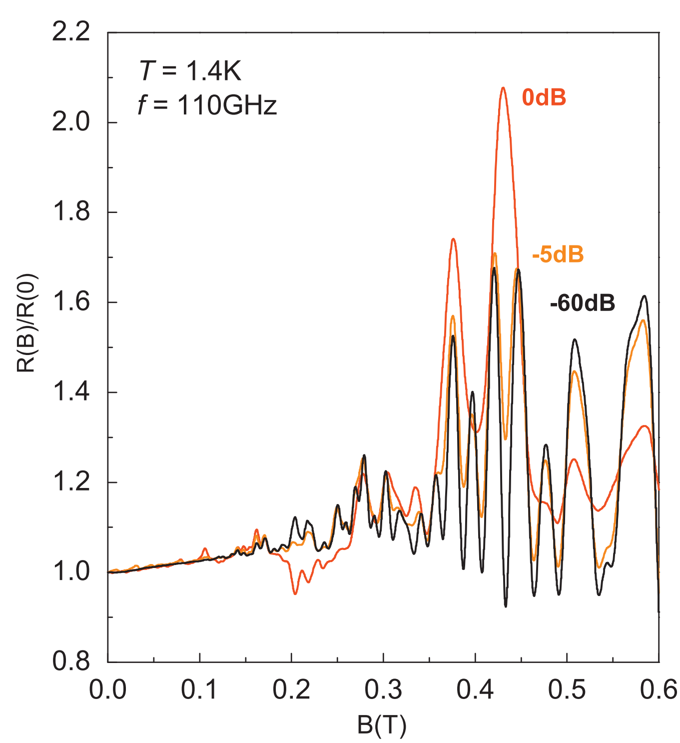

Fig. 2. Power-dependent photoresistance for -60, -5 and 0 dB at 110 GHz. For -60 dB, the microwave intensity is negligible and only MIS oscillations occur. With increasing power, the MIS oscillations are enhanced, suppressed, or even inverted.

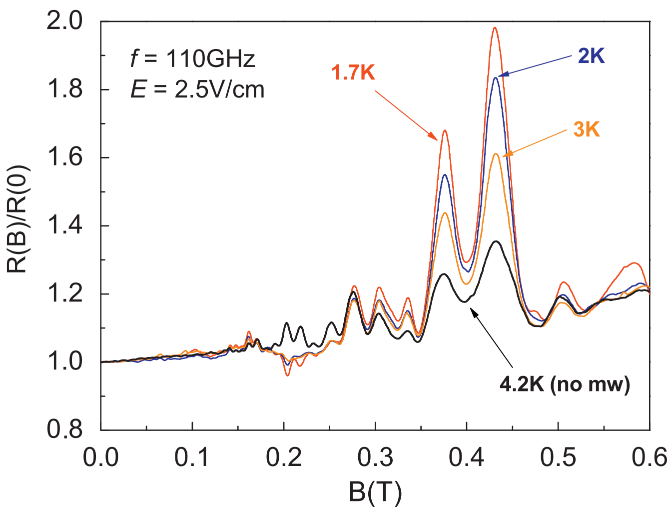

Fig. 3. Temperature dependence of photoresistance at a constant frequency 110 GHz and a constant MW electric field $E\simeq 2.5$ V/cm. The black curve ($T=4.2$ K) shows MIS oscillations without MW irradiation. With increasing temperature, the effect of MW irradiation on the 2D gas decreases.

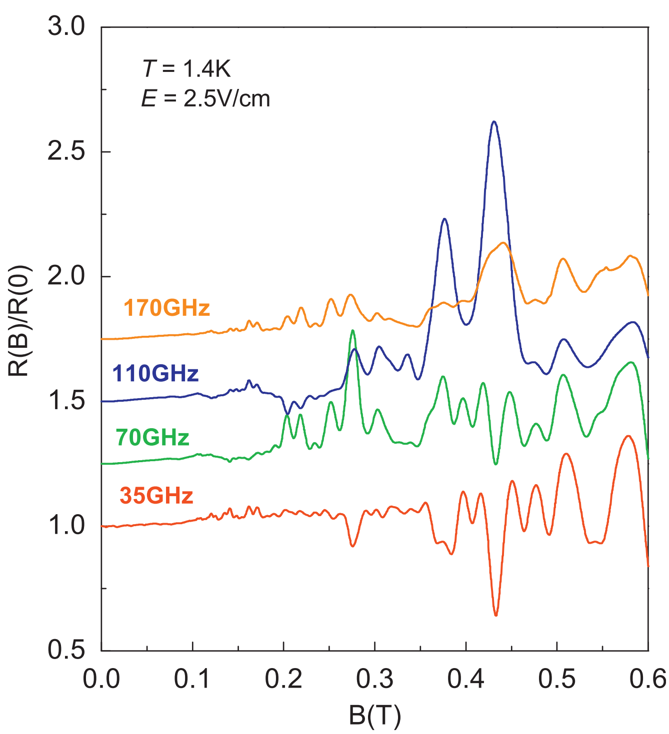

Fig. 4. Frequency dependence of photoresistance from 35 to 170 GHz at a constant MW electric field $E=2.5$ V/cm and a lattice temperature of $T=1.4$ K. The MIS oscillations are strongly modified with MW irradiation (the curves are shifted up for clarity, except the one for 35 GHz).

case, gives a reasonable explanation of the interference of MIS oscillations with MIROs in double quantum wells. This model is now extended to the three-subband case. The dissipative resistivity [10,11] can be presented as

$$\rho_d=\rho_d^{(0)}+\rho_d^{(1)}+\rho_d^{(2)}, \tag{1}$$

where $\rho_d^{(0)}$ is the classical resistivity, $\rho_d^{(1)}$ the first-order quantum contribution describing the SdH oscillations, and $\rho_d^{(2)}$ the second-order quantum contribution containing the MIS oscillations. In a simplified approach, we assume that the partial densities n_j, transport scattering rates $\nu_{jj'}^{tr}$, and Dingle factors $d_j=e^{-\pi/\omega_c\tau_j}$, where τ_j is the quantum lifetime for subband j, are equal to each other ($\tau_j=\tau$, $d_j=d$). Then, neglecting the SdH oscillations, one can write the magnetoresistance in the form:

$$\frac{\rho_d(B)}{\rho_d(0)}=1+\frac{2}{3}(1-A_\omega)d^2\left[1+\frac{2}{3}\cos\left(\frac{2\pi\Delta_{12}}{\hbar\omega_c}\right)+\frac{2}{3}\cos\left(\frac{2\pi\Delta_{13}}{\hbar\omega_c}\right)+\frac{2}{3}\cos\left(\frac{2\pi\Delta_{23}}{\hbar\omega_c}\right)\right], \tag{2}$$

which describes both the contribution of MIS oscillations governed by the intersubband energy gaps $\Delta_{jj'}$ and modification of the quantum part of the resistivity by the MW irradiation, given by a dimensionless factor

$$A_\omega=\frac{P_\omega(2\pi\omega/\omega_c)\sin(2\pi\omega/\omega_c)}{1+P_\omega\sin^2(\pi\omega/\omega_c)}. \tag{3}$$

In this expression,

$$P_\omega=\frac{\tau_{in}}{\tau_{tr}}\left(\frac{eEv_F}{\hbar\omega}\right)^2(|s_+|^2+|s_-|^2), \tag{4}$$

$v_F=\hbar\sqrt{(2/3)\pi n_s}/m$ is the Fermi velocity, m the effective mass of electrons, and τ_{tr} the transport time ($1/\tau_{tr}=\sum_{j'}\nu_{jj'}^{tr}$). For linear MW polarization,

$$s_\omega^{\pm}=\frac{1}{\sqrt{2}}\frac{1}{\omega\pm\omega_c+i\omega_p}, \tag{5}$$

where $\omega_p=2\pi e^2 n_s/mc\sqrt{\varepsilon_d}$ is the plasmon frequency and ε_d the dielectric permittivity. With increasing MW power the factor $(1-A_\omega)$ changes its sign, which leads to observed inversion of the MIS peaks.

The expression for A_ω accounts only for the inelastic mechanism of photoresistance. In general, the factor A_ω can be modified to include also the displacement mechanism of photoresistance. In high-mobility samples with one occupied subband, this mechanism recently has been found to be important, even at low temperatures such as 1–2 K [12]. The relative contribution of the displacement mechanism (compared to the inelastic one) is given by the ratio $\tau_{tr}^2/4\tau_{in}\tau^*$, where $1/\tau^*$ is approximately equal to $12\tau/\tau_{tr}^2$ but can be larger if short-range scatterers are present in the system [13]. Both the transport time τ_{tr} and quantum lifetime τ of electrons in our samples are much smaller than those of the sample from the experiment [12], because of much lower mobility. Consequently, according to our estimates, in the temperature range from 1.4 to 4.2 K corresponding to our measurements, the inelastic contribution still remains the dominant one. This is confirmed by our experimental studies on the temperature dependence of the amplitudes of oscillations in the presence of microwaves. Taking into account temperature dependence of inelastic scattering time and quantum lifetime, we obtain a reasonable agreement between experimental and theoretical magnetoresistance.

In summary, we have studied interference of MIRO and MIS oscillations in high-density TQWs. We conclude that the inelastic mechanism describes the frequency-dependent MW photoresistance in TQWs similar to the cases of one- and two-subband systems. The main difference compared to DQWs is a more complicated structure of the MIS peaks caused by the alignment of Landau levels originating from three subbands. Further studies in the systems with different barriers and well widths are necessary to get a complete understanding of this phenomenon.

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