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Magneto-intersubband oscillations in triple quantum wells

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ABSTRACT

We present magnetotransport studies of high-density triple quantum well samples with different barrier widths. Because of electron transitions between three occupied 2D subbands, the magnetoresistance shows magneto-intersubband oscillations whose periodicity is determined by the subband separation energies. Temperature-dependent measurements allow us to extract quantum lifetime of electrons. A theoretical consideration of the observed phenomenon is also presented.

1. Introduction

Magnetoresistance measurements, in particular, the investigation of Shubnikov-de Haas (SdH) oscillations, provide important information about band structure and electron interaction mechanisms in solids [1]. With increasing temperature, SdH oscillations are strongly damped as the thermal broadening of the Fermi distribution exceeds the cyclotron energy $\hbar\omega_c$. Two-dimensional (2D) electron systems with several occupied subbands exhibit another kind of magnetoresistance oscillations called the magneto-intersubband (MIS) oscillations [2], which have been studied in single quantum wells with two populated 2D subbands [3–5]. These oscillations occur due to the periodic modulation of the probability of intersubband transitions by a magnetic field when different Landau levels of two subbands are sequentially aligned. In contrast to SdH oscillations, the MIS oscillations are not considerably damped with increasing temperature. Recently, MIS oscillations have been observed and investigated [6] in double quantum well (DQW) systems which consist of two quantum wells coupled by tunneling. A small subband separation, a reasonably large quantum lifetime of electrons, and a high probability of intersubband scattering make DQWs the most convenient systems for studies of the MIS oscillations. Such studies allow us to determine the quantum lifetime of electrons in the region of temperatures where SdH oscillations are already absent [6].

So far, MIS oscillations have been investigated in the systems with two occupied 2D subbands. Triple quantum wells (TQWs) offer a possibility to study this phenomenon for the case of three 2D subbands with energies $\varepsilon_j, j = 1, 2, 3$. The magnetoresistance of such structures is different from the two-subband case, because the periodicity of the MIS oscillations is determined by several subband separation energies $\Delta_{jj'} = |\varepsilon_j - \varepsilon_{j'}|$. The peaks occur each time when $\Delta_{jj'}$ is equal to an integer number of cyclotron energies. Studies in TQWs concerning characterization and magnetotransport measurements have been carried out in Ref. [7] with remote doping. No observations about MIS phenomena in theses systems have been reported.

This paper is organized as follows: the first part gives an introduction into basics of a triple quantum well systems. The second and third part will introduce magnetotransport measurements which are used to extract the quantum lifetime. We also present a theoretical model which satisfactorily describes our obtained results.

2. Basics of triple quantum wells

This section gives an introduction into magnetotransport and a basic analysis of triple quantum wells with three occupied 2D subbands. Our samples are symmetrically doped GaAs TQWs with a total electron sheet density $n_s = 9 \times 10^{11}\,\mathrm{cm}^{-2}$ and mobilities of $5 \times 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$ (wafer A) and $4 \times 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$ (wafer B). The central well width is about 230 Å and both side wells have equal well widths of 100 Å. The barrier thickness d_b is 14 Å (wafer A) and 20 Å (wafer B).

The FFT analysis of longitudinal resistance allows us also to extract the corresponding energy gaps. We have found $\Delta_{12} = 4.0$ meV, $\Delta_{13} = 5.4$ meV and $\Delta_{23} = 1.4$ meV for a TQW with

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$d_b = 14\,\text{Å}$ in agreement with the fitted parameters in Table 1. Therefore, the density in the central well is 30% smaller than in the side wells [see Fig. 1(b)]. The energy gaps in Table 1 characterize the coupling strength between the quantum wells. Fig. 1(a) schematically presents the TQW system with central well (c) and the side wells (l1 and l2) with three occupied 2D subbands. In a perpendicular magnetic field, Landau levels (LLs) pass sequentially the Fermi energy and the LL staircases associated with each subband is sketched in Fig. 1(a).

3. Magnetotransport and theoretical model

We have performed temperature dependent measurements in a dilution fridge (down to 50 mK) and in a VTI up to 25 K. First, we present low-temperature magnetoresistance measurements for TQWs with different barriers in Fig. 2. For this low temperature, MIS oscillations are superimposed by SdH oscillations. With increasing barrier thickness, when tunnel coupling is weaker, the subband separation $\Delta_{jj'}$ becomes smaller and the probability of intersubband transitions of electrons decreases, which is reflected in the periodicity and in the amplitude of MIS oscillations.

In Fig. 3, we show temperature dependence of the MIS oscillations from $T = 1.4\,\text{K}$ to $T = 20\,\text{K}$. MIS oscillations are well-pronounced up to 10 K and are visible even at 20 K whereas SdH oscillations are completely damped for $T > 10\,\text{K}$ in the interval of magnetic field $B < 1\,\text{T}$. The MIS oscillation picture in

Table 1
Extracted energy gaps by fitting MIS periodicity of experimental data to the theoretical model in Eq. (2).

wafer	Δ_{12} (meV)	Δ_{23} (meV)	Δ_{13} (meV)
A	3.9	1.4	5.3
B	2.4	1.0	3.4

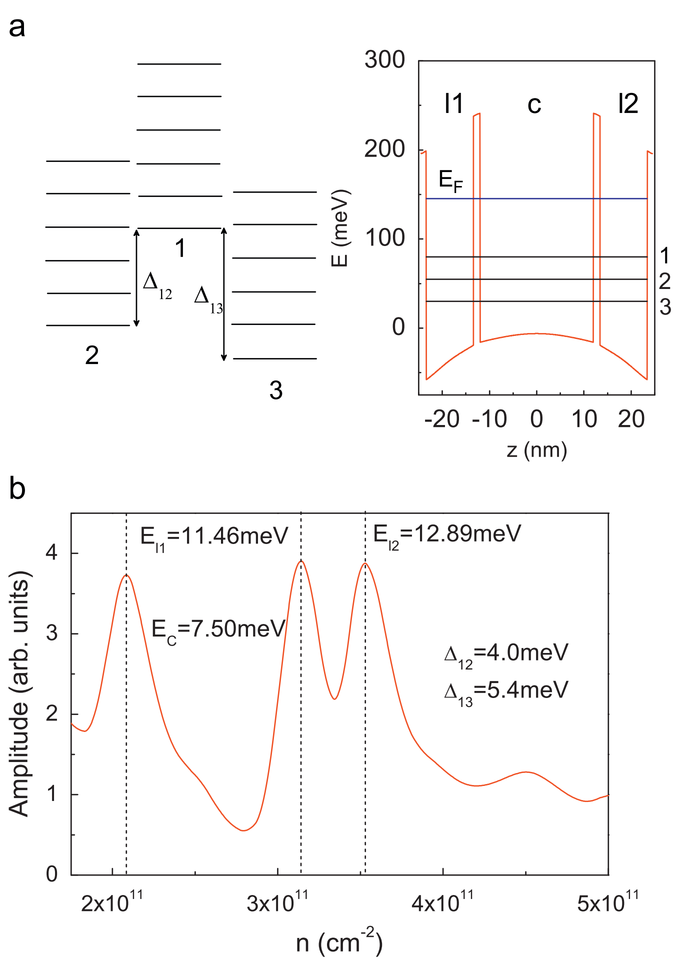

Fig. 1. (a) Staircase of Landau levels for three-subband system and picture of a triple quantum well with three occupied subbands (1,2,3). (b) FFT spectra for the TQW with a barrier thickness of $d_b = 14\,\text{Å}$.

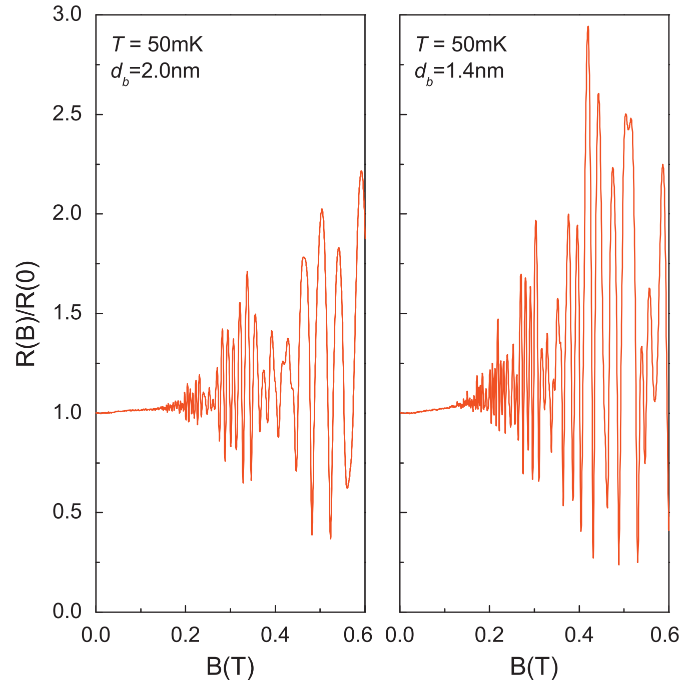

Fig. 2. Normalized magnetoresistance in TQWs with a barrier thickness of 14 Å and 20 Å at $T = 50\,\text{mK}$. MIS oscillations are superimposed by low-field SdH oscillations.

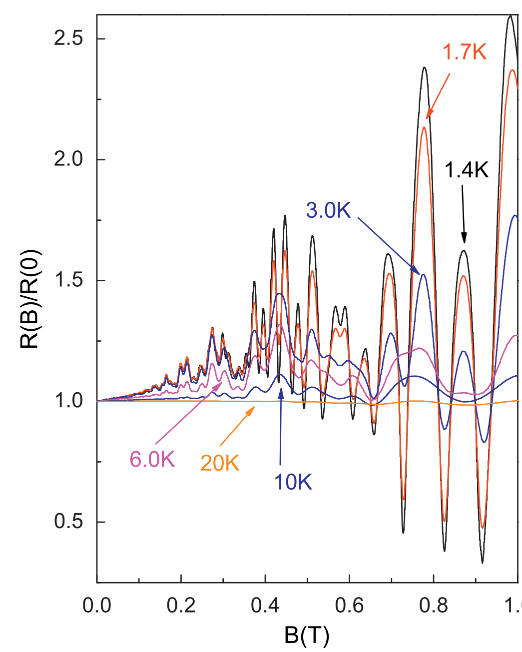

Fig. 3. Temperature dependence of the normalized magnetoresistance shows MIS oscillations which are, for low temperatures, superimposed by SdH oscillations. Whereas SdH oscillations are damped for high temperatures, MIS oscillations survive up to 20 K.

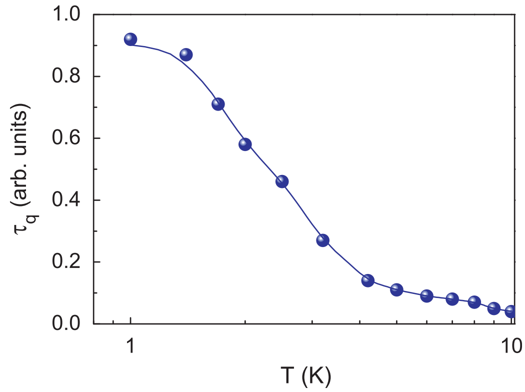

Fig. 4. Temperature dependence of the quantum lifetime τ_q extracted from the MIS oscillation amplitude. The blue line is a guide to the eye.

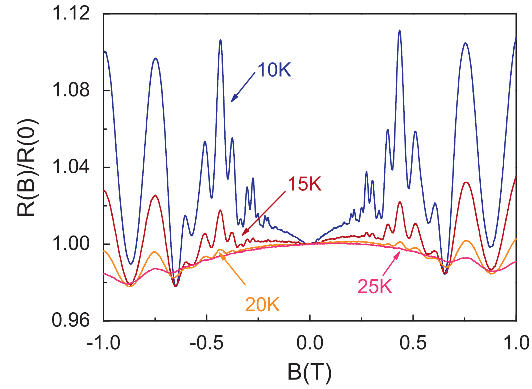

Fig. 5. MIS oscillations for high temperature from 10 to 25 K. Whereas SdH oscillations are already damped, MIS oscillations survive up to these temperatures.

TQWs is more complicated compared to DQWs and demonstrates the presence of more than one period, as seen also already in the FFT analysis in Fig. 1(b).

To describe the data in more detail, we have generalized the theory for DQWs [6] to the case of three subbands. The dissipative resistivity [8] is written as

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

where $\rho_d^{(0)}$ is the classical resistivity, $\rho_d^{(1)}$ is the first-order quantum contribution describing the SdH oscillations, and $\rho_d^{(2)}$ is the second-order quantum contribution containing the MIS oscillations. The contribution $\rho_d^{(1)}$ is linear in Dingle factors $d_j = \exp(-\pi/\omega_c\tau_j)$, where τ_j are the quantum lifetimes for each subband. The contribution $\rho_d^{(2)}$ is quadratic in d_j. However, $\rho_d^{(1)}$ always contains the thermal suppression factor $X/\sinh X$ with $X = 2\pi^2 T/\hbar\omega_c$, and can be neglected. The remaining terms are considered below under a simplified approximation that partial subband occupations n_j, transport scattering rates $\nu_{jj'}^{tr}$, and quantum lifetimes τ_j are equal to each other ($\tau_j = \tau_q$). Due to high total density and strong tunnel coupling, this approximation is reasonable for our system. In the regime of classically strong magnetic fields, we obtain the magnetoresistance in the form

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

where $d = \exp(-\pi/\omega_c\tau_q)$. This theoretical model is in a good agreement with our observations and confirms also the value of the energy gaps $\Delta_{jj'}$. The periodicity of the oscillations is determined by a mixture of terms with different subband separation energies $\Delta_{jj'}$, while the amplitude is governed by the quantum lifetime τ_q of electrons. It is well established, both theoretically and experimentally, that τ_q decreases with increasing temperature due to an enhancement of electron-electron scattering. This effect is reflected by the observed suppression of the MIS oscillation amplitude with increasing temperature.

4. Quantum lifetime of electrons

In order to investigate the quantum lifetime of electrons we have extracted from temperature dependent measurements between $T = 1.4$ K and $T = 10$ K the amplitude of several MIS oscillation maxima and constructed the Dingle plots.

The result is shown in Fig. 4. Note, that the quantum lifetime is constant for $T < 1$ K and decreases with increasing temperature. This behavior is similar to that observed in DQWs and is in agreement with the concept of electron-electron scattering contribution.

Finally, Fig. 5 presents magnetoresistance from $T = 10$ K to $T = 25$ K in order to point out that MIS oscillations survive up at high temperatures. The MIS feature at 0.43 T is visible up to 20 K and at 25 K, the feature at 0.75 T is still pronounced. Note that SdH oscillations are already damped.

In conclusion, we have studied the magneto-intersubband (MIS) oscillations in high-density TQWs and analyzed low-field transport properties for different barrier widths and temperatures in these systems. We have found that the MIS oscillations survive at high temperatures ($T \simeq 25$ K) and demonstrate peculiar behavior associated with more than two populated subbands. Using the magnetoresistance plots, we have extracted temperature dependence of quantum lifetime of electrons in a wide temperature range. Further studies, including gate-controlled measurements in the systems with different barriers and well widths are necessary to get a complete understanding of this phenomenon.

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