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Spin–Orbit Coupling in *n*-Type PbTe/PbEuTe Quantum Wells

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Magnetoresistance measurements were performed on an *n*-type PbTe/PbEuTe quantum well and weak antilocalization effects were observed. This indicates the presence of spin–orbit coupling phenomena and we showed that the Rashba effect is the main mechanism responsible for this spin–orbit coupling. Using the model developed by Iordanskii et al., we fitted the experimental curves and obtained the inelastic and spin–orbit scattering times. Thus we could compare the zero field energy spin-splitting predicted by the Rashba theory with the energy spin-splitting obtained from the analysis of the experimental curves. The final result confirms the theoretical prediction of strong Rashba effect on IV–VI based quantum wells.

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1. Introduction

The spin–orbit (SO) coupling for electrons in semiconductors nanostructures has been considered as one of the bases for new spintronic devices and has attracted much attention in the last two decades [1–6]. In particular, some effort has been dedicated to develop a spin-based field effect transistor [6]. For this reason a deep study of the main issues concerning the determination of SO coupling in different systems is necessary.

Spin–orbit interaction is a relativistic effect that occurs when a quantum mechanical particle with a non-zero spin moves in a region with a non-zero electric field. When an electron is moving with relativistic velocities in a static electric field, in the rest frame of the electron the original static electric field transforms into a field that has also a magnetic component. The presence of this effective magnetic field affects both the dynamics of the spin and the total energy of the electron. This interaction is called spin–orbit coupling and leads to the relaxation of the electron spin. The static electric field causing the spin–orbit interaction can have different physical origins, for example being the electric field of the atomic nucleus, or related to the crystal or the band structure of the solid.

Two main spin relaxation mechanisms were found to be the most relevant for conduction electrons in metals and semiconductors: Elliot–Yafet (EY) and D'yakonov–Perel (DP) [7]. The EY process leads to spin-relaxation due to the mixing of the valence-band states into the conduction band, which is more common in narrow-gap semiconductors [4]. In the DP case, there is a lift of the spin degeneracy due to the presence of a finite electric field in crystals lacking inversion symmetry (the crystal field). Therefore, the electrons feel a momentum-dependent effective magnetic field and the spin precesses around this effective field. Even if the internal electric field ($\boldsymbol{E}$) being constant, the direction of the effective magnetic field ($\boldsymbol{B}$) changes with each scattering event. The DP can also be separated into two terms named Rashba (caused by the asymmetry of the quantum well or heterojunction) and Dresselhaus (arises from the lack of inversion in the original crystal).

To study spin–orbit coupling, weak localization/antilocalization has been one of the most powerful tool and is commonly used to obtain the spin–orbit as well as the inelastic scattering times in films and quantum wells [8, 9]. Weak localization is a quantum effect that arises from the quantum interference between the electronic wave functions moving in the same path but in opposite directions. Its suppression by spin–orbit coupling gives rise to the phenomenon known as weak antilocalization which

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manifests itself as a negative magnetoconductance at low fields (the opposite picture of the weak localization).

There are many evidences that the Rashba term gives a bigger contribution to the splitting in the case of narrow-gap heterostructures [10–15] due to the strong spin–orbit interaction. In the particular case of the IV–VI lead-salt semiconductors, just a few studies had been carried out [16]. The lead-salts form an important family of semiconductor compounds used in different electronic applications [17, 18]. From the basic physics research point of view, PbTe QW's present an advantage as compared to the other III–V based structures since its lead-salt crystalline structure presents bulk inversion symmetry. Hence, the spin–orbit splitting in such structures is purely Rashba instead of a mixture of Rashba and Dresselhaus, commonly observed in III–V compounds.

2. Theory

The Hamiltonian proposed by Rashba for the 2D case using general symmetry arguments is [19]:

$$H = \frac{\hbar^2 k^2}{2m^*} + \alpha \left(\hat{\boldsymbol{k}} \times \boldsymbol{z} \right) \cdot \sigma \,, \tag{1}$$

where $\sigma = \sigma_x \hat{x} + \sigma_y \hat{y} + \sigma_z \hat{z}$ is the Pauli matrices vector, $\hat{\boldsymbol{k}}$ is the unit vector along the growth direction and α is a structure parameter, sometimes called spin–orbit coupling parameter.

Working within the effective mass approximation and the eight-band Kane model it is possible to obtain α.

An approximate expression for α can be derived through the infinite barrier approximation [20]. In this approximation, one considers that the electron is mainly localized in the well and that the penetration of the wave function in the barrier can be neglected. Hence, the parameter α can be written as

$$\alpha = \alpha_0 \langle E(z) \rangle e \,, \tag{2}$$

where e is the electron charge. The parameter α_0 and the average electric field in the well, $\langle E(z) \rangle$, are given by

$$\alpha_0 = \frac{\hbar^2}{2m^*} \frac{\Delta}{E_\mathrm{G}} \frac{2E_\mathrm{G} + \Delta}{(E_\mathrm{G} + \Delta)(3E_\mathrm{G} + 2\Delta)} \,, \tag{3}$$

$$\langle E(z) \rangle = \frac{4\pi e n}{\varepsilon} \,. \tag{4}$$

In these expressions, Δ is the spin–orbit valence band energy splitting, E_G is the energy gap, n is the carrier concentration and ε is the dielectric constant.

Table presents the values obtained for α_0 for PbTe, as given by Eq. (3), and for the InSb, InAs, GaSb and GaAs semiconductors according to Ref. [13], also using Eq. (3), together with the values of the energy gaps and valence band spin-splittings (Δ). Comparing some values of α_0 available in the literature and those obtained using Eq. (3), we observed that the values found in different publications are 5.3 Å^2 for GaAs [9] and 116 Å^2 for InAs [21] while the values calculated through Eq. (3) are 6.0 Å^2 and 114 Å^2, respectively, as presented in Ref. [13].

TABLE

Values obtained for α_0 for PbTe, as given by Eq. (3), and for the semiconductors InSb, InAs, GaSb and GaAs according to Ref. [13], together with the values of the energy gaps (E_G) and valence band spin-splitting (Δ). The values of α_0 decrease from InSb to GaAs while the energy gap increases. Data obtained for $T = 300$ K.

	InSb	PbTe	InAs	GaSb	GaAs
α_0 [Å^2]	498	445.7	114	33.1	6.0
E_G [meV]	170	300	360	700	1430
Δ [eV]	0.779	0.77	0.41	0.8	0.35

Considering the uncertainties in the material parameters and the approximation in the theoretical model, we see that the values obtained by Eq. (3) and presented in Table are in very good agreement with the values presented in the literature. Also, through Table, we can observe the dependence between the Rashba constant α_0 and the other materials parameters. In particular, we observe that the semiconductors with smaller energy gap present higher values of α_0 which leads to stronger Rashba splitting. Even though we compare the PbTe (IV–VI semiconductor) results with III–V materials, this comparison seems to be coherent according to Table.

The Rashba spin-splitting energy can be calculated according to the expression

$$\Delta_\mathrm{R} = \alpha k_\mathrm{F} \,, \tag{5}$$

where $k_\mathrm{F} = \sqrt{2\pi n}$ is the Fermi wave vector. Through magnetoresistance measurements performed on PbTe/PbEuTe quantum wells, it is possible to obtain the spin-splitting (Δ_so) due to spin–orbit interaction and compare with the values evaluated from Eq. (5).

3. Magnetoresistance measurements

The measurements were performed on a sample grown using molecular beam epitaxy (MBE) technique and the contacts were made using Van der Pauw geometry. The structure is as follows: a $Pb_{0.9}Eu_{0.1}Te$ buffer layer with 2.7 μm thickness, an n-type $Pb_{0.9}Eu_{0.1}Te$:Bi barrier with 308 Å, a 145 Å thickness PbTe quantum well and another n-type $Pb_{0.9}Eu_{0.1}Te$:Bi barrier with 308 Å. The carrier concentration in the quantum well varied in the range 5.0×10^{15} m^{-2}–3.6×10^{15} m^{-2} as the temperature is varied between 1.2 and 25 K.

Figure 1a presents the experimental values of the magnetoconductance for the sample as a function of B/B_0 ($B_0 = \hbar/4De\tau_0$ is the transport magnetic field with the diffusion constant D and the elastic lifetime τ_0). The weak antilocalization (negative magnetoconductance) observed is a clear signature of the presence of spin–orbit coupling. It is important to mention that the large weak antilocalization amplitude observed in these curves suggests the presence of a strong spin–orbit coupling as compared to other systems [9, 21–24].

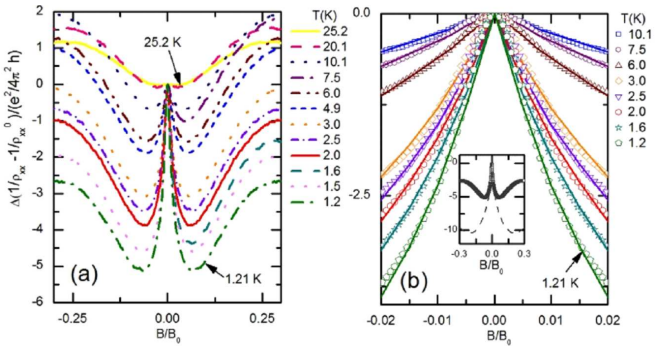

Fig. 1. (a) Experimental magnetoresistance measurement for n-type PbTe/$Pb_{0.9}Eu_{0.1}Te$ QW. (b) Fitting of the experimental points using the model of Iordanskii et al. For the sake of simplicity, we present a reduced number of fitted curves. The inset shows the deviation between theory and experiment for the lowest temperature measured.

The measurements were performed for magnetic field between -1 and 1 T.

4. Results and discussion

The minimum of the curves lies between 0.015 and 0.007 T from the lower to the highest temperature, respectively. These values should correspond to the field values where the weak antilocalization is suppressed ($B_{\min} \sim B_{so}$). To fit the curves presented in Fig. 1a we used the model developed by Iordanskii et al. [25] taking into account only the Rashba term. We also considered that just the first subband of the longitudinal valley is occupied based on the results presented in Ref. [26] and considering our Fermi energy ($E_F = \hbar^2 k_F^2/2m^*$, where k_F is the Fermi wave vector) of about 18 meV.

The fitting results obtained by the application of the theoretical model are presented in Fig. 1b. For sake of simplicity, only a few curves are presented, though all the curves presented in Fig. 1a had been fitted. The model is limited by the condition $B \ll B_0$ and it is in fact valid in the region where the antilocalization is observed. For the measurements presented in this work, the model could fit the experimental curves only for magnetic field values smaller than 4 mT ($B/B_0 < 0.02$). Attempts to fit the higher field points, lead to a deviation from the low field region and vice versa. This problem has been encountered by other groups using different compounds and other theoretical models [1, 27, 28]. The inset in Fig. 1b shows the fitting to the lowest temperature measured ($T = 1.2$ K) in a larger range of magnetic field exhibiting the deviation between theory (dashed line) and experiment (points).

Figure 2a shows the inelastic (τ_i) and spin–orbit (τ_{so}) scattering times obtained from the fittings presented in Fig. 1b. According to this figure, τ_i increases as the temperature decreases, while τ_{so} is almost constant between 25 and 5 K and starts to decrease more pronounced after this point. The theory of D'yakonov–Perel for spin-dephasing mechanism predicts that the spin–orbit scattering mechanism is temperature independent [29]. In Fig. 2a it is not possible to confirm such behavior. A fitting of τ_i following the temperature dependence law $\tau_i = T^{-\beta}$ gives a value of -0.76 for β (see Fig. 2b). It is well known that the electron–electron interaction, involving small energy transfer at each scattering event, has a temperature dependence like T^{-1} ($\beta = 1$) [30] suggesting that this can be the main inelastic scattering mechanism in this system. The Rashba field $B_R = (m^2/e\hbar^3)\alpha_0^2 E^2$ [9] is calculated and presented in Fig. 3a together with the $B_{so} = (\hbar/4De\tau_{so})$ and the $B_{\min}$ in order to compare the values. B_R depends only on the material properties and their calculated values are very close to $B_{\min}$, obtained from the minimum of the curves, indicating that the Rashba effect is possibly the main responsible for the spin-splitting in this system. Differences between B_R and the values obtained from the fittings indicates that additional considerations should be taken into account on the theoretical model in order to obtain a better description of the physical picture.

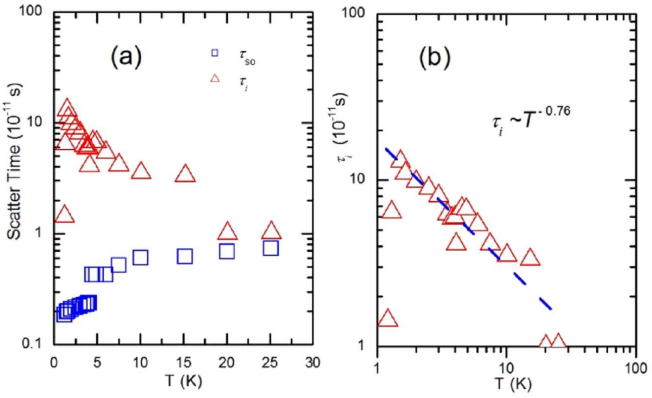

Fig. 2. (a) Inelastic (τ_i) and spin–orbit (τ_{so}) scattering times obtained from the fitting procedure. (b) The fitting of the inelastic scattering time according to temperature dependence law $\tau_i = T^{-\beta}$.

Using Eq. (5), we calculate the expected zero field spin-splitting energy for the PbTe/PbEuTe QW due to the Rashba effect (Δ_R). We have used the value of 0.77 eV for the spin–orbit split level below the valence band maximum [31]. The energy splitting due to spin–orbit interaction can be calculated using the relation: $\Delta_{so} = \hbar(\tau_0\tau_{so})^{-1}/2$. The values of Δ_R and Δ_{so} as a function of the carrier density can be observed in Fig. 3b and show a reasonable agreement. This also supports our assumption that the Rashba effect is the main reason for the spin-splitting energy in the PbTe QWs based on theoretical predictions [16, 31, 32].

5. Conclusions

We performed magnetoresistance measurements on an n-type PbTe/$Pb_{0.9}Eu_{0.1}Te$ quantum well and the ob-

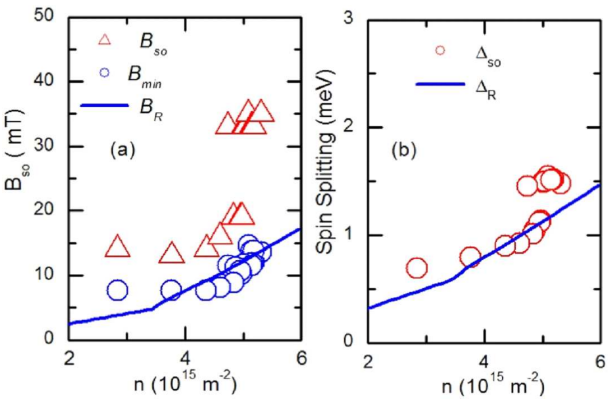

Fig. 3. (a) The Rashba field B_{R} together with the B_{so} and B_{min} values. (b) The values of Δ_{R} and Δ_{so} as a function of the carrier density (see text for further explanations).

served weak antilocalization effects indicated the presence of spin–orbit coupling. Using the model developed by Iordanskii et al. we analyzed the experimental curves and showed that this coupling is caused mainly by the Rashba effect. From the analysis, we obtained the inelastic and spin–orbit scattering times and the zero field spin-splitting which is very close to the Rashba prediction. These results confirm the theoretical prediction of a strong Rashba effect on IV–VI quantum wells.

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