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Rashba splitting of kinetically bound states in gated HgCdTe surface quantum wells

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Abstract

The Rashba spin–orbit splitting of 2D electron gas in gated HgCdTe surface quantum wells on *n*-HgCdTe is studied experimentally (by the magneto-capacitance spectroscopy of Landau level method) and theoretically with emphasis on the peculiarities of spectrum at surface densities N_s corresponding to the onset of 2D subbands occupancy, where the regime of kinetic binding is realized. Although the spin–orbit splitting in kinetic confinement regime is small, the "Rashba polarization" $\Delta n/n$ can achieve 100% because of strong difference in values of cutoff wave vector k_c for different spin-split sub-subbands.

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The Rashba mechanism of spin–orbit coupling, being the most promising for the gate voltage V_g control of spin dynamic in spintronics devices, is of high present-day interest. The largest magnitudes of Rashba splitting, arising from interband mixing by electrostatic confinement potential, are expected and observed experimentally in structures based on narrow- and especially zero-gap semiconductors (NGS) because of small effective mass and because the spin–orbit interaction in NGS is the largest among all materials [1–3]. Especially large splitting is achieved in inversion layers on HgTe and zero-gap HgCdTe in which the confinement potential is extremely asymmetrical [4–6]. Another specific feature arising from the multiband nature of the Hamiltonian in narrow-gap semiconductors is strong non-parabolicity. Because of this the carrier motion in the confinement direction is mixed with one in 2D plane and the electron confinement in quantum wells can induce not only by the electrostatic potential but by the 2D wave vector also. As a result, at near the onset of 2D subbands occupancy, the carriers with large enough 2D wave vectors $k > k_{ci}$ (the cutoff wave vector k_{ci} depends on parameters of quantum well and subband index *i*) can be bounded, whereas the bound states with zero or small $k < k_{ci}$ do not exist [7–9]. The surface quantum wells are also the most favorable subject to investigate such kinetically bound states (KBS) because of an opportunity to vary the depth of quantum wells near the start of 2D subbands to occupation (nearly flat potential profile for ground subband). The accumulation layers on degenerate semiconductors are of a special interest because KBS may be occupied in this system under thermodynamic equilibrium and thus, they can be manifested in magneto-oscillation effects. Because the cutoff wave vector k_c is strongly sensitive to the details of energy spectrum and confinement potential there is the reason to hope that the kinetic bounding is strongly affected by spin–orbit interaction also. The comparison between the magnitude of Rashba effect in inversion channels and in accumulation layers is also of appreciable interest because, as it was recently shown, the doping parameters of substrate not only affect the magnitude of the Rashba effect but also the gate-voltage dependence of spin–orbit splitting [10].

The zero-gap $Hg_{0.88}Cd_{0.12}$ Te ($N_D - N_A = 5 \times 10^{16}\,cm^{-3}$) MOS structures with a 70-nm thick anodic oxide film were investigated. The gate electrodes of typical

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area $5 \times 10^{-4}\,\mathrm{cm}^2$ were formed by evaporation of Pb. Because the traditional Shubnikov–de Haas measurements cannot be used in accumulations layers on degenerate semiconductors (because of the shunting of 2D channel by the bulk) the magneto-oscillations of differential capacitance of MOS structures were measured in the dark, typically at 1 MHz and with a test signal amplitude of 3 mV. In framework of magneto-capacitance spectroscopy of Landau level method we employed, the above drawback (strong charge exchange between the 2D layer and substrate) turns into advantage because it ensures the equilibrium regime of capacitance measurements. The results presented below are measured at $T = 4.2\,\mathrm{K}$, however, distinct capacitance oscillations and their beating are observed up to $T = 30\,\mathrm{K}$. For the theoretical analysis we used the Hartree approximation for 8×8 Kane model assuming an infinite potential barrier at the interface and zero boundary conditions for components of wave function corresponding to the light branch of Γ_8 band.

The capacitance magneto-oscillations caused by the Landau quantization of 2D subband spectrum (see inset in Fig. 1) show the population up to three 2D subbands at large gate voltages. The well-resolved split of Fourier spectra into two lines in each 2D subband is observed in wide range of subband densities. By magneto-oscillation methods, the values of wave vector at Fermi energy k_{Fi} are measured experimentally. In case of full occupied states ($k_{ci} = 0$) this quantity at low temperature is directly related to subband occupation $n_i^{\pm} = (k_{Fi}^{\pm})^2/4\pi$. Measured and calculated carrier distribution among the Rashba spin-split subbands is shown in Fig. 1 as a function of total electron concentration N_s (including the mobile surface-electron states) induced in semiconductor, which can be determined independently via capacitance of MOS structure and gate voltage.

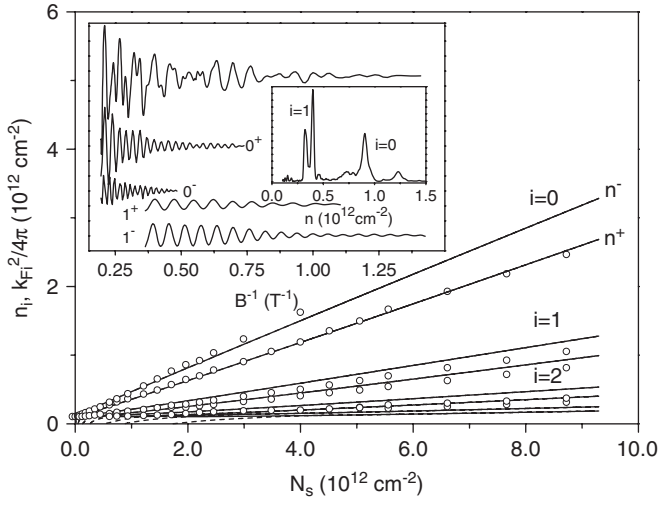

Fig. 1. The typical experimental capacitance oscillations, their Fourier transform (FT) and partial oscillations for different Rashba branches extracted from FT of experimental C(B) pattern (inset) and calculated subband concentrations n_i and $k_{Fi}^2/4\pi$ values vs N_s. Measured values of $k_{Fi}^2/4\pi$ are shown as circles.

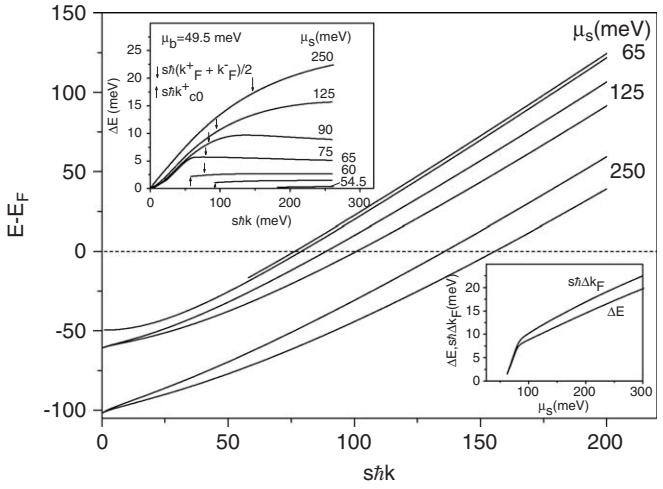

Fig. 2. The calculated in 8×8 Kane approximation dispersions $E^{\pm}(k)$ and spin–orbit splitting (upper inset; averaged Fermi wave vectors and cut-off wave vectors for high-energy Rashba sub-subband are shown by arrows) as a function of wave vector k (in energy units $s\hbar k$, where s is Kane velocity) for ground subband $i = 0$. The energy splitting at Fermi level and values of $s\hbar(k_F^- - k_F^+)$ are shown in low inset as a function of μ_s.

The Rashba sub-subband dispersions $E^{\pm}(k)$ and SO splitting ΔE we calculated with allowance for full band structures are shown in Fig. 2 as a function of k. At small band bending $V_s = \mu_s - \mu_b$ (μ_s and $\mu_b = 49.5\,\mathrm{meV}$ are surface and bulk chemical potential) corresponding to the beginning of subband occupation, the subband dispersions are terminated at small k, that is inherent to kinetic binding regime. At large k, the dispersions in two Rashba branches are very close to each other (and to dispersion in the bulk). In sample investigated the ground subband is occupied kinetically in μ_s intervals 54–57 and 62–75 meV for low- and high-energy branches correspondingly (see Fig. 3). In this regime the energy Rashba splitting ΔE is practically k independent (upper inset in Fig. 2). The Rashba splitting is essentially nonlinear in k at larger μ_s also, when the 2D states are occupied by usual way (with $k_{ci} = 0$). The above behavior refers equally to the excited subbands near their start. Thus, the simple Rashba model with linear in k term and energy independent α parameter is not applicable to describe the SO splitting in system we investigated. The energy ΔE_i and wave vector Δk_i splitting on Fermi level are small at V_s corresponding to the onset of 2D subbands occupancy and rapidly increase with V_s in the KBS occupation regime (lower inset in Fig. 2). At the same time, the cutoff wave vectors k_{ci} are essentially different for two Rashba branches. For the subbands occupied kinetically, the expression for $n^{\pm}$ have to be modified to $n_i = (k_{Fi}^2 - k_{ci}^2)/2\pi$. These values are plotted in Fig. 3 as a function of μ_s and total concentration N_s. The experimental values of $k_{Fi}^{\pm}$ determined from Fourier spectra are also shown.

Unfortunately, in the accumulation layers the Rashba polarization $P_R = (n^- - n^+)/(n^- + n^+)$ ($n^{\pm}$ are concentrations in different Rashba branches of spectrum) cannot be