Low Temperature Physics/Fizika Nizkikh Temperatur, 2019, v. 45, No. 2, pp. 185–191

Spin splitting of surface states in HgTe quantum wells

A.A. Dobretsova[1,2], Z.D. Kvon[1,2], S.S. Krishtopenko[3,4], N.N. Mikhailov[1], and S.A. Dvoretsky[1]

[1]*Rzhanov Institute of Semiconductor Physics, Novosibirsk 630090, Russia*

[2]*Novosibirsk State University, Novosibirsk 630090, Russia*

[3]*Institute for Physics of Microstructures RAS, GSP-105, Nizhni Novgorod 603950, Russia*

[4]*Laboratoire Charles Coulomb, UMR CNRS 5221, University of Montpellier, Montpellier 34095, France*

E-mail: kvon@thermo.isp.nsc.ru
dobretsovaaa@gmail.com

Received October 11, 2018, published online December 20, 2018

We report on beating appearance in Shubnikov–de Haas oscillations in conduction band of 18–22 nm HgTe quantum wells under applied top-gate voltage. Analysis of the beatings reveals two electron concentrations at the Fermi level arising due to Rashba-like spin splitting of the first conduction subband H_1. The difference ΔN_s in two concentrations as a function of the gate voltage is qualitatively explained by a proposed toy electrostatic model involving the surface states localized at quantum well interfaces. Experimental values of ΔN_s are also in a good quantitative agreement with self-consistent calculations of Poisson and Schrödinger equations with eight-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian. Our results clearly demonstrate that the large spin splitting of the first conduction subband is caused by surface nature of H_1 states hybridized with the heavy-hole band.

Keywords: spin splitting, Rashba effect, surface states, Shubnikov–de Haas oscillations, quantum wells.

Introduction

Thin films based on HgTe are known by a number of its unusual properties originating from inverted band structure of HgTe [1–4]. The latter particularly results in existence of topologically protected gapless states, arising at HgTe boundaries with vacuum or materials with conventional band structure. Although these states were theoretically predicted more than 30 years ago [5–7], clear experimental confirmation was not possible at that time due to lack of growth technology of high quality HgTe-based films. Experimental investigations of wide (the width $d \geq 70$ nm) strained HgTe quantum wells (QWs), which started only in 2011, confirmed existence of the predicted surface states and revealed their two-dimensional (2D) nature [4,8,9].

In comparison with other materials with the inverted band structure, in which the surface states are known being Dirac-like [10–12], HgTe spectrum involves heavy-hole band $|\Gamma_8,\pm 3/2\rangle$ modifying the surface state dispersion. Although strain opens a bulk band-gap and results thus in three dimensional (3D) topological insulator state of wide HgTe quantum wells [4,8,9], it does not cancel strong hybridization of the surface states with the $|\Gamma_8,\pm 3/2\rangle$ band. As a result, the surface states in strained HgTe films can be resolved only at large energies, while at the low ones they are indistinguishable from conventional heavy-hole states [13,14].

In thin films of 3D topological insulator the surface states from the opposite boundaries may be coupled by quantum tunneling, so that small thickness-dependent gap is opened up [15–17]. In strained HgTe thin films, the latter arises deeply inside the heavy-hole band at the energies significantly lower than the top of the valence band [4]. In the ultrathin limit, the HgTe quantum well transforms into semimetal [2,18] and then to 2D topological insulator [1,19] with both gapped surface and quantized bulk states.

On the other hand, the electronic states in HgTe QWs are classified as hole-like H_n, electron-like E_n or light-hole-like LH_n levels according to the dominant contribution from the bulk $|\Gamma_8,\pm 3/2\rangle$, $|\Gamma_6,\pm 1/2\rangle$ or $|\Gamma_8,\pm 1/2\rangle$ bands at zero quasimomentum $k = 0$ [19]. The strong hybridization in inverted HgTe QWs results in the upper branch of the gapped surface states being represented by the H_1 subband [4]. At large quasimomentum k the wave-functions of H_1 subband are localized at the QW interfaces, while at Γ point of the Brillouin zone they are localized in the QW center and are thus indistinguishable from other 2D states.

The gapped surface states in the films of 3D topological insulators exhibit sizable Rashba-type spin splitting, arising due to electrical potential difference between the two surfaces [20]. Such spin splitting was first observed in QWs of Bi_2Se_3 [21], which is a conventional 3D topological insulator with Dirac-like surface states [10–12,21]. The spin split-