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Interlayer current near the edge of an InAs/GaSb double quantum well in proximity with a superconductor

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Recent interest to an InAs/GaSb two-dimensional (2D) bilayer system is mostly connected with the problem of a topological insulator [1–3]. Bulk spectrum with band inversion is realized for the 12 nm thick InAs (electrons) and 10 nm thick GaSb (holes) layers [4]. On the other hand, interlayer effects are of primary importance in different bilayer systems [5]. Thus, it seems to be important to study interlayer effects also for a recently popular InAs/GaSb bilayer in proximity with a superconductor.

The samples are grown by solid source molecular beam epitaxy on semi-insulating GaAs (100) substrates. As obtained from Hall measurements, the 2D bilayer system is characterized by bulk hole-type conductivity. From magnetoresistance oscillations, the mobility at 4K is about $2 \cdot 10^4\,\mathrm{cm}^2/\mathrm{Vs}$ and the carrier density is $2 \cdot 10^{12}\,\mathrm{cm}^{-2}$. We fabricate *side* [6] superconductor-normal (NS) junctions by sputtering 50 nm thick Nb or NbN film over the 80 nm or 60 nm high mesa step. Charge transport is investigated in a three-point technique: one superconducting electrode (S1) is grounded; a current is fed through the normal Ohmic contact N1; we measure a voltage drop between two superconducting electrodes S1 and S2.

Fig. 1a–c presents examples of the $I - V$ characteristics in zero magnetic field for the 80 nm (a,b) and 60 nm (c) mesa step samples. The non-zero voltage at low currents in Fig. 1 is inconsistent with the (edge or bulk) Josephson supercurrent between the superconducting potential contacts. Instead, it seems that the jumps on the experimental $I - V$s originate from a single (grounded) Nb-InAs/GaSb junction, which is connected *in-series* with a part of the 2D bilayer system.

The $I - V$ slope at zero current demonstrates strong increase near the niobium superconducting critical field $B_c = 2.5$ T, as demonstrated in Fig. 1e for the 60 nm mesa step sample in normal magnetic field. In higher magnetic fields, well-developed Shubnikov-de-Haas magnetoresistance oscillations appear. The latter is a fingerprint of a 2D conducting system, so the $I - V$ curves in Fig. 1 reflect charge transport through the InAs/GaSb bilayer to the side superconducting Nb contact.

Suppression of the critical (jump) current $I_c(B)$ is sensitive to the magnetic field orientation. The oscillations in $I_c(B)$ with equal $\Delta B = 0.5$ T period are observed if the magnetic field is oriented within the 2D plane, either normal or parallel to the mesa edge. In contrast, $I_c(B)$ is diminishing slower, without any sign of oscillations, in the magnetic field which is normal to the 2D plane.

For the 80 nm mesa step sample, I_c weakly depends on temperature at low $T < 0.5$ K, but sharply falls to zero at higher 0.5 K$< T < 1.2$ K. There is only slow (within 5 %) $I_c(T)$ dependence below 1.2 K for the 60 nm mesa step sample. Because of the same niobium superconductor, this difference seems to be defined by different coupling of the Nb film to the InAs layer. For the 60 nm mesa step sample the Nb film is mostly coupled to the the bottom (electron) InAs layer, since this layer is not removed. This case corresponds to the maximum I_c in Fig. 1. For the 80 nm mesa step sample, the coupling to InAs and GaSb layers is also not equivalent: the common photoresist developer etches selectively the GaSb layer.

As a result, the jumps on the experimental $I - V$s correspond to some critical current I_c in a vicinity of a single (grounded) Nb-InAs/GaSb junction. We can identify the direction of the current from the $I_c(B)$ dependence on the magnetic field orientation. The oscillations in $I_c(B)$ are only observed if the magnetic field is oriented within the 2D plane, independently of the

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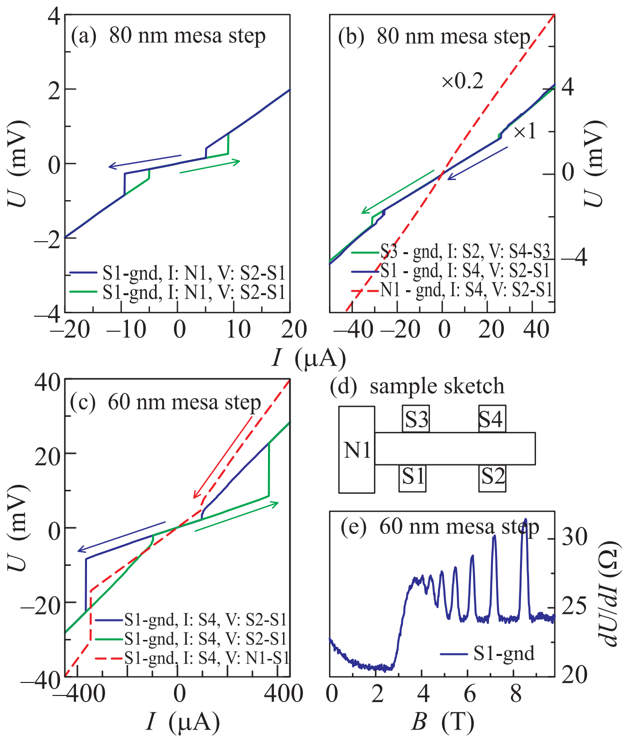

Fig. 1. (Color online) (a–c) – Examples of $I-V$ characteristics in different experimental configurations in zero magnetic field. (d) – Sample sketch to follow experimental configurations in (a–c). (a) – $I-V$s demonstrate two sharp jumps, which are subjected to hysteresis with the sweep direction (blue and green curves). The voltage drop is not zero between the jumps, it corresponds to $\approx 25\Omega$ differential resistance. (b) – $I-V$s coincide well for two symmetric probe connections (green and blue curves), the zero-bias slope corresponds to $\approx 60\,\Omega$. The $I-V$ curve is linear (red dash, $\approx 1\,k\Omega$ slope, please note $\times 0.2$ coefficient), if the normal (N1) contact is grounded instead of the niobium one. (c) – Similar $I-V$ characteristics with hysteresis (green and blue) for the 60 nm mesa step sample, the the zero-bias slope is $\approx 25\,\Omega$. The $I-V$ still demonstrates qualitatively the same behavior, if the voltage is taken from the normal contact N1 (red dashed curve). (e) – Zero-current differential resistance as a function of normal magnetic field. Magnetoresistance oscillations appear above 3.5 T, just after the superconducting critical field $B_c = 2.5$ T. All the curves are obtained at low temperature $T = 30$ mK $\ll T_c$

mesa edge orientation. On the other hand, $I_c(B)$ is diminishing slowly, without any sign of the oscillations, in the perpendicular to the 2D plane magnetic field. From this axial symmetry, I_c is only sensitive to the interlayer field-induced phase difference. The experimentally observed period $\Delta B = 0.5$ T corresponds ($S\Delta B \sim \Phi_0$) to the effective area $S \approx 10^{-10}\,\mathrm{cm}^{-2}$. If we assume the effective layers' spacing d as 10 nm, the lateral dimension of the proximity region can be estimated as $S/d \approx 1\,\mu$m. This value is consistent with the proximity-induced superconductivity, because of the niobium coherence length $\xi^0_{\mathrm{Nb}} = \hbar v_F/\Delta_{\mathrm{Nb}} \approx 1\,\mu$m.

Thus, the jumps on the experimental $I-V$ curves reflect the interlayer critical current. The proximity induced superconductivity can efficiently couple electron and hole layers due to the Cooper pair transfer. Thus, at low currents the experimental $I-V$ curve reflects the in-plane resistance of the 2D hole gas. The sharp jumps at high I_c are defined by the destruction of the coherent interlayer Cooper pair transport.

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