Quantum dot spectroscopy of proximity-induced superconductivity in a two-dimensional electron gas

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We report the realization of a hybrid superconductor-quantum dot device by means of top-down nanofabrication starting from a two dimensional electron gas in a InGaAs/InAlAs semiconductor heterostructure. The quantum dot is defined by electrostatic gates placed within the normal region of a planar Nb-InGaAs quantum well-Nb junction. Measurements in the regime of strong Coulomb blockade as well as cotunneling spectroscopy allow to directly probe the proximity-induced energy gap in a ballistic two-dimensional electron gas coupled to superconductors.

Hybrid devices in which a quantum dot (QD) is connected to superconducting (S) electrodes display a rich physical behavior, which stems from the coexistence of competing phenomena such as proximity superconductivity, Coulomb blockade and the Kondo effect. Several examples of hybrid QD devices have been demonstrated so far, all of which rely on nanostructures defined by bottom-up approaches such as carbon nanotubes, semiconductor nanowires and self-assembled QDs. Transport studies in these nanosystems have demonstrated Josephson currents in S-QD-S devices and tuning of the critical current by changing the QD charge state. Other authors have focused on quasiparticle transport, metal films has been probed using weakly-coupled tunneling and liftoff, and proximized normal states of the Nb films, proximity-induced superconductivity has been observed in a ballistic electronic system. While superconductivity in ballistic systems is a consequence of the proximity-induced energy gaps in the two-dimensional electron gas, it is not necessarily the case that the superconducting order in the leads and Kondo effect can coexist. In this letter we report the realization of a hybrid superconductor-quantum dot device by means of top-down nanofabrication starting from a two dimensional electron gas in a InGaAs/InAlAs semiconductor heterostructure.

In this letter we report the realization of a hybrid S-QD-S device by means of top-down nanofabrication, starting from a 2DEG confined in a In0.80Ga0.20As/In0.75Al0.25As heterostructure. Following previous work, the QD is formed by applying negative voltages to surface electrostatic gates placed on top of a narrow mesa strip etched in the heterostructure, and laterally contacted by superconducting niobium electrodes. We discuss the impact of the proximity-induced superconductivity on the transport properties in different regimes of coupling to the leads, and measure the proximity-induced energy gaps in the two-dimensional electron gas.

A scanning electron micrograph and the main nanofabrication steps are shown in Fig. 1(a,b). The active region of the heterostructure contains a 15 nm-thick δ-doped In0.80Ga0.20As quantum well sandwiched between In0.75Al0.25As barriers. The sheet electron density, measured from the period of Shubnikov - de Haas oscillations, is nS ≃ 5.9 × 1011 cm−2. The mobility μ ≃ 1.8 × 106 cm2V−1s−1 is equivalent to an electron mean free path lp ≃ 2.3 μm. InAs and In1−x,GaxAs alloys with high molar fraction x ≥ 0.75 have often been used in association with Nb for the realization of hybrid ballistic devices, thanks to their property of forming Schottky barrier-free junctions. For the same reason a suitable dielectric is required for the electrical insulation of the electrostatic gates.

The nanofabrication of the hybrid device requires several mutually-aligned steps of electron beam lithography (EBL). First [Fig. 1(a1)] we pattern a dielectric strip on the heterostructure surface, by means of EBL, using hydrogen silsesquioxane (HSQ) as a negative tone e-beam resist. Thickness and width of the strip are 60 nm and 600 nm, respectively. The mesa strip is defined by wet etching in a H3PO4 : H2O2 solution through an EBL-patterned poly(methyl methacrylate) mask (a2). Electrostatic gates are then added by thermal evaporation and liftoff (a3), followed by sputtering and liftoff of the Nb side contacts (a4). The junction has a width W = 3.0 μm, while the inter-electrode distance, equal to the width of the etched mesa strip, is L = 650 nm. In order to maximize interface transmissivity, the native oxide and possible contaminants must be removed from the mesa sidewalls before the deposition of the contacts. To this end we perform low-energy Ar+ sputter-cleaning in high vacuum, immediately before the deposition of Nb (a5). Low temperature measurements are performed down to 150 mK. Below the critical temperature Tc ≃ 9 K of the Nb films, proximity-induced superconductivity is observed in the semiconductor modifies the DOS at energies |e| < Δ (where Δ = 1.76kBTe ≃ 1.35 meV is the superconducting gap of the Nb films and kB the Boltzmann constant). The normal-state resistance of the junction is RN = 150 Ω, roughly two times larger than the lower bound set by the Sharvin resistance RSH = (πh)/(2e2W√2πnS) = 70 Ω, where h is Planck’s con-
FIG. 1: Device layout. (a1–4) Summary of the main nanofabrication steps and cross-sectional schematics of the hybrid superconductor-quantum dot device. (b) Scanning electron micrograph of the sample (scale bar is 500 nm). (c) Voltage-current characteristic at $T = 235$ mK of the open Nb-InGaAs-Nb junction (all gates set to ground).

The voltage-current characteristic of the open junction (all gates set to ground), measured at $235$ mK, is plotted in Fig. 1(c) and shows a switching current $I_c \approx 800$ nA. We note that in this configuration the junction length $L$ is smaller than the electron scattering length $l_p$ and larger than the induced coherence length $\xi_N = (\hbar^2/2m^*S) / (\Delta m^*) = 360$ nm (where $m^* = 0.03m_e$ is the electron effective mass in In$_{0.80}$Ga$_{0.20}$As), so that the normal region is ballistic and the junction falls in the intermediate length regime.

When negative voltages $V_L$, $V_R$ and $V_T$ are applied to the electrostatic gates [see Fig. 1(b)], the underlying 2DEG regions are depleted, forming a QD. The voltage $V_P$ applied to the fourth gate allows to tune the charge state of the QD. Two point_contacts with tunable transparency couple the QD island to the nearby Nb-InGaAs (S-2DEG) junctions. The distance between the Nb-InGaAs interfaces and the electrostatic gates that define the QD is of the order of 100 nm, below the induced coherence length $\xi_N$. For superconductor-normal metal (SN) junctions with a normal region length approaching or smaller than $\xi_N$ the proximity-induced energy gap $\Delta^*$ is expected to increase, reaching $\Delta$ in the case of ideal NS interfaces in the short junction limit; a suppression of $\Delta^*$ should occur for contacts with finite interface transparency. It is known that the stability diagram of a QD directly connected to superconductors reveals the presence of a gap in the DOS, both for weak and strong tunnel coupling to the leads.

Figure 2(a) shows measurements ($T = 235$ mK) in a regime of weak QD-lead coupling: the QD differential conductance $dI/dV_{SD}$ is plotted in color scale as a function of the source-drain bias $V_{SD}$ and $V_P$ (stability plot). In the diamond-shaped regions of low conductance electron tunneling through the QD is forbidden by Coulomb repulsion, and the QD occupation number $n$ is constant. Diamond edges with positive (negative) slope correspond to the onset of single electron tunneling from the left (right) lead. A sketch of the stability plot is given in Fig. 2(b): in the case of normal contacts (gray lines) the diamond edges cross at $V_{SD} = 0$, forming zero bias Coulomb blockade peaks at the charge-degeneracy points. The presence of gaps $\Delta_L^*$ and $\Delta_R^*$ in the DOS

FIG. 2: Stability diagram for the closed QD. (a) Sketch of the Coulomb diamond edges in the case of normal leads (gray lines) and in the presence of proximity-induced gaps $\Delta_L^*$ and $\Delta_R^*$. (b) energy diagram for single electron tunneling in the hybrid QD. (c) Left panel: color plot of the differential conductance versus $V_{SD}$ and $V_P$ (stability diagram) in the case of weak coupling to the leads at $T = 235$ mK. Right panel: $dI/dV_{SD}$ traces for three values of plunger gate voltage $V_P$ (indicated by dashed lines in the stability plot). The curves are horizontally shifted for clarity: dot-dashed lines indicate $dI/dV_{SD} = 0$. 

Our device architecture allows to easily tune the QD to a regime of stronger coupling to the leads by increasing the voltages $V_L$, $V_R$, $V_T$ of a few mV. In this regime cotunneling processes lead to the appearance of finite conductance inside the Coulomb diamonds [see Fig. 3(a)]. Symmetric peaks in $dI/dV_{SD}$ located at a constant voltage $V_{SD} = 330 \mu$V, independent of the charge state of the QD, are due to elastic cotunneling processes, such as the one sketched Fig. 3(b). In the upper panel of Fig. 3(a) the differential conductance is plotted versus $V_{SD}$ for constant values of $V_P$ indicated by the dashed lines of corresponding color in the lower panel. In this case our data indicate that $\Delta^*_L = \Delta^*_R \equiv \Delta^*$: the onset of elastic cotunneling takes place at $|eV_{SD} = 2\Delta^*$, where the particle- and hole-like DOS peaks in the two leads are aligned. We thus find $\Delta^* = 165 \mu$eV. This value is slightly smaller than the value of $\Delta^*_L$ found in the weak coupling regime (the difference being comparable with the uncertainty on $\Delta^*_L$). We note that the data shown in Fig. 2 and Fig. 3 were taken in different cooldowns of the device, and a fluctuation in $n_S$ could explain a variation in the strength of the proximity effect.

In conclusion, we demonstrated a hybrid QD device obtained by means of standard top-down nanofabrication, which combines a Nb-In$_{0.4}$Ga$_{0.6}$As-Nb planar junction with a lateral QD confined by electrostatic gates. Transport measurements allow to directly measure a proximity-induced gap in the 2DEG which results of the order of 200 \mu eV. As these results are relevant to the development of non-dissipative single electron transistors, further work will be devoted to the study of Josephson coupling through our device.

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