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Hybrid superconductor-semiconductor transistors

D. V. Goncharov, I. A. Devyatov and M. Yu. Kupriyanov

Institute of Nuclear Physics Moscow State University,
119899, GSP, Moscow, Vorob'evy Gory, Russia

Introduction

The combination of superconductors with semiconductor heterostructures represents a new field of investigation in terms of new physics as well as prospects for new superconductive transistors [1-3]. Studies of the proximity effect at semiconductor/superconductor (S/Sm) interfaces have demonstrated success in proximity induced superconductivity. Decay length $\xi_n \approx 120$ nm and supercurrent at the electrodes spacing as large as $0.8 \mu\text{m}$ has been observed in the InAs layers [4, 5].

So far the heterostructures had limited utilization in these investigations [6, 7]. The role of heterostructures, however, could be extremely high for several reasons:

(i) the well-advance technology permits fabrication of the high-quality barriers with controllable thickness shape and height;

(ii) the precise control of layer doping and thickness allows fabrication of any design multilayer structure for studying the physical processes in the junction;

(iii) the available technology provides the possibilities to fabricate the ohmic contacts to the edges of the 2D-gas layers with the interfaces having controllable transparency [8, 9].

On the other hand, the heterostructures introduce new physical features to the physical properties of the structures (geometrical resonances, resonant tunneling, quantum noise, mesoscopic effects, etc.). This opens a new field of investigation of superconducting current transfer through the structures and offers unique opportunities for development of the novel three-terminal devices.

The results obtained now, however do not look promising. The level of gate (input) voltages necessary for the switching the devices from superconducting to the highly resistive state $V_g \approx (1\div 3)$ V several orders of magnitude larger compare to the output (or controlled) voltage $V_{\text{out}} \approx (1\div 3)$ mV of the realized now three terminal devices [2–7]. To make these transistors operable, one must find a way to strongly increase the device transconductance and reduce V_g/V_{out} ratio.

The goal of this paper is to estimate theoretically the possibility of the enhancement employing the idea of geometrical resonances in the specially designed novel three-terminal Josephson devices.

The base

Practically in all realization of the three terminal Josephson devices the variable thickness bridge geometry has been used. The superconducting banks were deposited on the top of the semiconducting interlayer forming the "opening resonator junctions" [4–7]. The only possible way of the reduction the V_g/V_{out} ratio in these devices is the decreasing the density of the carriers n in semiconductor interlayer. Unfortunately, this immediately results in suppression of the decay length $\xi_n \propto n^{1/2}$ in semiconductor as well as the

transparency of the interfaces and provides serious difficulties in fabrication of the junctions. It seemed that the decision could be found by using 2D-gas as the interlayer material [3-5]. High mobility of the carriers permits to reduce the electron density n on several order of magnitude (from 10^{19} to 10^{12} cm^{-3}) on retention of the reasonable values of the decay length $\xi_n \approx 100$ nm. But even in this case, however, the gate voltage does not change considerably being on the level of several volts.

The analysis of the mode of operation of the three-terminal semiconducting field effect transistors [10-12] has shown that there are two kinds of the 2D-gas devices. The first of them based on the depletion of the 2D-gas in the conductive channel by the gate voltage and really needs $V_g \approx (1 \div 3)$ V for the operation. In the second types (lateral 2D-gas devices [11, 12]) the advantage of the quantization the energy levels of the carriers in the potential wells forming in 2D-gas by applying a constant voltages V_1 and V_2 on a split gate has been used. In this case it has been shown that it is enough to vary the difference $V_1 - V_2$ in the scale 10 mV to rearrange the energy levels in the potential well and, hence, to control the V_{out} .

On the other hand it was experimentally confirmed [1] that it is possible to fabricate clean $SSmS$ Josephson junctions which properties control by the geometrical resonances. Its physics does not differ from the one of the lateral 2D devices. Two naturally formed small transparent S/Sm boundaries at the edges of 2D-gas formed the Fabri-Perot resonator for the carriers. So the variation the electrode spacing on a few percent results in several orders of magnitude changing of the absolute values both critical current and normal junction resistance.

The combination of these experimental facts provides the possibility of the reliable reduction of the V_g/V_{out} ratio in field effect devices to a reasonable level.

Novel field effect Josephson device

The proposed structure consists of two superconducting banks separated by the semiconductor heterostructure with the 2D-gas layer. The interfaces between the banks and the edges of the 2D-gas form the Fabri-Perot resonator. To control the current across device it is enough slightly change by the gate voltage the de Brogue wavelength λ_{DB} of the carriers and breaking down the resonance condition $d = n\lambda_{DB}$. Here d is the electrode spacing.

To simplify the mathematical problems of analyzing the resonances in the structure we will assume that the rigid boundary conditions take place at the S/Sm boundaries and that the geometrical sizes of the gate electrode is large enough so that applied to 2D-gas gate electric field is space uniform and the dependence of Fermi momentum of 2D-gas electrons p_n on the gate voltage has the simplest form:

$$p_n = \sqrt{2m(E_F - eV_g)}, \quad (1)$$

where E_F is 2D-gas Fermi energy. We will also assume that the condition of clean limit is fulfilled in the 2D-gas interlayer and that the transparency of the S/Sm interfaces depends both on the difference of Fermi velocities of the metals and on the transparency of δ -functional barriers with the strengths W_1 and W_2 located on left and right interfaces correspondingly.

Under the conditions formulated above starting from Gor'kov equations and making use of the approach developed in [1] one can arrived at the following expressions for

the supercurrent I_s and normal resistance R_n of the junction

$$I_s R_0 = \frac{2\pi T}{e} \sum_{\omega} \left\langle \frac{x\Delta^2 \sin \varphi}{M(\varphi, d, x)} \right\rangle, \quad R_0 = \frac{Se^2 p_n^2}{2\pi^2 \hbar}, \quad \langle \dots \rangle = \int_0^1 (\dots) x dx \quad (2)$$

$$\begin{aligned} M(\varphi, d, x) = E^2 \left(\frac{1+w^2}{\gamma x} \right) & \left[\sinh^2 b + \sin^2(a) \right] \\ & + \frac{2}{\gamma x} \left[\omega E(1+w^2) \sinh(2b) + w(1+w)E^2 \sin(2a) \right] \\ & + 2 \cos \varphi + E^2 \cos(2a) + (2\omega^2 + E^2) \cosh(2b) \\ & + (wE)^2 [\cosh(2b) + 3 \cos(2a)], \end{aligned}$$

$$E = \sqrt{\omega^2 + \Delta^2}, \quad b = \frac{d}{2\xi_n x} \frac{\omega}{\pi T}, \quad a = \frac{2\pi dx}{\lambda_n}, \quad \xi_n = \frac{\hbar v_n}{2\pi T},$$

$$w = \frac{2mW_1}{p_s} = \frac{2mW_2}{p_s}, \quad \gamma = \frac{v_n}{v_s}.$$

$$R_n^{-1} = 2R_0^{-1} \left\langle \frac{8\gamma^2 x^3}{F_0 - F_1 \cos(2a) - F_2 \sin(2a)} \right\rangle, \quad (3)$$

$$F_0 = 16w_1^2 w_2^2 + 4(w_1^2 + w_2^2) [(\gamma x)^2 + 1] + (\gamma x)^4 + 6(\gamma x)^2 + 1,$$

$$F_1 = 16w_1^2 w_2^2 - 8(w_1 w_2) [(\gamma x)^2 + 1] - 4(w_1 + w_2)^2 [(\gamma x)^2 - 1] + [(\gamma x)^2 - 1]^2,$$

$$F_2 = 4\gamma x(w_1 + w_2) [(\gamma x)^2 - 1 - 4w_1 w_2], \quad w_{1,2} = \frac{2mW_{1,2}}{p_s}$$

Here $\omega = \pi T(2n + 1)$ are Matsubara frequencies, Δ and φ are modulus and phase difference of the order parameters of the superconducting electrodes, $v_{s,n}$ and $p_{s,n}$ are Fermi velocities and Fermi momentums of superconductor and 2D-gas correspondingly, S is cross-section of the junction.

Taking into account that in practically interesting interval of the gate voltage $V_g \ll E_F/e$

$$\frac{dp_n}{dV_g} = -e \sqrt{\frac{m}{2(E_F - eV_g)}} \approx -\frac{e}{v_n}$$

we have found that the voltage gain of the device equals to

$$G = \frac{d(I_c R_n)}{dV_g} = -\frac{e}{v_n} \left[R_n \frac{dI_c}{dp_n} + I_c \frac{dR_n}{dp_n} \right], \quad (4)$$

where I_c and R_n determined by equations (2)–(3). Estimate from (2)–(3) by numerical calculation the optimal values of the derivatives in (4) for typical values of the parameters $v_n \approx 3 \times 10^5 m/c$, $\gamma \approx 0.2$, $S \approx 10^{-14} m^2$, $p_n/v_n \approx 10^{-2} m_e$ and $T/T_c = 0.25$ we arrived at $G \approx 0.4$.

This value is three order of magnitude larger compare to achieved up to now in traditional Josephson field effect transistors, but still less than unity. Thus we can

conclude that the proposed structure can be effectively used in turnable SQUIDs or other devices for adjustment the optimal working points, but not as an amplifier or logic circuits where it is necessary to have the gain larger than one.

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