The resonance properties of Superconductor/Ferroelectric/Superconductor heterostructure

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***Abstract* — The phase dynamics of the Superconductor/Ferroelectric/Superconductor hetero structure, which can be considered as the Josephson junction with the ferroelectric barrier, is investigated. The dynamics of the Josephson junction is described based on the Resistively and Capacitively Shunted Junction model, and the Landau-Devonshire theory is used to describe the dynamics of polarization in ferroelectric layer. The current – voltage characteristic and the voltage dependence of polarization amplitude are calculated. It is shown that, when the Josephson frequency reaches the polarization eigenfrequency as a result of the resonance an increase in the polarization amplitude is observed and an additional resonance branch appears on the current – voltage characteristic.**

Keywords—Josephson effect, Josephson junction, resonance branch, Ferroelectric layer, Landau-Devonshire theory

I. INTRODUCTION

The Josephson effect, which consists in the tunneling of Cooper pairs between superconducting layers separated by a barrier (Josephson junction), is of great interest in connection with the prospect of using it in superconducting electronics [1-2]. As a barrier, we consider dielectrics, normal metals, ferromagnets, topological insulators, nanowires, etc., which lead to various physical phenomena, in particular, the shift of the phase difference and the manifestation of the Majorana mode [1-5].

In this work we investigate the Superconductor/Ferroelectric/Superconductor hetero structure, which can be considered as the Josephson junction with the ferroelectric barrier. The dynamics of Josephson junction is described by the RCSJ (Resistively and Capacitively Shunted Junction) model, and the Landau-Devonshire theory is used to describe the dynamics of polarization in ferroelectric layer. We have calculated the current – voltage characteristic of the Josephson junction and the voltage dependence of polarization amplitude in ferroelectric layer.

II. MODEL AND SIMULATION METHOD

In order to describe the dynamics of the polarization P in ferroelectric layer we can use the Landau-Devonshire theory. The free energy in the framework of this theory can be written as

$$F[P] = F_0 + A\frac{P^2}{2} + B\frac{P^4}{2}, \qquad (1)$$

where F_0 is the free energy in Curie temperature, A and B are the standard parameters of the Landau-Devonshire theory. The dynamics of the polarization in ferroelectric layer can be considered us the oscillator dynamics under the external field $F[P] - PV$, where V is the voltage in the junction [6]. In this case the dynamical equation of polarization can be written as

$$m_{\mathrm{eff}}\frac{d^2P}{dt^2} + \gamma_{\mathrm{P}}\frac{dP}{dt} = -\frac{\partial F}{\partial P} + V, \qquad (2)$$

where m_{eff} is the parameter of the inertia, γ_{P} - is the damping parameter in the ferroelectric.

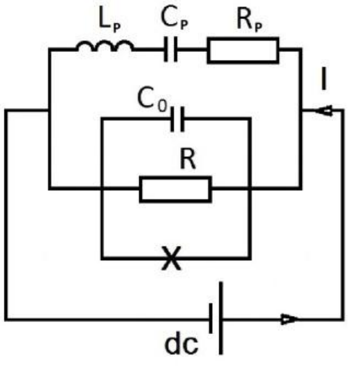

Fig. 1. Equialent scheme of superconductor/Ferroelectric/Superconductor structure. Here C_{P}, L_{P} and R_{P} are the capacitance inductance and resitance of oscillator, which describes the behavior of ferroelectric layer.

The dynamics of the standard Josephson junction can be described by the RCSJ model. To describe Josephson junction with ferroelectric barrier we suggest to use the modified RCSJ –model shunted by an extra resonator with an inductance L_P , capacitance C_P , and resistance R_P , which leads to the same equation as the (2). The equivalent scheme of modified RCSJ-model is shown in Fig.1.

In this case the total current through the system consists of the superconducting current, $I_s = I_c \sin\varphi$, quasiparticle current, $I_{qp} = V / R_J$, and displacement current. $I_d = d(C_0 V + P)/dt$, where φ is the superconducting phase difference of junction, I_c , R_J and C_0 are critical current, resistance and capacitance of the junction, respectively. The final system of equation takes a form

$$\begin{cases} \dfrac{dV}{dt} = I - \sin\varphi - \beta V - \dfrac{dq_1}{dt} \\ \dfrac{d\varphi}{dt} = V \\ L\dfrac{d^2 q_1}{dt^2} = V - \gamma\dfrac{dq_1}{dt} - \dfrac{q_1}{C_P[q_1]} \end{cases} , \qquad (3)$$

where I is bias current, $\beta = 1/(\omega_p R_J C_0)$ is the dissipation parameter of the JJ, ω_p is plasma frequency of JJ, $q_1 = P/q_0$ - is the polarization charge, $q_0 = I_c / \omega_p$, $\gamma = \gamma_P V_0 /(\omega_p q_0)$ - is the damping parameter of the ferroelectric layer, $L_P = m_{\text{eff}} V_0 / \omega_p^2 q_0$ is the normalized inductance, $C_P[q_1] = 1/(C_0 A + \alpha q_1^2)$ - is the nonlinear capacitance, with nonlinear parameter $\alpha = C_0 B q_0^2$. In the system of equations (3) time is normalized to the plasma frequency. We note that the considered system has its eigenfrequency, which is determined by the expression

$$\omega = \sqrt{(1 + C_P)/L_P C_P} \, . \qquad (4)$$

In this work we have considered the simples case, i.e. the dissipation and nonlinearity of the ferroelectric are neglected. The system of equation (3) is solved numerically using fourth order Runge-Kutta method. All calculations are performed for $C_P = 0.2$, $L_P = 1.5$. For this set of parameters corresponds eigenfrequency $\omega = 2$ in accordance with expression (2)

III. THE NUMERICAL RESULTS

Figure 2 (a) shows the current – voltage characteristic (CVC) of the Josephson junction. The calculation of this CVC was carried out in three stages of changing the bias current: a) increased from $I = 0$ to $I_{\max} = 1.5$ and decreased zero; b) increased from $I = 0$ to $I_{\max} = 1.5$ and decreased to $I = 0.27$ and then increased to $I_{\max} = 1.5$; c) increased from $I = 0$ to $I_{\max} = 1.5$ and decreased to $I = 0.79$ and then increased again to $I_{\max} = 1.5$.

The calculated CVC shows the branches at voltages $V = 2$ and $V = 4$, which are the result of resonance of Josephson oscillations and oscillations of the polarization charge, which leads to the appearance of an average superconducting current and a decrease in the differential resistance. At these voltage values, the Josephson frequency coincides with the eigenfrequency of the oscillations of the polarization charge.

On the other hand, as a result of this resonance, the amplitude of the oscillations of the polarization charge increases, as shown in Figure 2 (b), where is presented the dependence of the maximum amplitude of the polarization charge on the voltage in the JJ. It can be seen the increasing of the amplitude of the polarization charge at $\omega_J = \omega$ and $\omega_J = 2\omega$. We note that due to the small dissipation of the JJ, the I – V characteristic shows hysteresis, and therefore, only one side of the resonance peak is observed in the dependence of the maximum amplitude on voltage, the other side is shown by a dashed line.

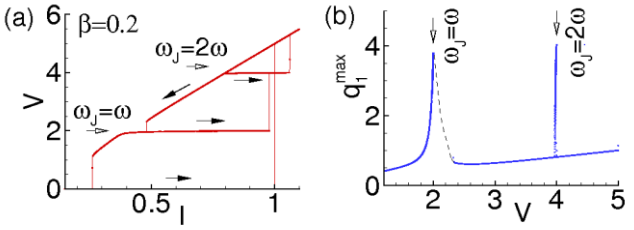

Fig. 2. (a) Current-voltage characteristic of a JJ with a ferroelectric barrier. Shaded arrows indicate the direction of change of the base current, hollow arrows indicate the resonant branches of the I – V characteristic; (b) Dependence of the maximum polarization charge on voltage (Josephson frequency) in the Josephson junction.

In conclusion we note that, we have demonstrated the interaction of ferroelectricity and superconductivity through the Josephson effect in the Superconductor/Ferroelectric/Superconductor hetero structure. It is shown that when the Josephson frequency and the eigenfrequency of polarization oscillations coincide, an increase in the amplitude of the polarization charge is observed as a result of the resonance and a resonant branch appears on the I – V characteristic of the Josephson junction.

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