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. The effect of nonlinerity on the IV characteristic is demonstrated.

Model and numerical 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

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

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. In this case the dynamical equation of polarization can be written as

$$m_{\text{eff}}\frac{d^2}{dt^2}P + \gamma_P\frac{d}{dt}P = -\frac{\partial F}{\partial P} + V \qquad (2)$$

where m_{eff} is the parameter of the inertia, γ_P is the damping parameter in the ferroelectric.
The dynamics of the standard Josephson junction (without ferroelectric barrier) 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 (**??**). The equivalent scheme of modified RCSJ-model is shown in Fig.1

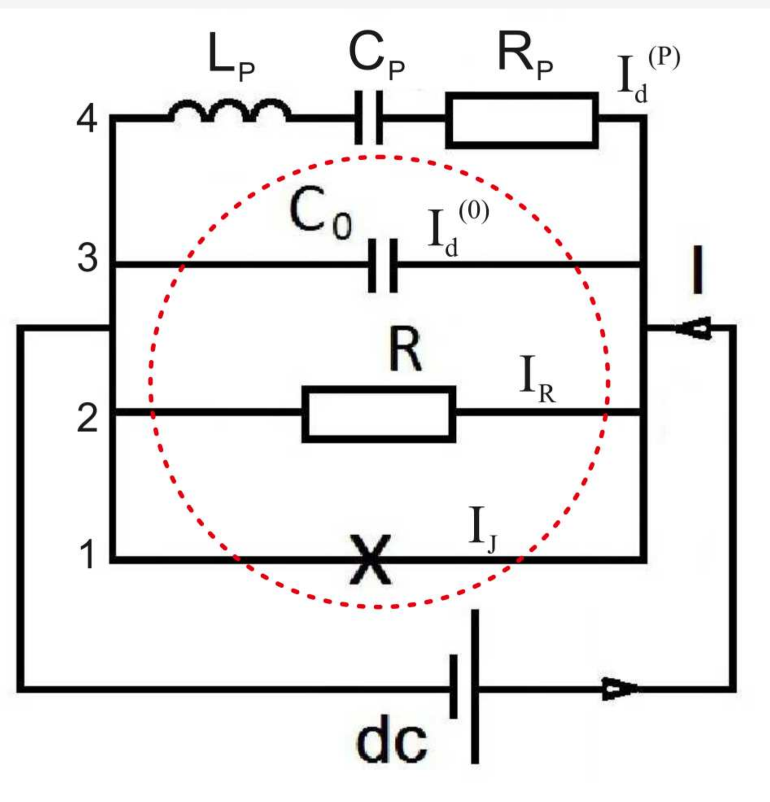

Fig.1 Equialent scheme of superconductor/Ferroelectric/Superconductor structure. Here C_P, L_P and R_P are the capacitance, inductance and resitance of oscillator, which describes the behaviour of ferroelectric layer.

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 $I_d = d(C_0V + P)/dt$, 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

$$\begin{aligned} \frac{d}{d\tau} &= I - \sin\varphi + \beta V - \frac{dq_1}{dt} \\ \frac{d\varphi}{dt} &= V \\ L\frac{d^2q_1}{dt^2} &= V - \gamma\frac{dq_1}{dt} - \frac{q_1}{C[q_1]} \end{aligned} \qquad (3)$$

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, $C_P[q_1] = 1/(C_0A + \alpha q_1^2)$ is the nonlinear capacitance, with nonlinear parameter $\alpha = C_0Bq_0^2$.
In the system of equations (3) time is normalized to the plasma frequency ω_p, bias current - to the I_c and voltage – to the V_0. The system of equation (3) is solved numerically using fourth order Runge-Kutta method.

IV characteristics of Josephson junction without ferroelectric barrier

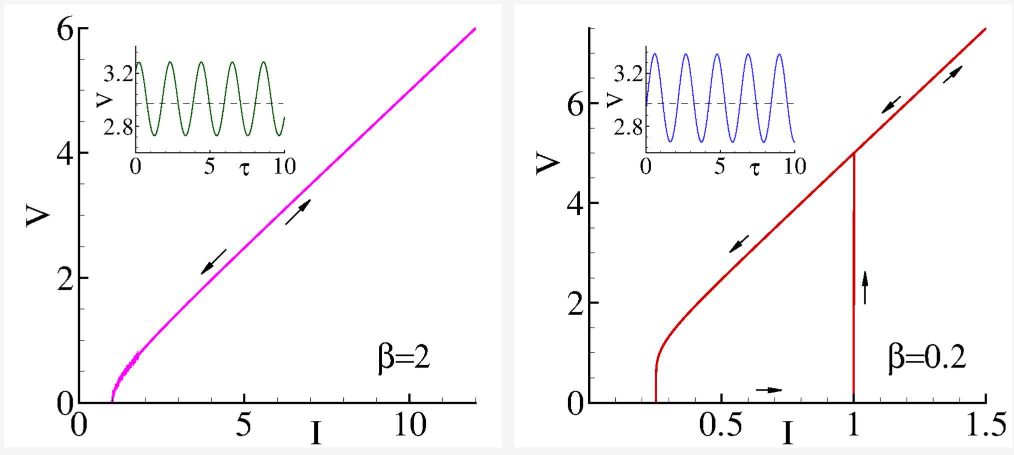

Fig.2 (Left) IV characteristics of the overdamped Josephson junction; (Right) IV characteristics of the underdamped Josephson junction.

Dynamics of the Josephson junction with ferroelectric barrier: linear case

We note that the considered system has eigenfrequencies corresponding to the serial and parallel resonances. These frequencies are determined by the expressions

$$\omega_{ser} = \sqrt{\frac{1}{L_P C_P}}$$

for the serial resonance and

$$\omega_{par} = \sqrt{\frac{1 + C_P}{L_P C_P}}$$

for the parallel resonance.

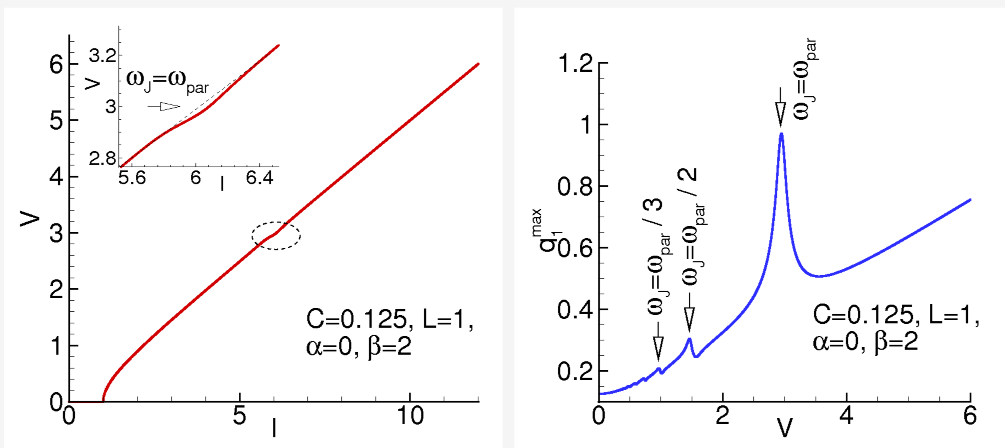

Fig.3(Left) IV-characteristic of overdamped Josephson junction with the ferroelectric barrier; (Right) The voltage dependence of maximum polarization charge in ferroelectric layer in overdamped case.

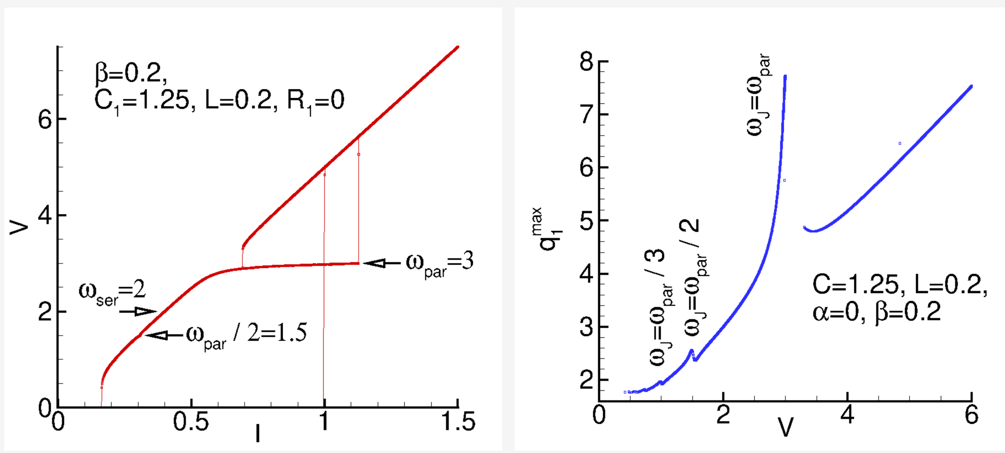

Fig.4 (Left) IV-characteristic of underdamped Josephson junction with the ferroelectric barrier; (Right) The voltage dependence of maximum polarization charge in ferroelectric layer in underdamped case.

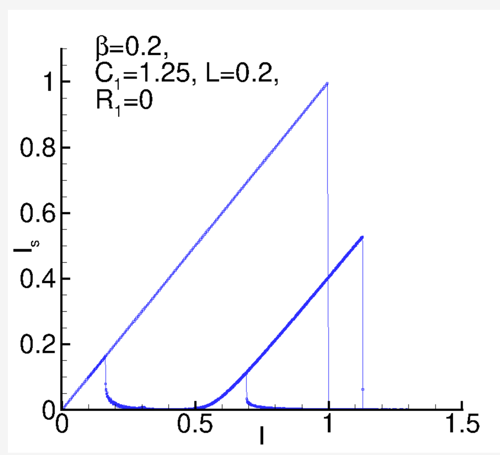

Fig.5 The superconducting current depending on bias current in Josephson junction with ferroelectric barrier.

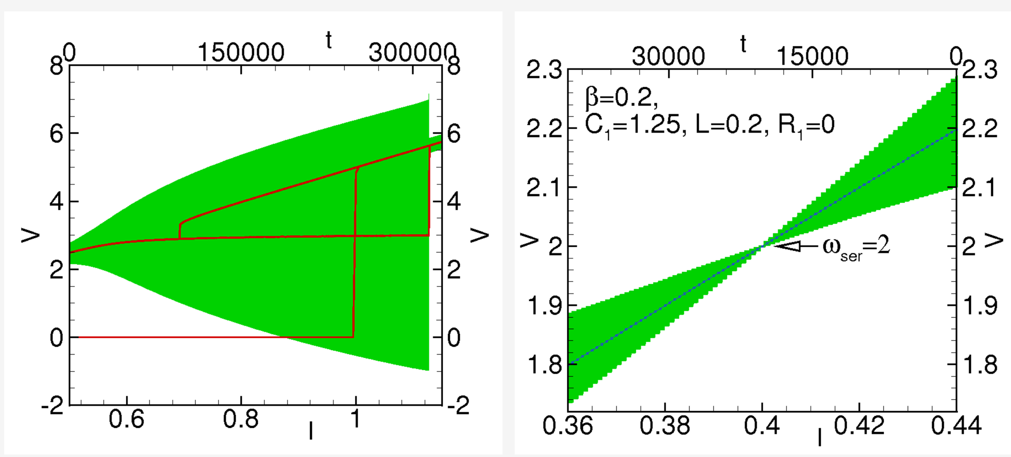

Fig.6 (Left) The time dependence of the voltage in the parallel resonance region. (Right) The time dependence of the voltage in the serial resonance region.

Dynamics of the Josephson junction with ferroelectric barrier: nonlinear case.

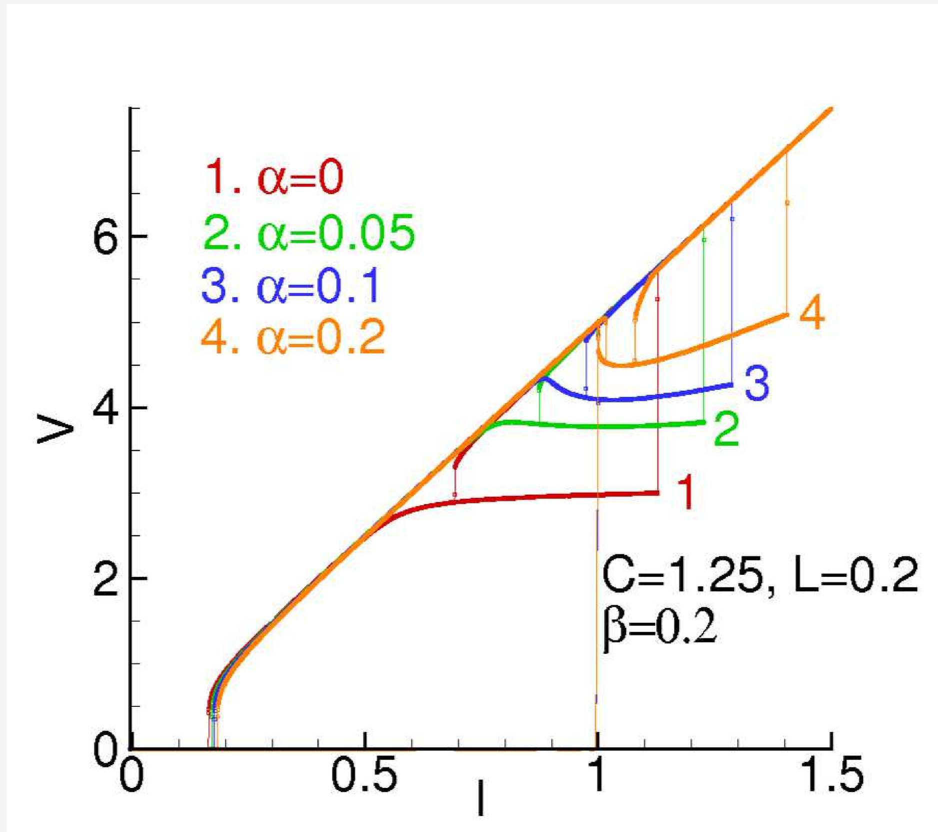

Fig.7 IV-characteristics of the underdamped Josephson junction with ferroelectric barrier for different value of nonlinear parameter in case of high capacitance.

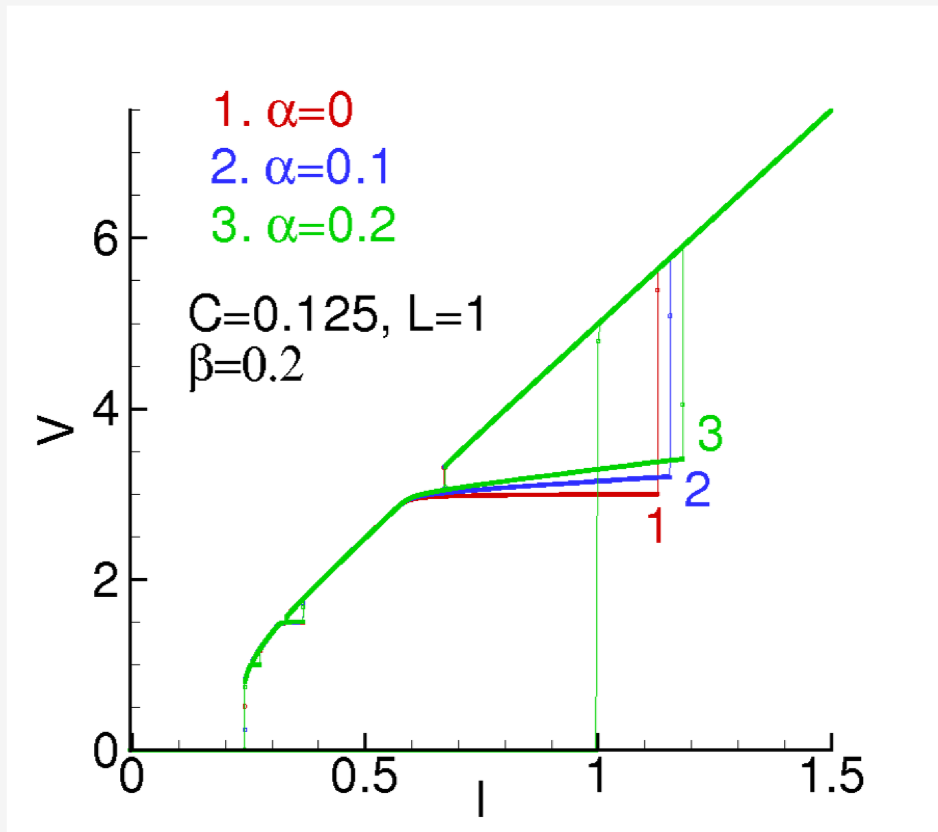

Fig.8 IV-characteristics of the underdamped Josephson junction with ferroelectric barrier for different value of nonlinear parameter in case of low capacitance.

With the increasing of the parameter of nonlinearity effective capacitance will decrease, which leads to the increasing of the eigenfrequency. This fact is demonstrated in Fig.7 and Fig.8 where is observed shifting of resonance branch with increasing of α. In case of Fig.7 the effect of nonlinearity is more strong because in this case effect of capacitance is stronger.

Conclusions

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. We have demonstrated the effect of the nonlinearity on the IV–characteristic.

Acknowledgements

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