Experimental observation of fine structure on the current-voltage characteristics of long Josephson junctions with a lattice of inhomogeneities

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Additional branches have been observed on the current-voltage characteristics of long Josephson junctions with a spatially periodic modulation of the critical current density. These additional branches are interpreted as a resonant interaction of a soliton with plasma waves which it emits.

A distributed Josephson junction is a model system for studying solitons and other excitations describable by a perturbed sine-Gordon equation[1,2]

$$\frac{\partial^2\varphi}{\partial x^2} - \frac{\partial^2\varphi}{\partial t^2} = f(x)\sin\varphi + \alpha\frac{\partial\varphi}{\partial t} - \gamma\,.$$

Here φ is the phase difference between the wave functions of the superconductors; α is a dissipation coefficient; γ is the external current; the coordinate x is normalized by division by the Josephson length λ_J; and the time t is normalized by division by the reciprocal of the plasma frequency, ω_0^{-1}.

The problem of the motion and emission of a soliton in a system with structural inhomogeneities positioned regularly along the x axis, described by the model $f(x) = 1 + f_0\Sigma_{n=1}^{N}\delta(x - na)$, was studied theoretically in Refs. 3–6. The frequency and amplitude of the emission were calculated as functions of the distance (a) between the inhomogeneities and the soliton velocity β (Refs. 3 and 4). It was shown that additional fine-structure steps should appear on the current-voltage characteristic of a Josephson junction with a lattice of inhomogeneities.[5,6] These steps would correspond to resonances between a soliton and the plasma waves which it emits as it moves in a junction of this sort.

Our purpose in the present study was to experimentally observe the structural features which were predicted theoretically in Refs. 5 and 6 to appear on the current-voltage characteristics of quasi-one-dimensional Josephson junctions with insulating-barrier inhomogeneities deliberately created.

We studied Nb-NbO$_x$-Pb junctions fabricated by the standard thin-film technique, involving the oxidation of niobium in the plasma of a glow discharge.[7] Twelve junctions of transverse geometry,[8] with dimensions of 500×20 μm^2, were fabricated by photolithography on a silicon substrate with dimensions of 15×24 mm^2 (Fig. 1). Inhomogeneities in the form of a film of silicon monoxide, 80 nm thick and 10 μm wide along the large dimension of the junction, were produced by oxidizing the niobium by a method of "explosive" photolithography. Four of the junctions served as

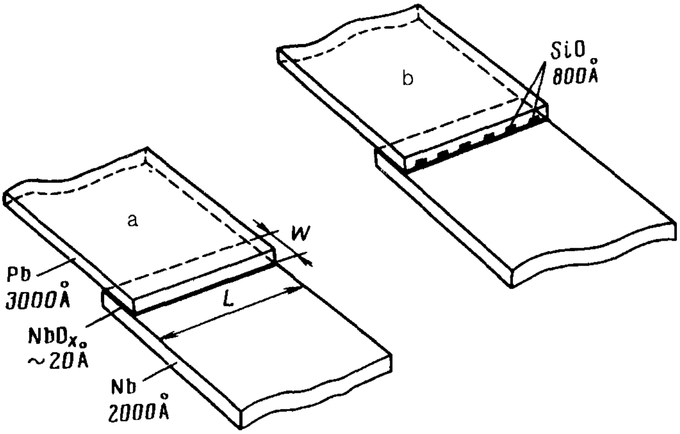

FIG. 1. Josephson junctions of transverse overlap geometry. a—Homogeneous; b—with artificial inhomogeneities.

controls (without inhomogeneities). The critical current densities in the junctions ranged from 30 to 60 A/cm^2, corresponding to $\lambda_J \sim 45$–60 μm.

In the experiments we studied the shape of the first zero-field step[2] on the I-V characteristic, which corresponds to the motion of a single soliton in the junction. The voltage of this step was ~ 27 μV at $T = 4.2$ K; the values of this voltage for the various junctions agreed within 2–3%. In the measurements of the branches of the I-V characteristics, it was crucial to adhere to requirements concerning the protection of the sample from external sources of stray pickup and noise. Measurements were carried out in a shielded cryostat with a residual magnetic field $\sim 1 \times 10^{-4}$ G. To set the current, we used a stable mercury-zinc cell; as the current and potential leads we used two twisted shielded pairs for each junction. The sensitivity of the dc measurements was limited by the induced thermal-emf in the measurement leads and the contacts; this sensitivity was ~ 0.5 μV before accumulation and averaging.

Figure 2 shows the first steps on the I-V characteristics of several of the junctions which we studied. For the junctions with the inhomogeneities, we observed additional branches on the I-V characteristics, at voltages below that corresponding to the first step. The shape and position of these branches along the voltage scale depend on the number of inhomogeneities and the parameters of the junctions. On the I-V characteristics of homogeneous junctions (Fig. 2a), we observe no structural features of any sort on the zero-field steps. In a junction with three inhomogeneities (Fig. 2d), the additional branch has a clearly defined negative differential resistance, in agreement with a numerical calculation carried out for a junction with similar parameter values.[5] On each of the characteristics in Figs. 2c and 2d we observe two stably reproducible values of the critical current; the lesser of the two, I_{th}, apparently stems from the pinning of a soliton by one of the inhomogeneities. When the current I_{th} is reached there is a "hop" to the first step corresponding to the motion of this soliton in the junction. As the distance between the inhomogeneities, in units of λ_J, is reduced, the

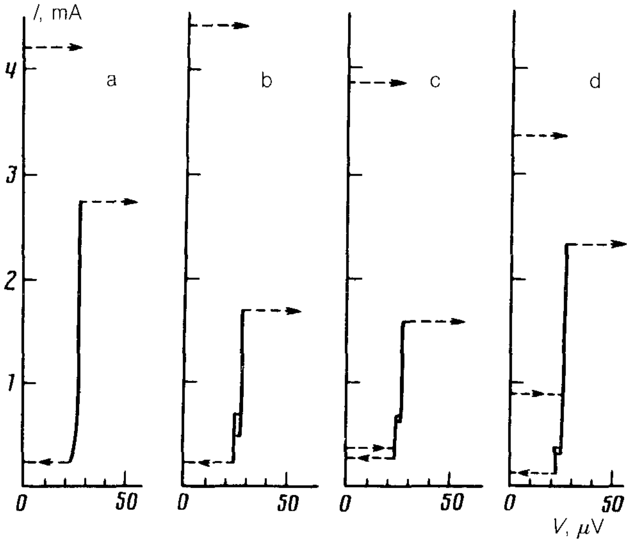

FIG. 2. First zero-field step on the current-voltage characteristics. a—Of a homogeneous (control) Josephson junction; b, c, d—of junctions with respectively nine, five, and three inhomogeneities.

threshold current I_{th} decreases, in accordance with a decrease in the pinning force.

This experiment thus revealed structural features on the I-V characteristics which can be interpreted qualitatively as the resonances which have been predicted theoretically[5,6] between a soliton and the emission which it generates under the condition $m\omega_{\text{sol}} = \omega_{pl}$. The positions of such resonances along the scale of the voltage V_m are given by[6]

$$V_m = \left[\left(1 - \frac{2l}{ma}\right)^2 + \left(\frac{l}{\pi m}\right)^2\right]^{1/2} \tilde{V}\,; \qquad V_m < \tilde{V}\,, \tag{1}$$

where $\tilde{V}$ is the voltage of the first zero-field step, l and a are respectively the length of the junction and the distance between inhomogeneities, expressed in units of λ_J, and m is the order of the resonance.

A comparison of the measured values of V_m with those calculated from expression (1) yields the order of the observed resonances: $m = 11$, 6, and 5 for the I-V curves in Figs. 2b, 2c, and 2d, respectively. The fact that each of the I-V characteristics studied has only a single fine-structure branch stems from the circumstance (in our opinion) that other branches are not observed at lower voltages because of the pronounced instability of the lower regions of the I-V characteristics with respect to external noise during the measurements. The voltage interval in which the I-V characteristics of the first zero-field steps are observed does not exceed $0.8\tilde{V} \lesssim V \lesssim 1.0\tilde{V}$, even for the homogeneous junctions. For a junction with five inhomogeneities, for example, expression (1) predicts that there could be resonances with orders $m \geqslant 6$, specifically, with $V_6 = 0.85\,\tilde{V}$, $V_7 = 0.634\,\tilde{V}$, and $V_8 = 0.47\,\tilde{V}$. The measured voltage of the additional branch was $V^* \approx 0.89\ \tilde{V}$. Consequently, under our experimental conditions the theoretically predicted branches with $m \geqslant 7$ lie outside the measured region of the I-V curves. The discrepancy between the theoretical and experimental results for cases 2b–2d, for the calculated values of m, does not exceed 5–8%.

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[1] A. Barone, F. Esposito, C. J. Magee, and A. C. Scott, Riv. Nuovo Cim. **1**, 227 (1971).
[2] N. F. Bedersen and D. Welner, Phys. Rev. B **29**, 2551 (1984).
[3] D. W. McLaughlin and A. C. Scott, Phys. Rev. A **18**, 1652 (1978).
[4] G. S. Mkrtchyan and V. V. Schmidt, Solid State Commun. **30**, 791 (1979).
[5] A. A. Golubov and A. V. Ustinov, Pis'ma Zh. Tekh. Fiz. **12**, 435 (1986) [Sov. Tech. Phys. Lett. **12**, 178 (1986)].
[6] A. A. Golubov and A. V. Ustinov, IEEE Trans. Magn. **23**, 781 (1987).
[7] A. N. Vystavkin, V. N. Gubankov, K. I. Konstantinyan, V. P. Koshelets, and Yu. V. Obukhov, Zh. Tekh. Fiz. **52**, 1637 (1982) [Sov. Phys. Tech. Phys. **27**, 1001 (1982)].
[8] K. K. Likharev, Introduction to the Dynamics of Josephson Junctions, Moscow, 1985.

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