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LETTER TO THE EDITOR

On piezophase effects in mechanically loaded atomic scale Josephson junctions

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Abstract. The response of an intrinsic Josephson contact to externally applied stress is considered within the framework of the dislocation-induced atomic scale Josephson effect. The predicted quasi-periodic (Fraunhofer-like) stress–strain and stress–current patterns should manifest themselves for experimentally accessible values of applied stresses in twinned crystals.

It is now well established (see, e.g., [1–5] and further references therein) that due to the extreme smallness of the superconducting coherence length in high-T_c superconductors (HTS), practically any defects are capable of creating rather pronounced weak-link structures in these materials. In particular, there are serious arguments to consider the twinning boundary (TB) in HTS as insulating regions of the Josephson SIS-type structure [6]. Given the fact that the physical thickness of the TB is of the order of an interplane distance (atomic scale), such a boundary should rather rapidly move via the movement of the twinning dislocations [7]. Indeed, using the method of acoustic emission, the flow of twinning dislocations with the maximum rate of $v_0 = 1$ mm s^{-1} has been registered [8] in YBCO crystals at $T = 77$ K under the external load of $\sigma = 10^7$ N m^{-2} (with the ultimate stress of $\sigma_m = 10^8$ N m^{-2}).

In an attempt to describe some anomalous phenomena observed in HTS and attributed to their weak-link structure, a rather simple model of the dislocation-induced atomic scale Josephson effect has been suggested [3, 9, 10]. Using the above model, in this letter we consider the response of a single Josephson contact (created by dislocation strain field ϵ_d acting as an insulating barrier in a SIS-type junction) to an externally applied mechanical loading. The resulting *piezophase effects*, given by stress–strain and stress–current diagrams, are found to show a quasi-periodic behaviour typical for Josephson junctions.

Recall that a conventional Josephson effect (i.e., a macroscopically coherent tunnelling of Cooper pairs through an insulating barrier) can be described by the following Hamiltonian

$$\mathcal{H}_J(t) = J(T)[1 - \cos\phi(t)] \tag{1}$$

where $\phi(t)$ is the phase difference between two superconductors separated by an insulating layer (of thickness l), and $J(T) \propto e^{-l\sqrt{U}}$ is the (temperature-dependent) Josephson coupling energy with U being the height of the insulating barrier.

According to our scenario [3, 9] of a dislocation-induced atomic scale Josephson junction (JJ), the length of the SIS-type contact L and the insulator thickness l supposedly correspond to the TB length and the TB thickness, respectively. Hence, l is proportional to the number of dislocations while $U(\epsilon_d)$ is created by defects with a strain energy $E_d \simeq C_{44}\epsilon_d^2$ (where C_{44} is the shear modulus).

As is well known, a constant voltage V applied to a JJ causes a time evolution of the phase difference, $\mathrm{d}\phi/\mathrm{d}t = 2eV/\hbar$, and as a result a conventional AC Josephson current occurs through such a contact

$$I_s^V(t) = I_c \sin(\phi_0 + \omega_V t) \tag{2}$$

where ϕ_0 is the initial (at $t = 0$) phase difference, $\omega_V = 2eV/\hbar$ the Josephson frequency and $I_c = 2eJ/\hbar$ the critical current.

In [10] another possibility for the AC Josephson effect was suggested which is based on the external-load (σ-) induced flow of dislocations through an unbiased ($V = 0$) superconducting sample. Indeed, if we assume that a TB (which is characterized by a non-zero dislocation-induced strain field ϵ_d) is the only source of an SIS-type Josephson contact, then a mechanical stress applied to such a contact will cause a flow of dislocations through a loaded crystal, leading to the corresponding displacement of the insulating layer (created by these TB dislocations). And as a result, a time-dependent phase difference $\mathrm{d}\phi/\mathrm{d}t = (\mathrm{d}\phi/\mathrm{d}\epsilon)\dot{\epsilon}$ (where $\dot{\epsilon} = \mathrm{d}\epsilon/\mathrm{d}t$ is the rate of plastic deformation under an applied stress) will occur in such a *moving* contact. For simplicity, a linear dependence for the induced phase difference $\phi(\epsilon) = A\epsilon$ (where $A \simeq 1$ is a geometrical factor) will be assumed. Besides, to neglect any self-field effects and to stay within a short-junction approximation, we assume (i) $L < \lambda_J$ (where λ_J is the Josephson penetration depth), and (ii) a constant (time-independent) rate v_d of flow of dislocations through a loaded crystal. In most cases [11], $v_d \simeq v_0(\sigma/\sigma_m)$, where σ_m is the so-called ultimate stress. Finally, taking into account the dependence of $\dot{\epsilon}$ on the number of moving dislocations (of density ρ) and a mean dislocation rate v_d, viz. [11] $\dot{\epsilon} = b\rho v_d$ (here b is the absolute value of the Burgers vector), we obtain

$$\mathcal{H}_J^\sigma(t) = J\left[1 - \cos(\phi_0 + \omega_\sigma t)\right] \tag{3}$$

and

$$I_s^\sigma(t) = I_c \sin(\phi_0 + \omega_\sigma t) \tag{4}$$

for the dislocation-induced single-junction Hamiltonian and unbiased AC Josephson current, respectively, with $\omega_\sigma = b\rho v_d(\sigma)$.

The response of this JJ, with an average energy

$$E_J(\sigma) \equiv \langle \mathcal{H}_J^\sigma(t) \rangle = \frac{1}{\tau} \int_0^\tau \mathrm{d}t\, \mathcal{H}_J^\sigma(t) \tag{5}$$

to the externally applied tensile stress field σ will produce the following change $\Delta\epsilon = \epsilon - \epsilon_d$ in the intrinsic dislocation-induced strain field ϵ_d

$$\Delta\epsilon(\sigma) = \frac{1}{V}\frac{\partial E_J(\sigma)}{\partial \sigma}. \tag{6}$$

Here $\langle \ldots \rangle$ means a temporal averaging with a characteristic time τ (which is related to the rate of dislocation v_0 and its length L as $v_0 \simeq L/\tau$), and V is the volume occupied by TB dislocations.

To consider applied stress-induced effects only, in what follows we assume that initially, in an unloaded crystal (with $\sigma = 0$), $\epsilon(0) = \epsilon_d$ and thus $\phi_0 = 0$. By resolving (3)–(6), we obtain a quasi-periodic stress–strain relationship for a single dislocation-induced JJ

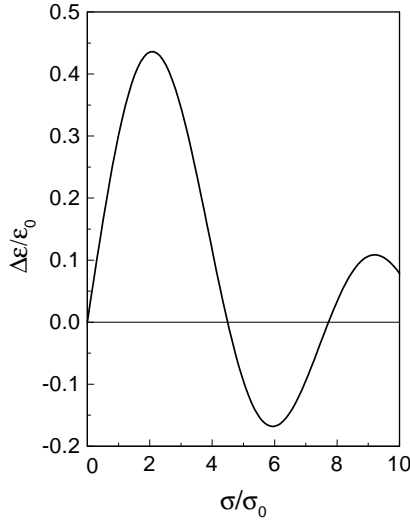$$\Delta\epsilon(\sigma) = \epsilon_0 f_1(\sigma/\sigma_0) \tag{7}$$

Figure 1. Stress–strain diagram of a single Josephson junction, according to (7).

with

$$f_1(x) = \frac{\sin x - x \cos x}{x^2}.$$ (8)

Here $\epsilon_0 = J(T)/V\sigma_0$ and $\sigma_0 = \sigma_m/b\rho L$.

Let us estimate the order of magnitude of the characteristic strain ϵ_0 and stress σ_0 fields in YBCO crystals. First of all, we note that at low enough applied stress ($\sigma \ll \sigma_0$), the above model relationship $\Delta\epsilon(\sigma)$ reduces to the linear Hooke's law, $\Delta\epsilon = S\sigma$ with $S \equiv C_{44}^{-1} = \epsilon_0/3\sigma_0$. Recalling [12] that in YBCO crystals the shear modulus $C_{44}^{exp} = 8 \times 10^{10}$ N m^{-2}, we arrive at the following two equations for the two parameters ϵ_0 and σ_0, namely (i) $3\sigma_0 = C_{44}^{exp}\epsilon_0$, and (ii) $\sigma_0\epsilon_0 = J(T)/V$. Taking $b = 1.2$ nm, $V \simeq b^3$ and $J(T = 77\ \mathrm{K}) = 0.5$ meV for the magnitude of the Burgers vector, the volume occupied by TB dislocations and the Josephson energy in YBCO crystals [12], from the above two equations we obtain $\sigma_0 \simeq 10^7$ N m^{-2} and $\epsilon_0 \simeq 10^{-3}$. It is worthwhile to mention that these numbers remarkably correlate with the ones usually seen in mechanically loaded type-II hard superconductors [13]. Figure 1 shows the stress–strain diagram of an atomic scale JJ beyond the linear approximation when rather strong plasticity effects come into action.

In the same manner, from (4) we can find the change of the Josephson supercurrent under external loading. The resulting stress–current relationship for a single JJ reads

$$\Delta I_s(\sigma) \equiv \left| \frac{1}{\tau} \int_0^\tau dt\, I_s^\sigma(t) \right| = I_c f_2(\sigma/\sigma_0)$$ (9)

with

$$f_2(x) = \left| \frac{1 - \cos x}{x} \right|.$$ (10)

The behaviour of the Josephson supercurrent under applied stress, given by (9), is depicted in figure 2. The elastic Hooke's region (valid for $\sigma \ll \sigma_0$) is characterized by a linear dependence $\Delta I_s(\sigma) \simeq K\sigma$ (with $K = I_c/2\sigma_0$) which can be seen in intrinsically defected samples under a relatively small loading [14]. By applying a relatively small elastic
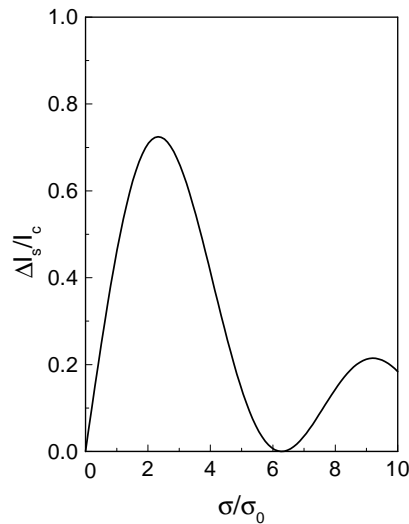
Figure 2. Stress–current diagram of a single Josephson junction, according to (9).

stress along the *ab* plane of sputtered YBCO thin films, Belenky *et al* [14] detected the following change of the critical current density $\Delta J_c(\sigma)/J_c(0) = 3 \times 10^{-3}$ in their samples under compressive load of $\sigma = 10^5$ N m^{-2} at $T = 77$ K. Assuming that this change is controlled by intrinsic inhomogeneities, we can compare it with the model prediction which yields (see (9)) $\Delta I_s(\sigma)/I_c \simeq 5 \times 10^{-3}$ for the same set of parameters (recall that in our model $\sigma_0 = 10^7$ N m^{-2}). However, a much larger compression (close to the ultimate stress σ_m, see above) is needed to check the validity of both predicted Fraunhofer-like patterns shown in figures 1 and 2.

In summary, using a model of an atomic scale Josephson contact, the change of the defect-mediated strain field and Josephson supercurrent under external loading was considered. A possibility of experimental verification of the resulting stress–strain and stress–current diagrams in defected superconductors was discussed.

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