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JOSEPHSON FLUXONS IN HIGH T_c SUPERCONDUCTORS

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An attempt is made to provide a quantitative basis for our model of the low-field non-resonant microwave absorption in high T_c superconductors. An expression for energy dissipation due to normal current in long Josephson junctions is derived from a postulated Lagrangian.

I. INTRODUCTION

Among the many interesting properties of the new high T_c superconductors [1] the strong magnetic field dependent microwave and radiofrequency absorption first reported for these materials by us [2, 3] promises early technical application. Recently, several groups of research workers have reported microwave absorption at very low magnetic fields and associated it mainly with the existence of the Josephson junctions. According to Portis et al. [4] the microwave absorption in high T_c oxide superconductors arises from the microwave conductivity loss through the dissipation from the fluxon motion driven by microwave induced currents.

In connection with our model [5, 6] for the low-field non-resonant microwave absorption, which is based on the existence of long Josephson junctions, a new approach to the calculation of energy dissipation in these junctions is proposed. An expression for the energy dissipation due to normal current in long Josephson juctions is derived from a postulated Lagrangian.

II. EXPERIMENTAL

Superconducting ceramic $YBa_2Cu_3O_7$ samples were prepared by the established solid-state reaction techniques [7]. The samples were sealed in pure helium gas in 2.5 mm × 25 mm cylindrical quartz EPR grade sample tubes.

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The superconductivity and the superconducting transition temperatures T_c of our samples were established by standard dc four-probe measurements (silver paint and pressed indium contacts were utilized), Meissner effect measurements using a Hewlett-Packard model 428BR flux-gate magnetometer, and our microwave absorption method using a Brüker ER 200D-SRC EPR spectrometer operating at an X-band with a TE_{103} cavity. All measured compounds exhibited an orthorhombic single phase as confirmed by X-ray powder diffraction.

III. RESULTS

As the superconducting $YBa_2Cu_3O_7$ samples are cooled through T_c a strong low-field microwave absorption is observed. Fig. 1 shows this non-resonant low-field absorption for different modulation amplitudes.

We used an EPR cavity to expose the sample of $YBa_2Cu_3O_7$ to microwave radiation, where we measured simultaneously the microwave induced dc voltage

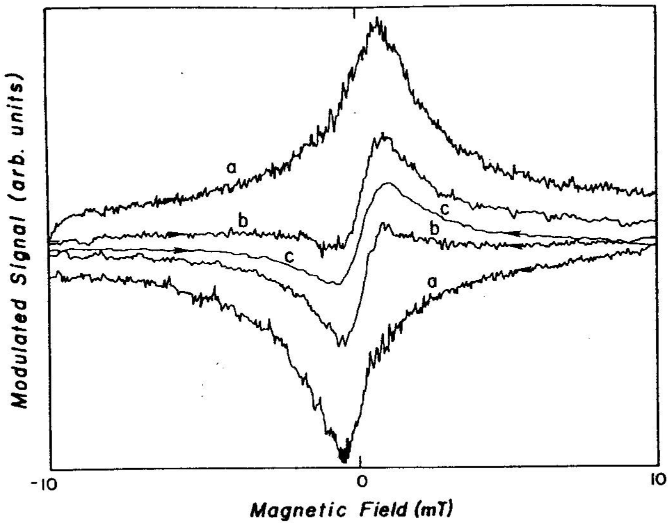

Fig. 1. Modulated low-field absorption for different modulation amplitudes (negative fields are applied in the opposite direction to positive fields): (a) modulation amplitude of 1.25×10^3 mT; (b) modulation amplitude of 2.5×10^{-2} mT; (c) modulation amplitude of 2.5×10^{-1} mT. Arrows indicate the direction of the field scan.

across a small bar of the sample, $10 \times 1 \times 1$ mm^3 (voltage contacts in a standard four-probe technique were utilized) when the dc bias current I_{dc} through the sample was zero. Since thermal EMF's of several µV can easily develop in these materials, the samples were allowed to reach steady state at all temperatures. We found an unusual magnetic field dependence of the microwave induced dc voltage V_{dc}: the voltage peaks at zero magnetic field and then it decreases gradually to zero for both field sweep directions in a slightly asymmetric way (Fig. 2). It is interesting to note that Fig. 1 (for small modulation amplitude) and Fig. 2 show a similar magnetic field dependence. It should be mentioned that the induced voltage across the sample is detected only when the sample is superconducting; that correlation was checked by simultaneous resistivity and microwave absorption measurements.

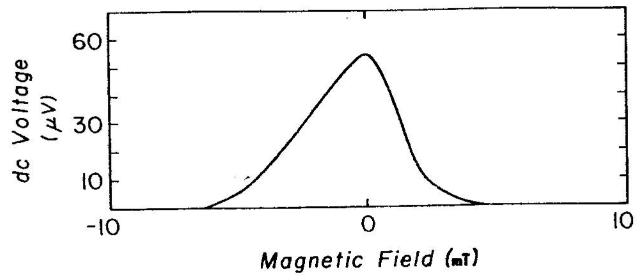

Fig. 2. Magnetic field dependence of the microwave induced dc voltage across the sample at 30 K, $f = 9.42$ GHz, and $P = 63$ mW. Negative fields are applied in the opposite direction to positive fields.

IV. DISCUSSION

Although there has been much discussion about naturally occurring Josephson junctions and arrays in samples of high T_c materials, not many data existed to support this view. Recently the results of transport [8] and low-field absorption [9] measurements have provided experimental evidence for the existence of Josephson junctions in a $YBa_2Cu_3O_7$ high T_c superconductor. The above mentioned experiments support our model for the behaviour of these materials in microwaves at low magnetic fields.

This model, which was first proposed in a preliminary communication [5] and further developed in a subsequent publication [6], is able to explain, e.g., the very low value of the critical magnetic field at which the microwave absorption starts to occur, the break in the field dependence of the absorption, etc., and it is substantiated by the microwave induced dc voltage across the sample (Fig. 2).

In our model the sample is considered as made of many long Josephson junctions (one dimension of such junctions $L > \lambda_J$, where λ_J is the Josephson penetration depth). The penetration depth, λ_J is equal to $(\Phi_0/\mu_0 d J_c)^{1/2}$, where J_c is the critical current density of the junction and d its magnetic thickness ($2\lambda_L + t$, where t is the natural thickness of the barrier). For the barriers at grain boundaries, twins, etc., current densities exist such that barrier dimensions achieve the limit $L > \lambda_J$. It is proposed [6] that at low magnetic fields (the most interesting region, see Fig. 1) the absorption of microwaves takes place in these junctions.

Let us now pay attention to the losses in the Josephson junctions. Is is well known that at certain simplifying assumptions [10] the equation of a one-dimensional Josephson junction is reduced to the non-stationary sine-Gordon equation

$$\lambda_J^2 \frac{\partial^2\varphi}{\partial x^2} - \frac{1}{\omega_p^2}\frac{\partial^2\varphi}{\partial t^2} = \sin\varphi, \tag{2}$$

where ω_p is the junction plasma frequency. In order to account for the power dissipation one should add the following terms (the most important ones) to the equation (2):

(a) The term $\omega_c^{-1}\dfrac{\partial\varphi}{\partial t}$, which accounts for the normal current in the junction (ω_c — characteristic frequency of the junction). Since the force created by this term is not conservative, the rate of the associate energy dissipation is the following

$$P = I_J \Phi_0 \omega_c^{-1} \int_{-\infty}^{\infty} \mathrm{d}x \left(\frac{\partial\varphi}{\partial t}\right)^2, \tag{3}$$

where $I_J = j_c \lambda_J$ (j_c — linear density of the critical current).

(b) The term $\lambda_J^2 \omega_L^{-1}\dfrac{\partial^3\varphi}{\partial x^2 \partial t}$, which accounts for the quasiparticle current in the junction electrodes and results in the following additional power dissipation

$$P = I_J \Phi_0 \lambda_J^2 \omega_L^{-1} \int_{-\infty}^{\infty} \mathrm{d}x \left(\frac{\partial^2\varphi}{\partial x\,\partial t}\right),$$

where ω_L is some constant with the dimensionality of frequency ($\omega_L \gg \omega_p$ but $\omega_L \sim \omega_c$).

The analysis of the relative effects of the dissipative terms (a) and (b) shows that the term (b) can be neglected [11]. Thus taking into account the dissipative term (a) only, the equation (2) becomes

$$\lambda_J^2 \frac{\partial^2\varphi}{\partial x^2} - \frac{1}{\omega_p^2}\frac{\partial^2\varphi}{\partial t^2} - \frac{1}{\omega_c}\frac{\partial\varphi}{\partial t} = \sin\varphi. \tag{5}$$

This is a rather complicated equation for which general analytical solutions have not been found but it has been checked up [12] that substituting the soliton solution of (2) into (3) gives a good description of the perturbed sine-Gordon equation (5).

We propose a different approach to this problem. Let us postulate the following Lagrangian

$$\mathscr{L} = \left\{\frac{1}{2}\frac{1}{\omega_p^2}\left(\frac{\partial\varphi}{\partial t}\right)^2 - \frac{1}{2}\lambda_J^2\left(\frac{\partial\varphi}{\partial x}\right)^2 + (\cos\varphi - 1)\right\}\exp\left\{\frac{\omega_p^2}{\omega_c}t\right\} \tag{6}$$

and observe that if the Hamilton variation principle is satisfied, that is, if the function S

$$S = \int_{t_1}^{t_2}\int \mathscr{L}(x,\tau)\,\mathrm{d}x\,\mathrm{d}\tau \tag{7}$$

has an extremum, the perturbed sine-Gordon equation is obtained. The variation of (7) gives

$$\frac{\partial S}{\partial\varphi(x',t)} = \int_{t_1}^{t_2}\int\left\{\frac{1}{\omega_p^2}\frac{\partial\varphi}{\partial\tau}\frac{\partial}{\partial\tau}\partial(x-x')\partial(\tau-t) - \right.$$
$$\left. -\lambda_J^2\frac{\partial\varphi}{\partial x}\frac{\partial}{\partial x}\partial(x-x')\partial(\tau-t) - \sin\varphi\,\partial(x-x')\partial(\tau-t)\right\}\exp\left\{\frac{\omega_p^2}{\omega_c}\right\}\mathrm{d}x\,\mathrm{d}\tau. \tag{8}$$

Integrating the right hand side of (8) by parts and setting it zero yields

$$\frac{1}{\omega_p^2},\frac{\partial^2\varphi}{\partial t^2} - \lambda_J^2\frac{\partial^2\varphi}{\partial x^2} + \frac{1}{\omega_c}\frac{\partial\varphi}{\partial t} + \sin\varphi = 0,$$

which is the perturbed sine-Gordon equation (5).

The generalized momentum

$$p = \frac{\partial\mathscr{L}}{\partial\dfrac{\partial\varphi}{\partial t}} = \frac{1}{\omega_p^2}\frac{\partial\varphi}{\partial t}\exp\left\{\frac{\omega_p^2}{\omega_c}t\right\} \tag{9}$$

and the Lagrangian (6), yield the Hamiltonian

$$\mathscr{H} = \exp\left\{\frac{\omega_p^2}{\omega_c} t\right\}\left\{\frac{1}{2}\frac{1}{\omega_p^2}\left(\frac{\partial\varphi}{\partial t}\right)^2 + \frac{1}{2}\lambda_J^2\left(\frac{\partial\varphi}{\partial x}\right)^2 + (1 - \cos\varphi)\right\}. \qquad (10)$$

Now, it is straightforward to obtain the energy

$$E = \exp\left\{\frac{\omega_p^2}{\omega_c} t\right\}\int_{-\infty}^{\infty}\left\{\frac{1}{2}\frac{1}{\omega_p^2}\left(\frac{\partial\varphi}{\partial t}\right)^2 + \frac{1}{2}\lambda_J^2\left(\frac{\partial\varphi}{\partial x}\right)^2 + (1 - \cos\varphi)\right\}dx. \qquad (11)$$

Finally, the rate of the dissipation of energy is

$$P = \frac{dE}{dt} = \frac{\omega_p^2}{\omega_c}\exp\left\{\frac{\omega_p^2}{\omega_c} t\right\}\int_{-\infty}^{\infty}\left\{-\frac{1}{2}\frac{1}{\omega_p^2}\left(\frac{\partial\varphi}{\partial t}\right)^2 + \frac{1}{2}\lambda_J^2\left(\frac{\partial\varphi}{\partial x}\right)^2 + (1 - \cos\varphi)\right\}dx. \qquad (12)$$

As the next step a series solution of the equation (5) should be considered. The number of terms in the series for φ, which is substituted into expression (12), is determined by the required precision of the energy dissipation calculations.

V. SUMMARY

The low-field microwave absorption, the microwave induced dc voltage measured across the sample, and the hysteresis in the temperature dependence of the microwave absorption in the fieldcooled samples [13] can be explained on the basis of the existence of arrays of long Josephson junctions formed at defects, grain boundaries, and twins in the high T_c superconductors. These Josephson junctions provide for the fluxon motion at low magnetic fields, which leads to dissipation, as observed. An expression for the energy dissipation due to the interaction of Josephson fluxons with the normal current in long Josephson junctions is derived from a postulated Lagrangian.

In a recent paper Portis and Blazey [14] also discusses the relevance of fluxon dissipation in Josephson junctions.

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ДЖОЗЕФСОНОВСКИЕ ФЛУКСОНЫ В ВЫСОКОТЕМПЕРАТУРНЫХ СВЕРХПРОВОДНИКАХ

В работе сделана попытка создать количественную основу модели нерезонансного поглощения слабых полей микроволн в высокотемпературных сверхпроводниках. Из постулированного Лагранжиана получено выражение для диссипации энергии при прохождении тока длинным переходом Джозефсона.