Physica B 169 (1991) 663-664
North-Holland

SHIELDING CURRENTS INFLUENCE ON INTERGRANULAR COUPLING IN HIGH T_c SUPERCONDUCTORS

S.Pace, A.Saggese, L.Liberatori, B.Polichetti, F.Celani *

Dipartimento di Fisica, Universita' di Salerno - 84100 Salerno, Italy.

* I.N.F.N. - Laboratori Nazionali di Frascati - 00044 Frascati, Italy.

In this paper we analyze the weakly coupled structure of high Tc superconducting granular samples in terms of a Josephson junctions network. We start from the well known results on superconducting loops closed by Josephson junctions, and show that the energy barrier for entrapping or de-trapping flux quanta is essentially determined by the shielding currents crossing the junctions which remove the states degeneration. This effect corresponds to the absence of degeneration of the thermodynamic potential as a function of different number of flux quanta trapped in the superconducting loops. Following this approach we remark that the superconducting glass model neglects the effects of shielding currents and may be a poor approximation. On the contrary a correct description of superconducting granular systems leads to a model very similar to the usual flux creep model.

1. INTRODUCTION

High Tc ceramic granular superconductors show a complex behaviour due to Josephson couplings between grains. Indeed, the transition to the superconducting state, recorded by resistive or a.c. susceptivity measurements, shows two steps: the first due to the grain transition and the second caused by the occurrence of the superconducting coupling between grains. This second step, in resistive measurements, appears to be strongly dependent not only on magnetic fields, but mainly on measuring currents crossing through the junctions. Analogously, in a.c. magnetic susceptibility measurements, a strong dependence on the d.c. magnetic fields and on the amplitude of the a.c. field exists. Moreover transport and magnetic properties strongly depend on the field cooling FC or zero field cooling ZFC condition, i.e. in presence or in absence of shielding currents.

The complex behaviour of granular samples sometimes is described using a flux creep model (1). Otherwise, the weakly coupled granular systems are analyzed as Josephson junctions arrays (2) described by the Hamiltonian:

$$\mathcal{H} = (\hbar/2e) \sum_{ik} I_{jik}(\mathbf{h}) \{1 - \cos(\varphi_{ik} + A_{ik})\} \qquad 1$$

In Eq.1 the sum is done only on adjacent grains, $I_{jik}(\mathbf{h})$ is the Josephson current of the junction located between two adjacent grains in the local magnetic field $\mathbf{h}$, φ_{ik} and A_{ik} are respectively the phase difference and the integral of the vector potential between the two grains. Analogies with a spin glass system suggest the use of a superconducting glass model (2).

In this paper, in section 2, we show that the use of Eq.1 is a too simplified description of junction arrays, and that the effects of shielding currents cannot be neglected (3).

Conclusions are drawn in the last section.

2. SHIELDING CURRENT EFFECTS

A realistic model for coupled granular samples is a network of superconducting loops closed by one or more Josephson junctions. In order to describe these systems, we start from well established theoretical and experimental results on a single Josephson junction in isolated loops deeply analyzed for SQUID applications (4). In this particular case for a single junction in the loop, the system dynamic is determined by using the following thermodynamic potential (5):

$$G = (\Phi - \Phi_{ex})^2/2L + I_j(\mathbf{h})\,(\hbar/2e)\,[1 - \cos(2\pi\Phi/\Phi_0)] \qquad 2$$

In Eq.2 Φ and Φ_{ex} are respectively the flux of the actual magnetic field and the flux generated by the external field $\mathbf{H}$, while L is the loop inductance and Φ_0 is the flux quantum. The Eq.2 can be generalized to many junctions in the loop. In Eq.2 the first term takes into account both the magnetic field energy and the work done by the shielding currents for the magnetic field expulsion. The second term is equivalent to Eq.1. As recently reported (3), we remark that:

1) the term $-2\Phi\Phi_{ex}$ modifies the thermodynamical potential in the same way as an external current source modifies the hamiltonian of a biased junction (4); by extending such result to the Josephson array, Eq.1 becomes :

$$\mathcal{H} = (\hbar/2e) \sum_{ik} I_{jik}(\mathbf{h}) \{1 - \cos(\varphi^*_{ik}) - \alpha_{ik}\varphi^*_{ik}\} \qquad 3$$

where $\varphi^*_{ik} = \varphi_{ik} + A_{ik}$, $\alpha_{ik} = I_{B\,ik} / I_{jik}(\mathbf{h})$, and $I_{B\,ik}$ is the bias current of the junction generated by the shielding currents;
2) the presence of the shielding currents removes the state degeneration present in Eq.1, so that the relative minima of Eqs.2,3 are metastable states;
3) the potential barriers ΔE_{ik} are:

$$\Delta E_{ik} = \Delta E_{ik}^0 \left[(1 - \alpha_{ik}^2)^{1/2} - \alpha_{ik}\cos^{-1}\alpha_{ik}\right] \qquad 4$$

where $\Delta E_{ik}^0 = I_{jik}(\mathbf{h})\,(\hbar/e)$.
4) at T=0 metastable shielding states behave as stable states, until the bias currents reach the maximum Josephson currents.

For any loop two parameters $LI_{jmin}(\mathbf{h}) / \Phi_0$ and $\Delta E^0_{min} / k_B T$ are relevant; where $LI_{jmin}(\mathbf{h})$ and ΔE^0_{min} refer to the weakest junction of the loop. In this paper we restrict our analysis to the case of strong coupling between grains determined for any loop by the conditions:

$$LI_{jmin}(\mathbf{h}) \gg \Phi_0 \qquad 5a$$

$$\Delta E^0_{min} \gg K_B T \qquad 5b$$

If Eq.5a is not valid, the loop has not hysteresis neither magnetic flux trapping and relative minima are absent. In this case, single loop results cannot be extended to the Josephson array, and the network should be described by a model very similar to the distributed model of long Josephson junctions, so that different features are shown. The Eq.5b leads to the stability of the shielding states, which, in a loop with a surface S, make the lower critical field $H_{hC1} = \Phi_0/2S$ meaningless. Since by Eq.4 shielding currents reduce the barrier heights, as $\Delta E_{ik} \approx K_B T$, the probability of metastable states decay becomes not negligible. As reported by S.Pace et al. (6) these phenomena lead to a creep analysis of the Josephson array (CJA model).

From previous arguments it is evident that the presence of currents crossing through the junctions radically modifies the system dynamic. In particular in Eq.1 the magnetic field is present only in the term A_{ik} of the gauge invariant phase. This contribution depends only on the local vector potential in the junction and is insensitive to the vector potential in the loop. In the superconducting glass model the magnetic flux is considered only as a frustration source, which pushes the phase to stationary values different from the minima of Eq.1. In this way the frustration reduces the barrier height, but its value is different from Eq.4 because Eq.3 considers also the work made by the junction bias current for carrying the phase from the equilibrium value to the value corresponding to the maximum of the potential.

The Eq.1 can be used as an approximation of Eq.3 only in case of negligible currents circulating in the superconducting loops.

High quality samples, at low magnetic field, show a complete and stable shielding of the magnetic field, so that Eqs.5a,b hold and shielding currents cannot be neglected. At high fields or at temperatures just below T_c, where these equations are not valid the single loop results cannot be used.

3. CONCLUSIONS

We believe that the magnetic field dependence of the diamagnetic behaviour of a granular system is mainly determined by the shielding currents, which circulate in superconducting loops closed by Josephson junctions. Indeed the analysis of the single loop thermodynamic potential allows us to affirm that shielding states are metastable and may be far from the thermodynamic equilibrium. By removing the hamiltonian degeneration, the shielding currents play a key role in the decay toward the equilibrium, so that any correct model must consider explicitly the presence of shielding currents. This picture is quite similar to the pinning potential in the presence of Lorentz forces, so that the creep in Josephson junction array becomes identical to the flux creep in usual superconductors.

REFERENCES

(1) Y.Yeshurun, A.P. Malozemoff, Phys. Rev. Lett. 60 (1988) 2202
(2) I. Morgenstern, K. A. Muller, J. G. Bednorz, Z. Phys. B69 (1987) 33.
(3) S. Pace et al. Proceedings of SATT3 confer. Genova 12/2/90, in print.
(4) A. Barone and G.Paterno', Physics and applications of the Josephson effect , Wiley, New York, 1982.
(5) L. D. Jackel et al., Phys. Rev., B9 (1974) 115.
(6) S.Pace et al., Creep in Josephson junction array, in print.