The peak in the nonlinear ac resistivity of granular superconductors

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Abstract

We model s-wave and d-wave disordered granular superconductors with a three-dimensional random network of Josephson junctions with finite self-inductance. The nonlinear ac resistivity ρ_2 was calculated numerically. We find a peak in ρ_2 as a function of temperature, in good agreement with recent experiments. The value of ρ_2 at the peak temperature T_p depends on the current amplitude I_0 as a power law, $\rho_2(T_p) \sim I_0^{-\alpha}$. We find that α depends on the self-inductance and current regimes. In the weak current regime is $\alpha = 0.5 \pm 0.1$ and independent of the self-inductance for both of s- and d-wave materials. In the strong current regime, α depends on the screening, with $\alpha \approx 1$ for some interval of inductance in agreement with measurements in d-wave high T_c ceramic superconductors.

Key words: granular superconductors; pi junctions; d-wave superconductivity; Josephson networks

Recently, Yamao *et al.*[1] have measured the ac linear resistivity ρ_0 and the nonlinear resistivity ρ_2 of ceramic superconductor $YBa_2Cu_4O_8$. ρ_2 is defined as the third coefficient of the expansion of the voltage $V(t)$ in terms of the external current I_{ext} as $V = \rho_0 I_{ext} + \rho_2 I_{ext}^3 + \ldots$. When the sample is driven by an ac current $I_{ext}(t) = I_0 \sin(\omega t)$, one can obtain ρ_2 from

$$\rho_2 = -\frac{4V'_{3\omega}}{I_0^3} \ , \ \ V'_{3\omega} = \frac{1}{2\pi} \int_{-\pi}^{\pi} V(t) \sin(3\omega t) d(\omega t) \ . \quad (1)$$

Yamao *et al.* have found that ρ_2 has a maximum value at a temperature T_p near the intergrain ordering temperature of their sample. They observed that ρ_2 depends with I_0 as $\rho_2(T_p) \sim I_0^{-\alpha}$, with $\alpha \approx 1.1$.

It is now believed that the gap of high-T_c superconductors has d-wave symmetry. This makes possible to have weak links with negative Josephson coupling between the superconducting grains in high-T_c ceramics, which are called π-junctions [2]. Therefore, they can be modeled with a network of Josephson junctions with random couplings, given by the hamiltonian [3–5]

$$H = -\sum_{<ij>} J_{ij} \cos(\theta_i - \theta_j - A_{ij}) + \frac{1}{2L} \sum_p \Phi_p^2 \ . \quad (2)$$

Here θ_i is the superconducting phase of the grain at the i-th site of a cubic lattice, J_{ij} is the Josephson coupling between grains, and L is the self-inductance of a loop (mutual inductances are neglected). The first sum is taken over all nearest-neighbor pairs and the second sum is taken over all elementary plaquettes on the lattice. The total magnetic flux threading through the p-th plaquette is $\Phi_p = \frac{\phi_0}{2\pi} \sum_{<ij>}^{p} A_{ij}$ with $A_{ij} = \frac{2\pi}{\phi_0} \int_i^j \mathbf{A}(\mathbf{r}) d\mathbf{r}$. We model the d-wave superconducting case by taking J_{ij} as a random variable equal to J or $-J$ with equal probability (representing 0 and π junctions respectively), and also the s-wave superconducting case by taking $J_{ij} > 0$ and uniformly distributed in $[0, 2J]$. The effect of screening currents is characterized by the dimensionless inductance $\tilde{L} = (2\pi/\Phi_0)^2 LJ$. The d-wave model has been able to reproduce the paramagnetic Meissner effect [3] observed experimentally in ceramic high-T_c cermamics [6]. Kawamura [4,5] proposed that there is a chiral glass phase, which a has been seen experimentally in the nonlinear ac magnetic susceptibility [7] and in the aging phenomenon [8].

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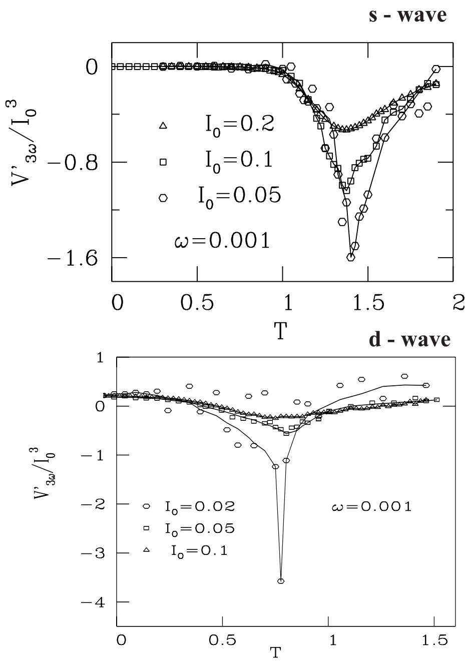

Fig. 1. Temperature dependence of the nonlinear resistivity $\rho_2 \propto V'_{3\omega}/I_0^3$ for the s-wave (upper panel) and the d-wave case (lower panel) for $\tilde{L} = 1$, $\omega = 0.001$ and $8 \times 8 \times 8$ samples.

To calculate transport porperties we use the resistively shunted junction model in which the dissipative ohmic current due to an intergrain resistance R and the temperature dependent Langevin noise current are added to the Josephson current [3]. This leads to a set of dynamical equations for θ_i and A_{ij} [3], which are solved numerically for a given temperature T and driving current $I_{ext} = I_0(\sin \omega t)$ [9,10]. The temperature dependence of the *nonlinear* resistivity ρ_2 for different values of I_0 is shown in Fig.1 for the s-wave system (upper panel) and for the d-wave system (lower panel) for $\tilde{L} = 1$ and $\omega = 0.001$. We find that in both cases $\rho_2(T)$ has a peak at a temperature T_p (different for each case). In the s-wave case, T_p coincides with the metal – superconductor transition at which the linear resistivity vanishes [10], while for the d-wave case T_p coincides with the temperature for the onset of the paramagnetic Meissner effect [9]. The maximum value of ρ_2 at T_p tends to diverge when I_0 decreases. We have studied [9,10] the dependence of $\rho_2(T_p)$ with I_0 for the two cases and for different values of $\tilde{L}$. We have clearly distinguished two different regimes of power law behavior for small and large currents [10]. In the weak current regime ($I_0 \leq 0.1$) we can fit a dependence $\rho_2(T_p) \sim I_0^{-\alpha}$. We obtain $\alpha = 0.5 \pm 0.1$ independently of the value of $\tilde{L}$ and both for the s-wave and for the d-wave cases. In the strong current regime (SCR) we can fit a different exponent α. However, the value of α in this regime is different in the s-wave and d-wave case and

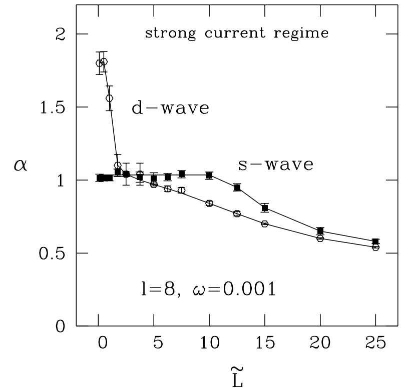

Fig. 2. Dependence of the power-law exponent α with self-inductance $\tilde{L}$ obtained in the strong current regime for $\omega = 0.001$ and $8 \times 8 \times 8$ samples.

depends strongly on $\tilde{L}$, as it is shown in Fig. 2.

In conclusion, we have calculated the non-linear ac resistivity exponent α for s and d-wave granular superconductors, obtaining two distinct current regimes. For weak currents α is independent of the screening strength and of types of pairing symmetry, while in the opposite case this exponent depends on $\tilde{L}$. Since real current is $I = \frac{2eJ}{\hbar} I_0$, and $J \sim 10^2$ K, then for $I_0 \sim 0.1$ we have $I \sim 10^{-2}$ mA. The experiments of [1] used a current $I \sim 10$ mA. This suggests that they were performed in the SCR. A typical value of inductance for ceramics is $\tilde{L}$ are bigger than 3 [11]. As seen from Fig. 2, the value of α in the SCR for $1 < \tilde{L} < 5$ agrees very well with the experimental value.

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