INFLUENCE OF DISSIPATION ON THE FINITE TEMPERATURE PHASE TRANSITION IN JOSEPHSON JUNCTION ARRAYS

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We investigate the phase diagram of an array of Josephson junctions at finite temperatures, taking charging effects as well as the flow of normal currents due to single electron tunneling into account. Using a quantum Ginzburg-Landau theory we derive the fluctuation conductivity and find, depending on junction parameters, fluctuation broadened superconducting transitions, reentrant, or quasireentrant behavior.

1. INTRODUCTION

Arrays of Josephson junctions are realizations of X-Y models. They exhibit different phase transitions, e.g. in two dimensions the Kosterlitz-Thouless transition. Quantum fluctuations associated with the charging energy inhibit the order and provide the possibility for a fluctuation driven phase transition (1,2). On the other hand, the dissipation due to the flow of normal currents tends to suppress the quantum effects (3). Here we show how the dissipation influences the resistive phase transitions of the arrays (4,5) at finite temperatures.

2. THE MODEL

In this paper we will consider a regular cubic array of superconducting islands with lattice constant a. We neglect fluctuations in the modulus of the superconducting order parameters of the individual islands assuming that we are well below the single grain transition temperature. The relevant degrees of freedom are the phase differences of the order parameters on neighboring islands and the charges accumulating on the electrodes. Quantum statistical properties of this system are characterized by an effective action (6) in imaginary times $0 \le \tau \le \hbar\beta$:

$$S[\varphi]=\int_0^{\hbar\beta} d\tau \sum_i \frac{C}{2} \left(\frac{\hbar}{2e} \frac{\partial\varphi_i}{\partial\tau}\right)^2 + S_J[\varphi]+S_D[\varphi]$$

$$S_J[\varphi] = E_J \sum_{<ij>} \int_0^{\hbar\beta} d\tau (1-\cos(\varphi_{ij}(\tau))$$

where $\varphi_{ij}=\varphi_i-\varphi_j$ is the difference of the phases on neighboring islands. We assume that the Coulomb energy of charges Q_i on the islands is dominated by the self-charging energy $Q_i{}^2/2C$. E_J is the Josephson coupling energy arising from Cooper pair tunneling between nearest neighbor grains.

A complete description of the junction array also has to take into account the tunneling of quasiparticles (qp). This gives rise to dissipation which in a fully quantum mechanical way is described by the effective action:

$$S_D[\varphi]=\int_0^{\hbar\beta} d\tau \int_0^{\hbar\beta} d\hat{\tau} \sum_{<ij>} \alpha_{qp}(\tau-\hat{\tau})[1-\cos(\frac{\varphi_{ij}(\tau)-\varphi_{ij}(\hat{\tau})}{2})]$$

The qp damping kernel $\alpha_{qp}(\tau)$ involves BCS equilibrium Green's functions which we extend to include the effects of temperature dependent scattering mechanisms (see Ref.5 for details). At high frequencies the Fourier transform of $\alpha_{qp}(\tau)$ approaches the Ohmic form

$$\alpha_{qp}(\omega_\mu) = -\alpha|\omega_\mu|/\pi$$

where $\alpha=h/4e^2R_n$ and R_n is the normal state resistance of a single junction which for an ordered array is identical to the sheet resistance. If $\alpha_{qp}(\tau)$ is short ranged, i.e. if the subgap conductance vanishes, one can approximate the trigonometric function in $S_D[\varphi]$ by its quadratic expansion, provided the

*New address: Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands phases vary slowly on the time scale $\Delta/\hbar$ (see Ref.7).

III. MEAN FIELD PHASE TRANSITION

Analogous to the coarse graining approach (2) we introduce local field variables ψ_i in a conventional Hubbard Stratonovich procedure. A second order cumulant expansion of the resulting free energy functional $F[\psi]$ is performed above the transition temperature. To lowest order in $\underline{k}$ and ω_μ we obtain

$$F[\psi] = \sum_{\underline{k},\mu} [r + (ak)^2/z + c_0\omega_\mu^2]\,|\psi(\underline{k},\omega_\mu)|^2$$

with the coefficient r given by

$$r = 1 - \frac{zE_J}{\hbar}\int_0^{\hbar\beta} d\tau\, g(\tau)$$

All the information about quantum effects and dissipation is contained in the correlation function

$$g(\tau) = \langle \exp(i[\varphi_i(\tau) - \varphi_i(0)]) \rangle_0$$

which is evaluated with the quadratic part of the action $S[\varphi]$ containing the charging energy and the dissipation:

$$g(\tau) = \exp\left(-\frac{1}{\hbar^2\beta N}\sum_{\underline{k},\mu}\frac{1-\cos(\omega_\mu\tau)}{\frac{\omega_\mu^2}{8E_C} - \frac{1}{2}\alpha_{qp}(\omega_\mu)(z-\gamma_{\underline{k}})}\right)$$

The mean field phase diagram is determined by the condition r=0. Fig.1 shows the critical temperature as a function of the ratio zE_J/E_C, where $E_C=e^2/2C$ and z=4 in 2 dimensions) for different strengths of the dissipation. An important feature of the phase boundary is the reentrant type behavior at low temperatures for all values of α

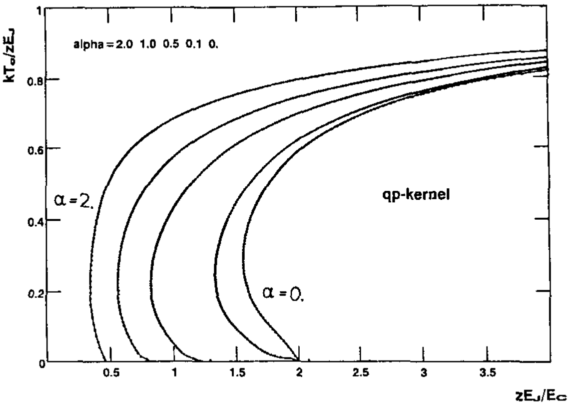

FIGURE 1
Mean field phase boundary for different strengths of the quasiparticle dissipation $\alpha=h/4e^2R_n$.

IV. FLUCTUATION CONDUCTIVITY

After analytical continuation to real times a time dependent quantum Ginzburg-Landau equation can be deduced from $F[\psi]$ (8). By calculating the supercurrent correlation function we derive the static fluctuation conductivity which close to the phase boundary ($r \ll 1$) is given by

$$\sigma^{2D} = (e^2/16\hbar)\, r^{-1}$$

The resistivity R of the array then follows from adding the fluctuation contribution to the normal conductance $1/R_{qp}$ arising from the qp tunneling. R is plotted in Fig.2 for a given ratio E_J/E_c and different values of α.

Depending on α we find ordinary fluctuation broadened superconducting transitions, reentrant behavior (not shown in the figure), quasireentrant behavior with a resistivity minimum, or semiconducting behavior.

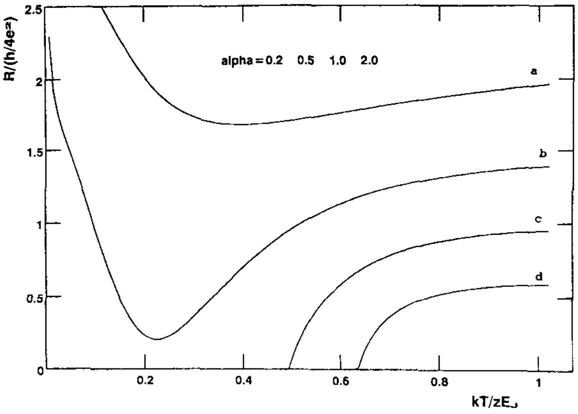

FIGURE 2
Temperature dependence of the resistivity, measured in units of $h/4e^2$ for $zE_J/E_C=0.8$ and different values of α: (a) $\alpha=0.2$, (b) $\alpha=0.5$, (c) $\alpha=1.0$, (d) $\alpha=2.0$.

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