Current-Induced Relaxation of Charge Imbalance in Superconducting Phase-Slip Centers*

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In superconductors with a relatively long inelastic scattering time, relaxation of charge imbalance generated in phase-slip centers will be dominated by elastic scattering in the presence of a supercurrent. The spatial dependence of the electrochemical potential is calculated. Important qualitative differences occur from the usual model of phase-slip centers, based on relaxation by inelastic scattering.

1. INTRODUCTION

Charge imbalance in superconductors\(^1\) can be relaxed by several mechanisms: inelastic scattering or elastic scattering in the presence of a pair-breaker, such as a magnetic field, paramagnetic impurities, a supercurrent, or gap anisotropy. Following Schmid\(^2\) in discussing the work of Schmid and Schön\(^3\), the relaxation time for charge imbalance \(\tau^T\) is equal to

\[
\tau^T = \frac{4k_BT}{\pi\Delta} \left( \frac{\tau_E}{2\Gamma} \right)^{1/2}
\]  

(1a)

where

\[
\Gamma = \frac{1}{\tau_s} + \frac{1}{2\tau_E} + \frac{D}{2} \left( \frac{4m^2v_s^2}{\hbar^2} - \frac{1}{\Delta} \frac{\partial^2 \Delta}{\partial r^2} \right)
\]  

(1b)

Here \(\tau_E\) is the inelastic scattering time for electrons at the Fermi surface, \(\Delta\) is the energy gap, \(\tau_s\) is the spin-flip scattering time, \(D = v_F l / 3\) is the diffusion constant, \(m\) is the single-electron mass, and \(v_s\) is the velocity of the superfluid. We used the shorter notation \(\tau^T\) for Schmid's \(\tau^T_R\).

In phase-slip centers\(^4\), charge imbalance is generated by a bias current that exceeds the critical current. The imbalance, generated within a short

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region of the order of the Ginzburg–Landau coherence length $\xi_{GL}$, spreads over a much longer region, given by the diffusion length $(D\tau^T)^{1/2}$. Usually, for phase-slip centers it has been assumed that relaxation occurs only by inelastic scattering, so that in Eq. (1), $\Gamma = (2\tau_E)^{-1}$ and the relaxation time is

$$\tau_E = \frac{(4k_B T/\pi \Delta)}{\tau_L}$$

As $\Delta$ is proportional to $(T_c - T)^{1/2}$ near $T_c$, the associated diffusion length and the differential resistance of the phase-slip center should diverge proportional to $(T_c - T)^{-1/4}$ near $T_c$, as has been observed experimentally in tin and indium. Kadin et al. have studied phase-slip centers in tin while decreasing $\tau^T$ below the value of Eq. (2) by applying a magnetic field. Qualitatively, the nature of the phase-slip center is not changed by this procedure; the same temperature dependence is expected and was observed.

It is interesting to consider the influence of the supercurrent on charge imbalance relaxation in this context. Lemberger and Clarke recently confirmed the influence of $v_s$ on $\tau^T$ by measuring $\tau^T$ in a tunneling experiment in the presence of a transport current. Ivlev et al. performed calculations on a current-carrying normal metal–superconductor interface. However, although the presence of a supercurrent of the order of the critical current is an essential feature of phase-slip centers, so far the dependence of $\tau^T$ on $v_s$ has been ignored. We will show that this is justified for some superconductors close to $T_c$, but wrong for others.

2. HOMOGENEOUS CASE

In order to investigate the importance of the supercurrent in relaxing charge imbalance, we will compare its influence with that of the second term in Eq. (1b). We ignore scattering by paramagnetic impurities and spatial dependences. In the presence of a position-independent supercurrent at the critical level we then find

$$\Gamma_{ic} = \frac{1}{2\tau_E} + \frac{D p_e^2}{2\hbar^2}$$

where $p_e$ is the value of the superfluid momentum at the critical current. According to Ginzburg–Landau theory, $p_e$ is equal to $\hbar/(3^{1/2}\xi_{GL})$. We see that

$$\Gamma_{ic} = \frac{1}{2\tau_E} + \frac{D}{6\xi_{GL}^2} = \frac{1}{2\tau_E} + \frac{1}{6\tau_{GL}}$$

where $\tau_{GL}$ is the Ginzburg–Landau time, equal to $(\pi\hbar/8k_B T_c)(1 - T/T_c)^{-1}$. 