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Relaxation processes in mesoscopic superconductors

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ABSTRACT

We investigate the possibility of a novel kind of optical pump probe spectroscopy where the two laser pulses are focused on different areas of the sample. The response to the destruction of the superconducting state in a large part of a mesoscopic ring is studied numerically. We use the time dependent Ginzburg–Landau equations with periodic boundary conditions and external magnetic field. We evaluate the relaxation rates of the superconducting order parameter as well as the voltage induced by the charge imbalance. Computer simulations confirm that the perturbation of superconductivity on one part of the ring induces a voltage which decelerates the superconducting electrons on the other part of the ring. This deceleration results in the decrease of the superconducting current and the superfluid density. The relaxation times are of the order of the picosecond, the induced voltage of few millivolts and the variation of the superconducting gap of 10% which we believe to be suitable for time resolved femtosecond optical spectroscopy.

1. Introduction

In the last two decades, many new experimental techniques have been used to study the superconducting state. The main idea is of course to investigate the new high temperature superconductors in order to get a better understanding of the underlying mechanisms. As such, the time resolved pump probe optical spectroscopy technique has been used in various works with constructive results [1–4]. It is indeed a powerful tool to describe ultrafast phenomena and in particular to study the local superfluid dynamics. The underlying idea is simple: the first laser pulse excites the sample and the second laser pulse is used to measure the optical characteristics. The first pulse, called "pump", excites electron–hole pairs which relax to states around the Fermy energy. This relaxation is made via electron–electron and electron–phonon scattering and results in the multiplication of quasiparticles. The distribution of quasiparticles might modify the optical characteristics of the material such as the absorbance and the reflectivity. In particular in the case of superconductors, the gap will induce a nonuniform distribution of the quasiparticles which will accumulate near the gap. The second laser pulse, called probe, will then detect the change of reflectivity. By changing the delay between pump and probe, one can then obtain the time dependency of the reflectivity which can be linked to the intrinsic mechanisms after further analysis. Of course, the probe pulse should have a low intensity not to alter the superconducting state.

With modern lasers delivering pulses in the femtosecond regime, one can thus study the ultrafast response in superconductors and try to get a better understanding of the dynamics linked to the superconducting gap. However, one needs to take into account local effects due to the intensity of the pump pulses and in particular, the local heating and the change in the local carrier concentration. These effects can be minimized and it is generally accepted that they do not threaten the general validity of such measurements. Nevertheless, we realize in the present work that it is possible to completely get rid of these parasite effects by modifying the original setup. The idea is to apply the pump and probe pulses at two different places as seen in Fig. 1. Indeed, in the case of a ring, the modification of the state in one half of the ring directly affects the state on the other half of the ring due to the coherence of the superconducting state. Such a setup should enable experimentalists to apply pump pulses with high fluences without the usual drawbacks. However, the geometry might be more complex to realize and the dynamics involved at the probe will not necessarily be large enough to be detected. This work therefore constitutes a preliminary investigation to determine whether this setup would be relevant. First, we discuss the theoretical model chosen to describe the non-equilibrium situation that will be undoubtedly be encountered in such experiments. This framework is the time dependent Ginzburg–Landau (TDGL) equations. Then, we present the results of numerical simulations and more specifically the variation of the order parameter in the probe region. Last, we interpret the data in terms of experimentally observable quantities.

2. The time dependent equations

As this work is not meant to give an extensive analysis, we are not interested in the microscopic details. We therefore choose to

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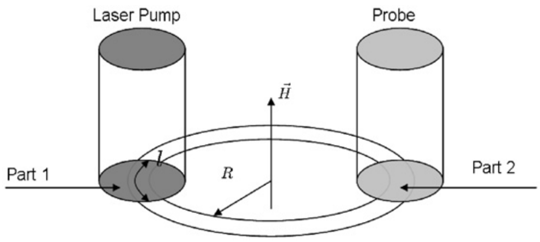

Fig. 1. Geometry of the proposed setup.

use the TDGL equations derived from the phenomenological Ginzburg–Landau theory. The validity of the TDGL equations is generally accepted close to the critical temperature. Moreover, the wide range of recent works tends to show that they provide a qualitative picture for a larger variety of situations. We here use the simplest version of the TDGL equations that takes into account the presence of magnetic field and the possibility of charge imbalance by introducing the vector potential **A** and the electrostatic potential $\tilde{\Phi}$ as derived by Gor'kov and Kopnin [5] in CGS units. We consider a superconducting ring of thickness d, radius R and length L as represented in Fig. 1. For simplicity, we consider $d \ll \xi \ll \lambda_{\rm eff}$, $R \approx \xi$ and $R \ll \lambda_{\rm eff}$, where ξ is the coherence length and $\lambda_{\rm eff}$ is the Pearl [6] penetration depth. The first two conditions allow us to treat the ring as one dimensional and the last two conditions account for the mesoscopic size of the ring. We apply a constant magnetic field **H** perpendicular to the ring. The magnetic field determines the properties (superfluid density, current, etc.) of the stable state.

We used the following dimensionless variables: vector potential $\mathbf{a} = 2\pi\xi\mathbf{A}/\phi_0$, time $t = (c^2)/(4\pi\lambda_{\rm eff}^2\sigma_n)\tilde{t} = \tilde{t}/\tau_\theta$, spatial coordinates $\mathbf{r} = \tilde{\mathbf{r}}/\xi$, electrostatic potential $\Phi = \tilde{\Phi}\sigma_n 8\pi^2\lambda_{\rm eff}^2/c\phi_0$ and order parameter $\psi = \Psi\sqrt{\beta/|\alpha|} = \rho(\mathbf{r},t)e^{i\theta(\mathbf{r},t)}$ where γ is a positive constant accounting for the slow relaxation of the order parameter. $\Psi(\tilde{\mathbf{r}},t) = \tilde{\rho}e^{i\tilde{\theta}}$ is the Ginzburg Landau order parameter which depends on the coordinate $\tilde{\mathbf{r}}$ and the time $\tilde{t}$. m and e are the electron mass and charge, σ_n is the normal state resistivity of the material, ħ the reduced Planck constant and c the speed of light. α and β are the coefficient appearing when deriving the free energy (see [7] for example). The spacial derivatives have also been modified by using $\mathbf{r} = \tilde{\mathbf{r}}/\xi$. In our case we will use x for the dimensionless longitudinal coordinate.

The Pearl penetration depth $\lambda_{\rm eff} = \lambda^2/d$ has been introduced instead of the London penetration depth $\lambda = \sqrt{mc^2\beta/8\pi e^2|\alpha|}$ since the thickness d is small. The coherence length is defined by $\xi = \sqrt{\hbar^2/4m|\alpha|}$.

There are two characteristic time scales: $\tau_\rho = \gamma\hbar/|\alpha|$ corresponds to the characteristic time of the evolution of the amplitude of the order parameter, whereas τ_θ accounts for the dynamics of the phase. The ratio between those two characteristic times is the only parameter left when using the dimensionless variables: $u = \tau_\rho/\tau_\theta$.

We neglect the corrections to the vector potential due to the small dimensions of the ring and large Ginzburg–Landau parameter $\kappa = \lambda_{\rm eff}/\xi$. Moreover, using the electroneutrality relation $div\mathbf{j} = 0$ as discussed in [5] we obtain

$$u\left(\frac{\partial\psi}{\partial t} + i\Phi\psi\right) = \psi - \psi|\psi|^2 - (i\nabla + \mathbf{a})^2\psi, \quad (1)$$

$$\nabla^2\Phi = -\nabla\left(\frac{i}{2}(\psi^*\nabla\psi - \psi\nabla\psi^*) + \mathbf{a}|\psi|^2\right). \quad (2)$$

As studied in [8], the stable state will depend on the applied magnetic field. In the case when the initial state is unstable, the order parameter will undergo one or more resistive phase slip events. For the proposed setup, we believe that the presence of magnetic field is important, in order to trigger interesting dynamics. Indeed, we might need the presence of a superconducting current in order to transmit the dynamics from one side to the other side of the ring. We will study the influence of the induced current in the forthcoming section.

The simplest way to modelize the laser pump pulse is to consider that the order parameter is completely destroyed in the pump region. We thus start from a solution where the superconducting state has been destroyed on the length l of the ring:

$$\begin{cases} \psi(x,t=0) = 0 & \text{for } 0 < x < l : \text{part 1} \\ \psi(x,t=0) = \sqrt{1-a^2} & \text{for } l < x < L : \text{part 2}. \end{cases} \quad (3)$$

According to [8] we can also prevent phase slip phenomena from happening, by fixing the magnetic flux to one half of the flux quantum.

3. Simulations of the relaxation process

Starting from the initial state (3), we study the recovery of the ring to the stable state. when we destroy superconductivity, we immediately create a voltage in the ring caused by the normal region and therefore a charge imbalance and resistivity. We can describe two mechanisms that can happen in the simple framework of the phenomenological theory.

Mechanism A: In the superconducting part (part 2), the density of superconducting electrons stays constant, but they are slowed down by the voltage: we observe a decrease of the total current. In this situation, we consider that we have a very low normal current appearing in that region. In the part where the superconductivity has been destroyed (part 1), we observe a strong normal current, going in the same direction as the superconducting current before the pump pulse. The Cooper pairs are broken but the electrons continue to move in the same direction. This normal current is progressively reduced as the superconducting state is recovered: the normal electrons are accelerated by the voltage and reduce the charge imbalance and the voltage. However, if in part 1 the superconducting current gets too low and if in part 2 the total current gets too high, we have an inversion of the voltage and the relaxation will be similar to a damped oscillator.

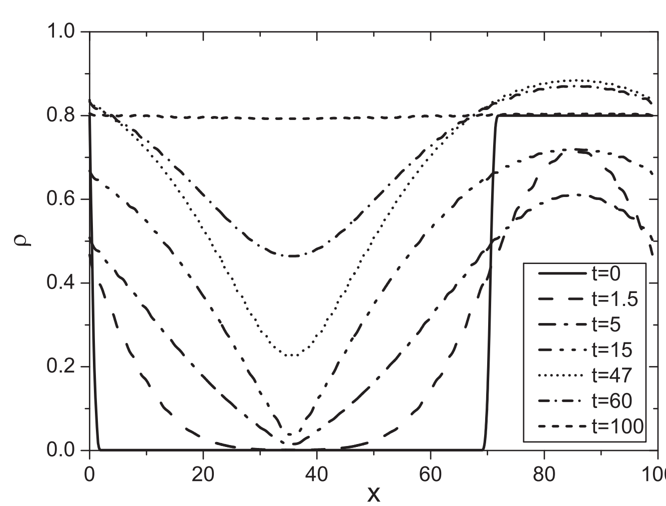

Fig. 2. Distribution of the order parameter amplitude ρ at different times, for $l/L = 70\%$ and $a = 0.6$.