Effect of Electron-Beam Irradiation on Superconducting Films

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Scanning electron microscopy performed at cryogenic conditions can be used for the two-dimensional display of various properties of superconducting thin-film samples. The Rothwarf–Taylor phenomenological equations are used to treat the spatial and temporal decay of the perturbation generated by the electron-beam irradiation. In the limit of high phonon trapping in the superconducting film, the spatial extension of the perturbed area determining the resolution of this imaging method is given by the thermal healing length. In the case of low phonon trapping, however, the healing length is given by the quasiparticle diffusion length. Also calculated is the characteristic time scale of the temporal decay after switching off the electron-beam irradiation. Modulating the electron beam at frequencies high compared to the inverse of this characteristic time can reduce the healing length considerably below the low-frequency value.

1. INTRODUCTION

Low temperature scanning electron microscopy (LTSEM) is an excellent tool for probing the spatial inhomogeneity of the superconducting properties of thin films. Of particular interest is the investigation of superconducting electronic circuits and their elements, such as tunnel junctions. The principle of LTSEM simply consists in perturbing a superconducting sample locally by the electron beam and recording the sample response as a function of the coordinates of the beam spot. In this manner a two-dimensional image of the sample response can be obtained. The general aspects of the response of a superconducting sample to electron-beam irradiation were discussed recently by Clem and Huebener. The apparatus required for LTSEM consists of a scanning electron microscope equipped

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with a low temperature stage. Recently LTSEM has been used for investigating the behavior of hotspots in superconducting microbridges and for imaging spatial structures in superconducting tunnel junctions.

The most important feature of using electron-beam or laser-beam excitation is that of being able to disturb the superconducting sample locally. The spatial resolution of either the electron-beam or laser-beam probing technique is not determined by the spot size of the electron or laser beam. However, it depends on how far the localized perturbation actually spreads into the surrounding unperturbed region. It has been shown that in many cases the perturbation of the superconducting sample caused by the electron beam can be treated as a local heating phenomenon. The spreading of the perturbation into the unperturbed regions is therefore determined by the thermal healing length. In a more accurate treatment, however, it is necessary to consider the detailed nonequilibrium behavior of the superconducting film exposed to the electron-beam perturbation and the various relaxation processes. In such a treatment the nonequilibrium distribution of the quasiparticles and the phonons must be found by solving the Boltzmann equations consistently with the BCS gap equation. It has been shown that the phenomenological Rothwarf-Taylor (RT) equations are a good approximation for the Boltzmann equations as long as one is not interested in the detailed energy distribution of the quasiparticles and of the phonons. Therefore to obtain a physical picture of the processes in a superconducting film perturbed by the electron beam it is more useful to take the approach of the RT equations rather than using the more elaborate Boltzmann equations. In the present paper we treat the question of the proper length scale for the transition region between a perturbed and an unperturbed region for a superconducting film with a high and a low phonon trapping factor using the RT equations. Further, we investigate how this length scale depends on the frequency of a modulated electron beam. Finally, we consider the decay time after switching off the perturbation.

In Section 2 we briefly discuss the characteristic times included in the RT equations. In Section 3 we analyze the time-dependent RT equations for pointlike electron-beam perturbations that are either constant or varying in time and for a homogeneous electron-beam irradiation switched off at a certain time. In Section 4 we discuss the results of the analysis in Section 3 and compare them with those obtained by the treatment with the heat diffusion equation. The analysis in Section 3 is for the one-dimensional case only. Since we often investigate two-dimensional samples by LTSEM, we discuss the two-dimensional case in Section 5. Concluding remarks are given in Section 6.