TRANSIENT RESPONSE OF SUPERCONDUCTING Pb MICROBRIDGES IRRADIATED BY PICOSECOND LASER PULSES AND ITS POTENTIAL APPLICATIONS

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Summary

We have observed voltage pulses having half-widths of less than 500ps generated by constant-current-biased superconducting Pb variable thickness microbridges driven normal by short (3-5ps) light pulses. This represents a first step in the effort to generate even shorter pulses, which according to our analysis of the Rothwarf-Taylor equations should be possible. The ultimate width should be equal to the phonon pair-breaking time, which for materials such as Nb can be as short as a few picoseconds. In addition to monitoring the voltage pulses directly, we have used a novel adoption of the optical autocorrelation technique having a time resolution limited only by the laser pulse width. It is pointed out that even shorter voltage pulses, and therefore greater potential for device applications, can be achieved by direct injection of quasiparticles.

Introduction

It is well known[1] that superconducting materials with a strong electron-phonon interaction, such as Pb, can have a very short characteristic electron-phonon interaction time. This characteristic time can be defined to be the inelastic scattering time, $\tau_{E=0}$, for an electron at the Fermi surface at the superconducting transition temperature T_c. For Pb, $\tau_{E=0}$ is estimated to be 10 picoseconds or less.[1] This time also approximately corresponds to the recombination time of quasiparticles near the energy gap of the superconductor at temperatures near T_c. When superconductivity is destroyed by excess quasiparticle density due to any external pair-breaking mechanism, the intrinsic recovery time should be in the order of $\tau_{E=0}$ unless there are other bottlenecks in the relaxation process. One commonly encountered bottleneck is the trapping effect[2] of the phonons created by the quasiparticle recombination process. The phonon escape time from a 100nm Pb film into superfluid He or a quartz substrate is about 2~3ns.[3] It would be of considerable interest if we could reduce or eliminate this phonon bottleneck. We have proposed using quasiparticle diffusion to achieve this purpose.[3] The present experiment is a successful first step toward this goal using a Pb variable-thickness bridge to reduce the effective superconductivity recovery time from 2~3ns to less than 500ps. A simple theoretical calculation with the Rothwarf-Taylor equations[2] is used to semi-quantitatively describe the experimental results and project possible future improvements.

Experiment

Pure Pb variable thickness bridges (VTB) fabricated by an Ar ion milling technique[4] are used for this experiment. Typical dimensions of the Pb VTB are 14μm wide and 1μm long. The thicknesses of the bridge and the bank are 100 and 500nm respectively. Either quartz or sapphire disks, 250μm thick, were used as substrates. The samples were mounted with a pair of twisted copper wires as the current leads and a coaxial cable as the voltage probe in an optical He immersion dewar. Short laser pulses (typically 3~5ps) produced by a dye laser synchronously pumped by a mode-locked Ar laser were used to irradiate the Pb VTB. The laser spot is estimated to be 20~100μm in diameter, which is large enough to cover the entire bridge area. A typical I-V curve of the Pb VTB at T≲2K without laser irradiation is shown in Fig. 1. The presence of a small hysterisis, instead of the much larger one typical for long bridges, indicates that the electron diffusion into the thick banks does provide substantial cooling for the bridge. The bridges were usually current-biased at a level much less than the critical current to avoid the complication of the depairing or heating effects due to the bias current when the bridge is in supercon-

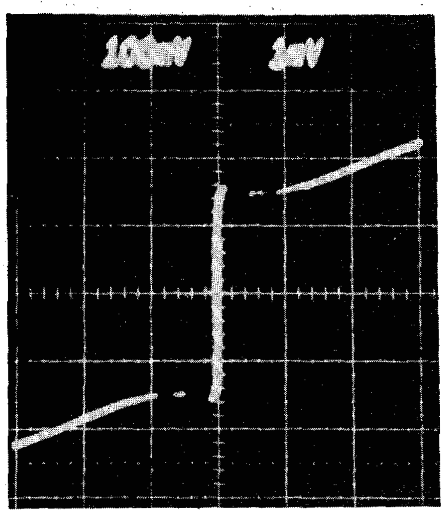

Figure 1 Current-voltage characteristics of a Pb VTB at T≲2K. Vertical scale: 10mA/div., horizontal scale: 1mV/div.

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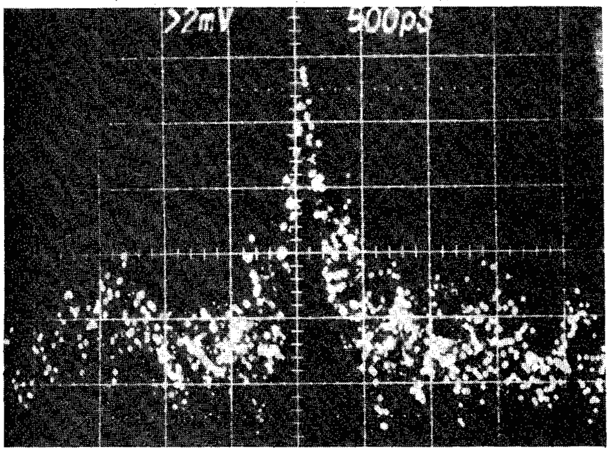

Figure 2 The sampling scope trace of the voltage pulses of a constant-current biased VTB induced by picosecond laser pulses.

ducting or dissipative states respectively. The voltage pulses induced by the laser irradiation were amplified by two fast amplifiers (B and H DC3002, total gain ~200, risetime ~130ps) in tandem and displayed by a Tektronix sampling scope (risetime ~25ps) as shown in Fig. 2. Both risetime and falltime of the voltage pulses were limited by our detection resolution which is dominated by the risetime of a pair of short twisted connection wires (about 6mm long) between the sample and the end of the coaxial cable, as determined by a separate time-domain-reflectometry measurement. In order to determine whether the actual voltage pulse is even shorter than 500 picoseconds, we used a novel optical autocorrelation technique in which the pulse train of the laser beam was split into two beams of equal intensity and then recombined and focused onto the sample after passing one of the beams through a variable length optical delay line. The nonlinearity necessary in such an autocorrelation measurement is provided by the threshold nature of the superconducting to normal transition of the VTB. In this setup, the intensities of the two beams were adjusted so that neither by itself was capable of driving the bridge normal. It should be noted that in order to avoid the interference effect of the two beams, the polarization of one beam was deliberately rotated 90° from that of the other beam. Somewhat surprisingly, we were unable to observe an autocorrelation signal of duration less than 500ps, indicating that the true decay time of the voltage pulse is indeed in the order of 500ps.

Theoretical Calculation

In order to quantitatively describe the dynamics of the quasiparticle-phonon system in the VTB, we use Eqs. 1 and 2, the Rothwarf-Taylor equations, which provide a simple yet useful model in which the energy dependences of the quasiparticle recombination and phonon pair-breaking rates are ignored:

$$\dot{N}_q = I_q - RN_q^2 + 2\tau_B^{-1}N_p - \tau_D^{-1}(N_q - N_{qT}) \qquad (1)$$

$$\dot{N}_p = I_p + \frac{1}{2}RN_q^2 - \tau_B^{-1}N_p - \tau_\gamma^{-1}(N_p - N_{pT}) \qquad (2)$$

where N_p, N_q are the densities of pair-breaking phonons and quasiparticles, respectively. N_{pT} (N_{qT}) is the thermal equilibrium value of N_p (N_q) at a temperature T; I_q and I_p are the quasiparticle and phonon generation rates due to an external perturbation; R is the recombination rate for one quasiparticle with another; τ_D is the diffusion time of the quasiparticles from the bridge into the bank; τ_B and τ_γ are the phonon pair-breaking and escape times, respectively.

This simple model does not explicitly describe the initial relaxation processes of the "hot" quasiparticles generated by direct photon absorption, but since the initial "cooling" process is very fast[3] ($\lesssim$1psec), the proliferation of quasiparticles and phonons due to the initial fast "cooling" process can be accounted for by adjusting the ratio of the generation terms I_p and I_q. We estimated previously that $I_p/I_q=15$ for 2eV photons.[3]

Numerical solutions to Eqs. 1 and 2 were obtained with the following parameters for superconducting Pb:[3]

$$4N(0)\Delta_0 R = 2\times10^{12}s^{-1}$$

$$\tau_B = 3\times10^{-11}s$$

$$\tau_\gamma = 1\times10^{-9}s$$

The exact value of τ_γ is unimportant in evaluating the short time behavior so long as it is much longer than τ_B and $(4N(0)\Delta_0 R)^{-1}$. In Fig. 3 the results of the calculations of N_q expressed in units of $4N(0)\Delta_0$ are shown as a function of time for three values of τ_D, i.e. 1, 3, 10ps (solid lines). The calculations assumed T=0K and an excitation pulse half-width of 0.25ps, essentially a delta function perturbation. The excitation amplitudes were adjusted to give identical peak values for N_q, namely $0.4\times(4N(0)\Delta_0)$, which corresponds to the threshold density for the superconducting to normal transition in both the T^* model and the simple heating model. The results for finite temperatures $T/T_c \lesssim 0.5$ are essentially the same as shown here for T=0K because of the high level excitation.

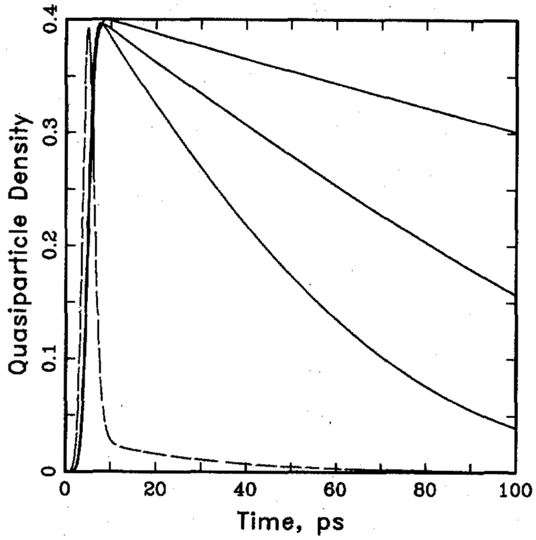

Figure 3 Quasiparticle density, in units of $4N(0)\Delta_0$ vs. time after a delta function perturbation. The three solid lines are for the photon excitations with τ_D=10, 3, 1ps. respectively from the top to the bottom. The dashed line is for the quasiparticle tunneling injection with τ_D=1ps.

We note that the decay of the quasiparticle density is non-exponential due to the nonlinear nature of the Eqs. 1 and 2, and its half-width is approximately $\tau_B(1+2N_{q,max}\ R\ \tau_D)$, where $N_{q,max}$ is the peak value of N_q. For very small τ_D, the quasiparticle decay is essentially dictated by the phonon pair-breaking time because of the large ratio of I_p/I_q for the photon-excitation. After the quasiparticles are created by phonons, they can diffuse out of the bridge region or recombine into phonons, which will be converted back into quasiparticles after another period of pair-breaking time τ_B. The branching ratio for quasiparticles to recombine or to diffuse is $2N_qR\tau_D$, which depends on the instantaneous quasiparticle density. Since we are interested in the half-width of the quasiparticle pulse instead of the decay tail, N_q can be approximated by its peak value.

The quasiparticle diffusion time for our Pb VTB can be estimated by using $\tau_0 \approx L^2/lV_F$($\approx$10ps), where L($\simeq$1μm) is the bridge length, ($l\approx$1000Å) is the mean free path essentially limited by the film thickness, and V_F($\approx 10^6$m/sec) is the Fermi velocity. According to the numerical calculation, this τ_D gives an effective half-width of the quasiparticle decay to be approximately 500ps, in agreement with our experimental results.

For the sake of projecting future improvements toward obtaining shorter pulses, we also carried out the numerical calculations for pure quasiparticle injection, i.e. $I_p/I_q=0$, which is appropriate for quasiparticle tunneling through a tunnel junction. The dashed line in Fig. 3 corresponds to τ_D=1ps. It is interesting to note that a short spike exists even for $\tau_D = \infty$ (the spike has the same width as the dashed line in Fig. 3, superimposed on a much longer decaying tail). This is because the phonons in the Pb film cannot reach the quasi-equilibrium state with the injected quasiparticles in the time scale much shorter than τ_B so that the initially injected quasiparticles recombine into phonons according to the intrinsic recombination rate R until a quasi-equilibrium is established. We have numerically verified that when the quasiparticle injection pulse width is comparable to or greater than τ_B, there is no such short spike without the benefit of fast quasiparticle diffusion.

Conclusions and Potential Applications

According to the result of the theoretical calculation in the previous section, we obtain good agreement between the experimental results and the theory with a diffusion time $\tau_D \approx$10ps for our 1μm long Pb VTB. Since τ_D depends on the length of the bridge quadratically, a factor of 10 or more reduction in pulse width is expected if the bridge length is reduced to 0.3μm. Further improvement can be made by choosing superconducting material with a shorter τ_B, e.g. Nb ($\tau_B \simeq$4ps). The autocorrelation technique mentioned in this paper offers a simple way to measure the half-width of the short pulse to the resolution of the laser pulse width (subpicosecond lasers are available). Once the potential of picosecond or even subpicosecond pulses from a superconducting VTB is realized, many applications are conceivable. One example is to use such a superconducting VTB as the nonlinear element in the optical autocorrelation technique to analyze an unknown optical pulse shape. Because of its threshold response to the light intensity, one can determine the optical pulse shape by studying the autocorrelation signal as a function of the light intensity.

In light of the theoretical calculation for the pure quasiparticle injection case, a superconducting VTB with a tunnel junction fabricated on the bridge portion can be a fast logic switch. Experiments to test such a quasiparticle injection device are currently underway.

Acknowledgements

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References

1. S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang, S. Jafarey and D. J. Scalapino, Phys. Rev. B**14**, 4854 (1976).
2. A. Rothwarf and B. N. Taylor, Phys. Rev. Lett. **19**, 27 (1967).
3. C. C. Chi, M. M. T. Loy and D. C. Cronemeyer, to be published in Phys. Rev. B.
4. R. D. Sandell, G. J. Dolan and J. E. Lukens, p. 93 in SQUID Proceedings of the International Conference on Superconducting Quantum Devices, ed. by H. D. Hahlbohm and H. Lübbig, publ. by Walter de Gruyter, Berlin-New York, 1977. (Our method differs from the one mentioned in this reference by using Pb film instead of Al film as ion milling mask.)