

Laser-Induced Signals from Superconducting Tunnel Junction

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Electric signals induced by $Ga_xAl_{1-x}As$ pulse-laser light in an Sn-SnO_x-Sn superconducting tunnel junction have been observed in the temperature region of 1.4~4.2K. Brief analysis of the time spectra has revealed that heat escape from the junction critically affects the spectra. The relaxation of excess quasiparticles was clearly distinguished from the simple heat effect. Some discussions on the time spectra are also given.

KEY WORDS: Superconducting tunnel junction/ Quasiparticles/
Tin/ Laser/ Relaxation time/

I. INTRODUCTION

The epoch-making work on the microscopic behavior of superconductors under an external influence was by Testardi,¹⁾ who found the appearance of electric resistance by irradiation of a laser light even at temperature below the transition temperature T_c . Using Pb films of thickness comparable to the optical penetration depth and less than the superconducting coherence length, he found that the electric resistance observed is definitely due to excitation of electron system.

At that time, the relaxation process of excess quasiparticles produced by any external effect was considered to take place in two steps; first the energy losing process by the electron-electron or electron-phonon interaction down to near the edge of energy gap, and second the recombination process resulting in a Cooper-pair production. In other words, the recombination time of quasiparticles is considered to be much longer than the characteristic scattering time.

Based on this two-step process, Owen and Scalapino²⁾ proposed a model for a superconductor under an external dynamic pair-breaking influence. In this model, both the lattice and electron gas are treated at the same temperature, and thus the energy distribution of anomalously large population of free electrons is still characterized by the lattice temperature. By introducing an effective chemical potential μ^* , they calculated half of the energy gap Δ as a function of a normalized number n of excess quasiparticles. Note that in their model the first-order transition was predicted.

On the contrary, Parker³⁾ developed another model where the bottleneck in the relaxation process is, in stead of the long recombination time, the smallness of phonon escape probability from the superconductor in question. In this case, phonons having

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$\hbar\omega > 2\Delta$ are assumed to be in the thermal equilibrium at temperature T^* , being higher than the surrounding temperature. With this T^* , he calculated Δ from the BCS theory and found that Δ continuously goes to zero at $T^* = T_c$, i. e., the second-order transition is expected.

Motivated by the interesting prediction, the first-order transition, Parker and Williams⁴⁾ made an experiment, where Sn and Pb tunnel junctions (1000~2000Å) biased at $\sim 2\Delta$ were irradiated by He-Ne laser light, and the change in Δ and the relation between μ^* and n were measured. Sai-Halasz *et al.*⁵⁾ irradiated Sn films of 150~1100Å by GaAs pulse-laser light and measured the density of excess quasiparticles by means of the reflectivity of cw 70-GHz microwave. Both experiments showed pretty well agreements with the theories under weak perturbation (small n), but no first-order transition predicted by Owen and Scalapino was found even for a large number of n .

Above two models *a priori* assume the energy distribution of quasiparticles by introducing μ^* or T^* . There is another approach to the nonequilibrium state. From the electron-phonon kinetic equation and the BCS gap equation, Chang and Scalapino⁶⁾ studied thin films driven out of equilibrium under spatially uniform steady-state conditions by thermal phonon injection and others. From the derived energy distributions of quasiparticles and phonons, they obtained the changes in the ultrasonic attenuation, electrical conductivity, and the S-I-S tunneling characteristics in various nonequilibrium states.

The interesting problem related to the relaxation of quasiparticles is the change in Δ , of which the characteristics at temperature much below T_c can well be explained by the recombination of quasiparticles in terms of the BCS theory.^{4,5)} However, at $T/T_c \geq 0.99$, the relaxation time τ of Δ increases rapidly and diverges at $T = T_c$.

The first experiment on this phenomenon was by Gray *et al.*,⁷⁾ but they could not confirm it. Peters and Meissner⁸⁾ measured τ in the temperature range of $0.95 \leq T/T_c \leq 0.995$, and found $\tau \propto (1 - T/T_c)^{-1/2} \propto \Delta^{-1}$. The first direct observation of τ was performed by Schuller and Gray.⁹⁾ Using an Al(1000Å)-Sn(2500 Å) tunnel junction, they measured Δ_{Al} by irradiating GaAs pulse-laser light from the Al side. Their results agree well with the theory by Schmid and Schön.¹⁰⁾

Recently, we investigated the impulsive response of an S-I-S tunnel junction of Sn by means of α particle irradiation, and first observed the pulse-height distribution generated by the change in the current-voltage (I - V) characteristics.¹¹⁾ Using a simple model, we found that excess quasiparticles produced over the energy gap of the junctions are essential for the impulsive change in the I - V characteristics.

To extend above study, we attempted to observe and to analyze the electric signal induced by $\text{Ga}_x\text{Al}_{1-x}\text{As}$ pulse-laser light in an Sn-SnO_x-Sn superconducting tunnel junction (STJ). In the present paper, details of the experiment are presented as well as some discussions on the observed pulses through an electric device developed by us.

II. EXPERIMENTAL

1. Sample Preparation

In Fig. 1 are shown the details of the low-temperature vacuum evaporation chamber

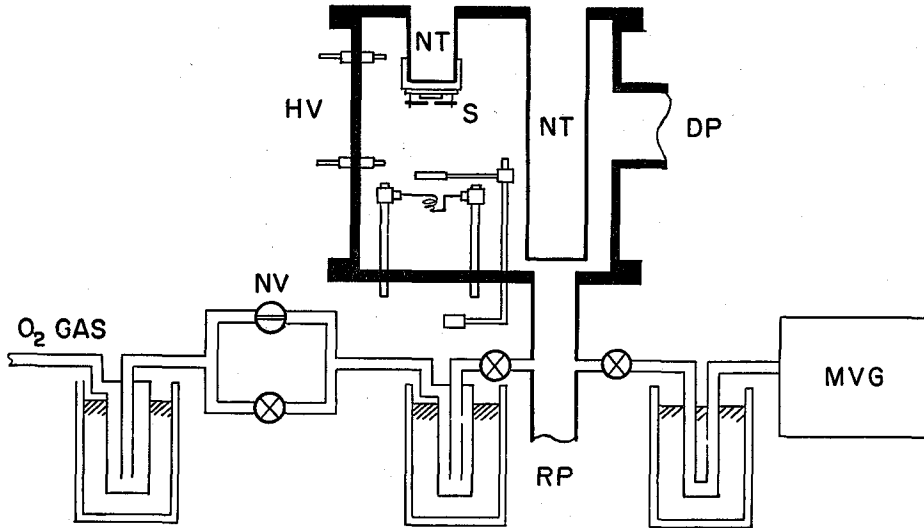


Fig. 1. Low temperature ($\sim 80\text{K}$) vacuum evaporation chamber. HV-high voltage terminals for glow discharge oxidation; NT-liquid nitrogen tank; S-sample; DP-diffusion pump; NV-needle valve; RP-rotary pump; MVG-MacLeod vacuum gauge.

Table I. Specifications of Typical Junctions

| No. | Thickness (\AA) | Evaporation Velocity ($\text{\AA}/\text{sec}$) | Area (mm^2) | Oxidization | | | Resisance ($\text{m}\Omega$) | | | |
|-----|-------------------------------|--|---------------------------|----------------|-------------------------------|---------------|--------------------------------|------|------|-----------------|
| | | | | Thermal (h) | Glow Discharge | | Room Temp. | 77K | 4.2K | |
| | | | | | Pressure (mmHg) | Time (sec) | | | | Current (mA) |
| 1 | 2000 | 2.5 | 0.18 | 60 | | | 55 | 75 | 82 | |
| | 2000 | 2.5 | | | | | | | | |
| 2 | 1800 | 10 | 0.06 | | 3×10^{-1} | 30 | 3 | 28 | 144 | 180 |
| | 2900 | 21 | | | | | | | | |
| 3 | 1700 | 19 | 0.12 | | 5×10^{-1} | 45 | 3 | 84 | 200 | 240 |
| | 3000 | 20 | | | | | | | | |
| 4 | 1700 | 19 | 0.12 | | 5×10^{-1} | 60 | 3.5 | -1.6 | 83 | 60 |
| | 1700 | 19 | | | | | | | | |
| 5 | 1700 | 24 | 0.12 | | 5×10^{-1} | 60 | 3 | -50 | -96 | 7 |
| | 1700 | 9 | | | | | | | | |
| 6 | 1700 | — | 0.06 | | 5×10^{-1} | 110 | 4 | -41 | 20 | 40 |
| | 2000 | 15 | | | | | | | | |
| 7 | 2200 | 12 | 0.06 | | 8×10^{-1} | 120 | 7 | 4000 | 4900 | 5100 |
| | 1700 | 6 | | | | | | | | |

for preparation of S I S tunnel junctions of Sn (99.999%). On a glass plate kept at $\sim 80\text{ K}$, Sn films were first evaporated ($\sim 2000\text{ \AA}$) through a mask having 5 slits, where the initial pressure in the chamber was $1.8 \times 10^{-8} \sim 2 \times 10^{-7} \text{ mmHg}$. Then either by ther-

mal oxidization in O_2 atmosphere (150 mmHg) or glow discharge oxidization, SnO_x ($\sim 10 \text{ \AA}$) was produced on the surface of Sn films. After oxidization, the second vacuum evaporation of Sn was carried out again through a mask. The crossed-film tunnel junctions thus prepared have total thickness of about 4000 \AA . We prepared 26 S-I-S tunnel junctions, and in Table I specifications of typical junctions are listed. The negative resistance appeared in the table can be reasonably explained for the case where the the insulating layer is extremely thin and consequently the junction impedance is too small compared with the electric resistance of Sn films. The samples were always kept below 80 K in order to avoid characteristic deterioration, probably due to thermal diffusion of the oxide layer.

2. Measurements of Induced Signals

The characteristics of laser diode ($Ga_xAl_{1-x}As$) used for excitation are; weve length

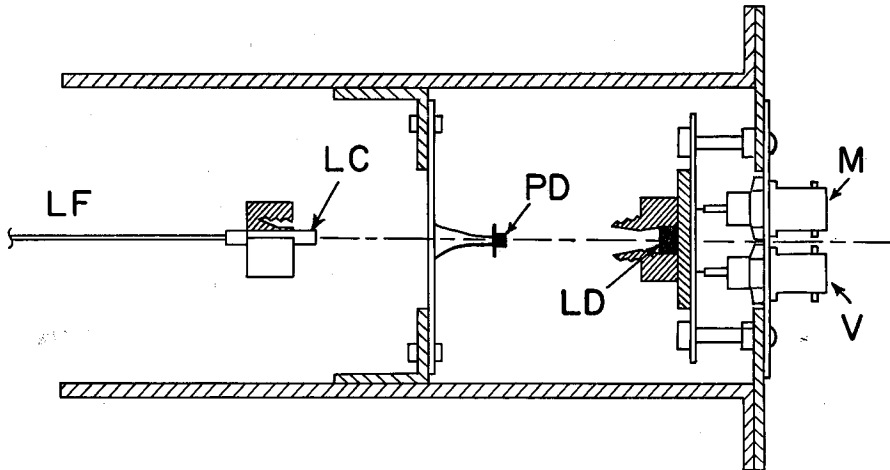


Fig. 2. The arrangement of laser diode, photo diode, and light fiber. LF-light fiber; LC-light collector; PD-photo diode; LD-laser diode; M-pulse shape monitor; V-power supply. The photo diode is removed when the light collector is set in front of the laser diode.

8300 \AA , threshold current 200 mA , rise time 1 nsec , and the maximum power 5 mW . We used this diode in the repetition rate of 30 kHz . In Fig. 2 is shown the arrangement of laser diode, photo diode, and light fiber. The pulsed current supplied to the laser diode and its power output measured by the photo diode are shown in Fig. 3, where the width of pulsed current is 300 nsec and the rise time of the photo diode is 0.8 nsec .

The junction to be irradiated by laser light is mounted in a sample room immersed in a helium bath. As shown in Fig. 4, laser light is introduced onto the junction through a 30-m long light fiber, of which the core diameter is $50 \mu\text{m}$. Temperature was controlled by He evacuation and heater in the region of $1.4 \sim 4.2 \text{ K}$, where the automatic temperature control system with a carbon thermometer was used. A Ge thermometer was used to measure sample temperature within uncertainty of 5 mK . The signal induced

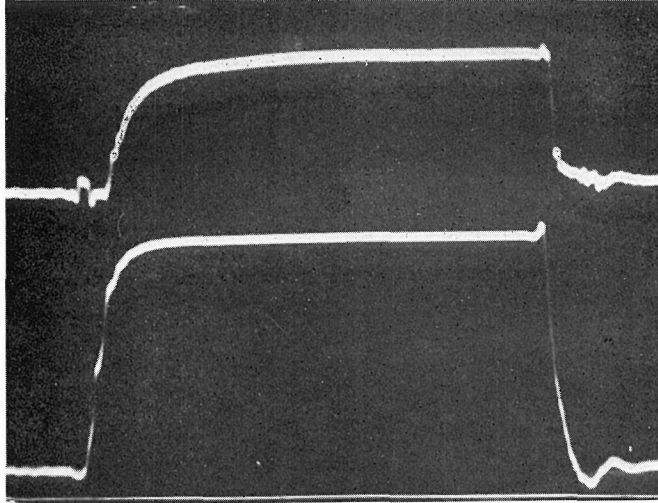


Fig. 3. Pulse current supplied to the laser diode (lower) and the output from the photo diode (upper). Pulse width is 300 nsec.

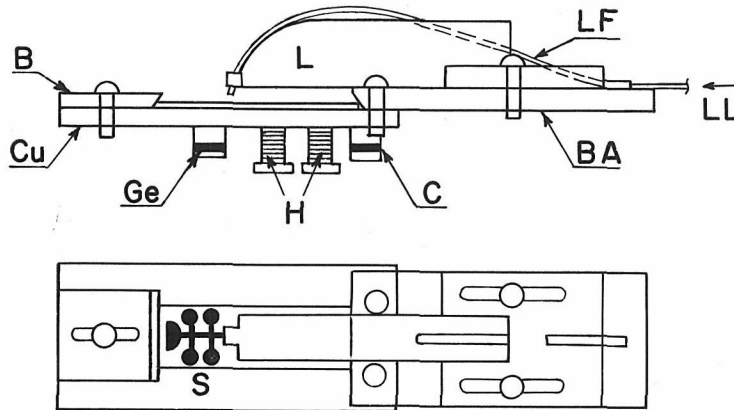


Fig. 4. Sample holder. B-brass; Cu-copper; Ge-Ge thermometer; L-lucite; H-heater; C-carbon thermometer for automatic temperature control; LF-light fiber; BA-bakelite LL-laser light; S-superconducting tunnel junctions.

by laser light was measured by the conventional four probe method, where a constant current was supplied through the junction and the fractional change in voltage was measured.

Since the expected signal from the junction is so small, less than $50\mu\text{V}$, elimination of electric noise is critical for the present experiment. There are two predominant sources of noise, random noise and systematic noise, which make it very difficult to pick up the true signals from the noise level.

In order to find the true signals embedded in noise level, we have developed a detection system which consists of a sampling oscilloscope, a voltage-frequency converter,

Laser-Induced Signals from Superconducting Tunnel Junction

and a multichannel pulse-height analyzer operated in the MCS mode. In principle, random noise can be smoothed out by accumulating sufficiently large number of noise signals. On the other hand, systematic noise can not be smoothed out, but grows up as a function of accumulation time. However, it can be conveniently eliminated by subtracting the signals without true ones. Based on above consideration, we succeeded to observe the true signals generated from the junctions. Details of the measuring system will appear elsewhere.

III. RESULTS AND DISCUSSION

Typical I - V characteristic curves are shown in Fig. 5. From the curves, we can derive several interesting behaviors of STJ.

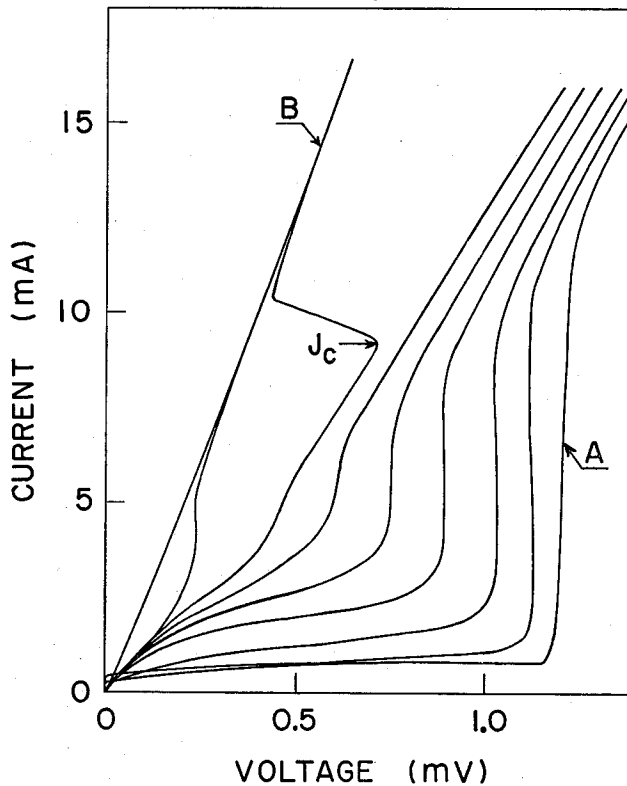


Fig. 5. Typical I - V characteristic curves of an STJ. A is at 1.4K and B at 4.2K. J_c indicates the critical current at that temperature. At low temperature, dc Josephson current appears.

- (1) The dependence of energy gap on temperature is similar to all samples.
- (2) At temperature near T_c , the critical current J_c can be approximately determined. When current through the junction exceeds $J_c(T)$, the I - V characteristic curve shifts to the normal state curve.
- (3) When temperature increases, dc Josephson effect disappears.

Although the characteristics of samples are not identical, (1) guarantees the reproducibility of fundamental properties of the junctions. (2) indicates that $J_c(T)$ becomes comparable to the bias current at temperature near T_c . (3) can be qualitatively explained by the following relation¹²⁾

$$J_0 = \frac{\pi \Delta(T)}{2e R_n} \tanh \frac{\Delta(T)}{2kT}, \quad (1)$$

where $\Delta(T)$ is half of the gap energy at temperature T .

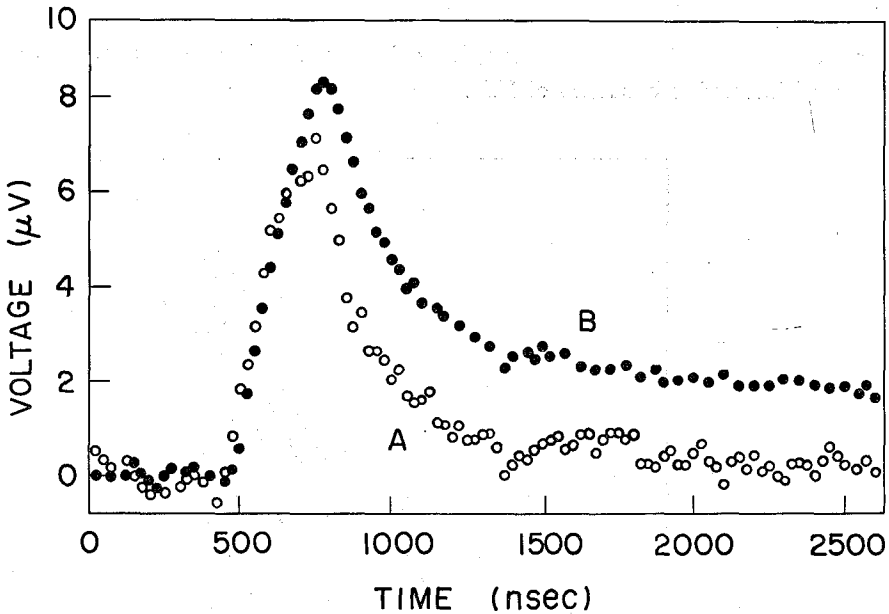


Fig. 6. Time spectra of laser-induced signals. A and B are taken in different pressures of heat exchange gas (see Table II).

In Fig. 6 are shown typical time spectra of laser induced signals observed with No. 5 sample in Table I. Specifications of each spectrum are listed in Table II. The spectra are confirmed to be surely laser-induced in STJ by the following two reasons; first, as expected no signals were observed at $T > T_c$, and second, the rise time of observed time spectra is 300 nsec, which corresponds to the pulse width of supplied laser light.

Notable differences between two spectra A and B in Fig. 6 are:

- (a) Peak voltage of B is about 20% greater than that of A.

Table II. Experimental Conditions and Observed Relaxation Time

| | Temp. (K) | Bias current (mA) | Exchange gas (mmHg) | Peak height (μ V) | τ (nsec) |
|---|-----------|-------------------|---------------------|------------------------|-----------------------------------|
| A | 1.41 | 3.3 | $\sim 10^{-1}$ | 7.2 | $\tau_1 = 180$ |
| B | 1.45 | 3.1 | $< 10^{-3}$ | 8.4 | $\tau_1 = 350$ $\tau_2 = 3500$ |

Laser-Induced Signals from Superconducting Tunnel Junction

- (b) The initial decreases of A and B have different time constants, $\tau_1=180$ nsec and 350 nsec, respectively.
- (c) During irradiation by a laser light (300 nsec), both A and B continuously increase. After the end of irradiation, B decreases with two different time constants, $\tau_1=350$ nsec and $\tau_2=3500$ nsec, but A decreases rapidly to zero voltage.

In order to understand these characteristic differences in time spectra A and B, we have to consider different pressures of heat exchange ^4He gas in the sample room. As listed in Table II, spectrum A is taken at pressure of $\sim 10^{-1}$ mmHg., and B at pressure of less than 10^{-3} mm Hg. Since exact pressure was not measured, quantitative discussion can not be made. However, qualitative explanations for different time spectra are possible.

In case A, heat exchange of the STJ is expected to be much better than case B. Therefore, after irradiation of laser light (300 nsec), the signal rapidly falls down with the relaxation time of excess quasiparticles. On the other hand, in case B, due to poor exchange of heat the probability of thermal excitation of quasiparticles is increased. Besides, the phonon escape probability is expected to decrease. As is well known, the effective relaxation time τ_{eff} of quasiparticles is related to the intrinsic recombination time τ_R by¹³⁾

$$\tau_{eff} = \tau_R \left(1 + \frac{\tau_r}{\tau_B} \right), \quad (2)$$

where τ_r is the mean time for phonons to become useless for quasiparticle production and τ_B is that of Cooper-pair breaking. This equation indicates that heat exchange of the junction critically affects τ_{eff} , which is equivalent to $2\tau_1$ in the present measurement. From above discussions in terms of heat exchange, different peak heights and different values of τ_1 in spectra A and B are qualitatively understood.

In order to reveal the structure distinguishably appeared in the decay curve of B, brief analysis of the time spectra in Fig. 6 is attempted. Suppose that the electrical response of an STJ is similar to behavior of an integral circuit, and that pulsed-laser light acts on the junction as a square pulse. In this case, the shape of signal is expressed by

$$V_u = V_0(1 - e^{-t/\tau}) \quad \text{for } t < t_0, \quad (3)$$

$$V_d = V_0(1 - e^{-t_0/\tau}) e^{-(t-t_0)/\tau} \quad \text{for } t > t_0, \quad (4)$$

where t_0 is the laser pulse width, V_0 is a constant, and τ is the time constant of the junction (*i. e.*, the relaxation time). Equations (3) and (4) imply the most simple case, of which the relaxation in the junction is unique. However, in general the response of an STJ should be treated as a combination of quasiparticles and phonons. We assign the relaxation time of quasiparticles as τ_1 and the mean time of phonon escape as τ_2 , respectively. Using τ_1 and τ_2 , modified expression for Eq. (3) can be obtained as

$$V_u = V_1(1 - e^{-t/\tau_1}) + V_2(1 - e^{-t/\tau_2})$$

$$+V_3[(1-e^{-t/\tau_2}) + \frac{\tau_1}{\tau_2-\tau_1}(e^{-t/\tau_1}-e^{-t/\tau_2})], \quad (5)$$

where $V_1 \sim V_3$ are constants. The first term means the effect that quasiparticles excited far above energy gap by incident photons produce additional quasiparticles during the energy losing process down to just above the gap. The second term represents the effect that quasiparticles excited by incident photons produce new phonons during the energy losing process and these phonons contribute to raise sample temperature, resulting in the production of additional quasiparticles. The third term is derived on the assumption that the contribution of the first term is predominant compared with the second and third terms. This term corresponds to the effect that phonons produced by the quasiparticle recombination plays a similar role to the second term. Modified equation for Eq. (4) is easily obtained as

$$\begin{aligned} V_d = & \left[V_1(1-e^{-t_0/\tau_1}) + V_3 \frac{\tau_1}{\tau_1-\tau_2}(1-e^{-t_0/\tau_1}) \right] e^{-t-t_0/\tau_1} \\ & + \left[V_2(1-e^{-t_0/\tau_2}) - V_3 \frac{\tau_1}{\tau_1-\tau_2}(1-e^{-t_0/\tau_1}) \right. \\ & \left. + V_3 \left[(1-e^{-t_0/\tau_2}) - \frac{\tau_1}{\tau_1-\tau_2}(e^{-t_0/\tau_1}-e^{-t_0/\tau_1}) \right] \right] e^{-t-t_0/\tau_2}. \quad (6) \end{aligned}$$

From Eq. (5), one sees that, in the case of $t_0 \gg \tau_1, \tau_2$, V_d should have a saturated value for $t > \tau_1, \tau_2$. However, the observed time spectra in Fig. 6 ($t < t_0$) do not show the saturation, and thus we can say that τ_1 and τ_2 are larger than t_0 or at least comparable, supporting the present results.

As given in Eq. (6), V_d is a superposition of two exponential curves. When heat exchange is sufficient and phonons can immediately escape from the STJ, τ_2 becomes much smaller than τ_1 . In this case, the second term of Eq. (6) can be neglected. The time spectrum A corresponds to this case. On the contrary, if heat exchange is poor, phonon escape probability is expected to be considerably small, and consequently the time spectrum is expected to have a tail. The curve B corresponds to this case.

Present results permit us to give only qualitative discussions. By changing essential experimental parameters, pulse width, laser power, and temperature, more refined measurements are in progress.

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Laser-Irradiated Signals from Superconducting Tunnel Junction

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