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Collection of athermal phonons into doped Ge thermistors using quasiparticle trapping

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We have developed a low-temperature particle detector that uses a novel quasiparticle trapping mechanism to funnel athermal phonon energy from an 80 mg Ge absorber into a 1.6 mg doped Ge thermistor via a superconducting Al film. We report on pulse height spectra obtained at 320 mK by scanning a ^{241}Am alpha source along the device, and show that up to 20% of the energy deposited in the Ge absorber by a 5.5 MeV alpha particle interaction can be collected into a thermistor via quasiparticle trapping. We show that this device is sensitive to the position of an alpha particle interaction in the Ge absorber for interaction distances of up to 5 mm from a quasiparticle trap.© *1995 American Institute of Physics.*

I. INTRODUCTION

Small thermometers operating at cryogenic temperatures have been used to detect small amounts of energy deposited in a target material by single-particle interactions.[1] Such detectors are potentially useful for broad-band x-ray spectroscopy, the search for dark matter candidates, and the determination of neutrino properties, as they provide high energy resolution, the ability to detect low energy nuclear recoils, and flexibility in the choice of target materials. However, these thermometers are typically poorly coupled to high-energy phonons in the target which, before they thermalize, carry information about high-energy phonons in the target which, before they thermalize, carry information about the location and nature of the initial event. One way to greatly increase the sensitivity of such a thermometer to athermal phonons is to couple it to the target via a thin film superconductor. The superconducting film readily absorbs athermal phonons, which create quasiparticles that quickly diffuse through the film and can be concentrated through the quasiparticle trapping mechanism (see Sec. II). Quasiparticle trapping is a recently developed technique which has been used to significantly improve the performance of particle detectors that measure the quasiparticle current through superconducting tunnel junctions (STJs). Such detectors have been of two types, with quasiparticles diffusing into the trapping region of the junction from a thin strip of superconducting film[2] deposited on top of an absorber (quasiparticle diffusion over distances of ~0.5 mm), and directly from superconductors used as the absorber material.[3–5] However, to our knowledge the quasiparticle trapping technique has never been used in conjunction with a calorimetric detector or to study quasiparticle diffusion in thin films over distances of ~1 cm.

To study the feasibility of using quasiparticle trapping to collect athermal phonons over distances of up to 10 mm, we have built the superconducting large area phonon sensor (SLAPS). As shown in Fig. 1, the SLAPS device consists of four symmetrically located doped Ge thermistors (1 mm^2×300 μm) attached with epoxy to the edge of a Ge absorber (10 mm×5 mm×300 μm). The Ge absorber was thermally heat sunk to a 320 mK temperature-regulated stage through a thin layer of vacuum grease. Electrical contacts were made on opposing faces of each thermistor by boron implantation followed by thermal annealing and evaporation of 200 Å of Pd and 4000 Å of Au. An 8000-Å-thick Al film was sputtered onto the top surface of the composite device, covering the Ge substrate and three of the four thermistors. These three thermistors were used to study the quasiparticle trapping mechanism, while the fourth uncovered thermistor is sensitive only to thermal phonons and was used for comparison and device calibration.

II. PRINCIPLES OF OPERATION

When an incident particle interacts in the Ge substrate, it produces high-energy phonons which propagate to the surface of the crystal. Phonons which strike the superconducting Al film and have energies greater than the Al gap energy $E_g=2\Delta\approx350$ μeV can break Cooper pairs, creating quasiparticles which diffuse through the Al film. If the quasiparticles have a sufficiently long mean free path and lifetime, they will diffuse to the ends of the detector where the ther-

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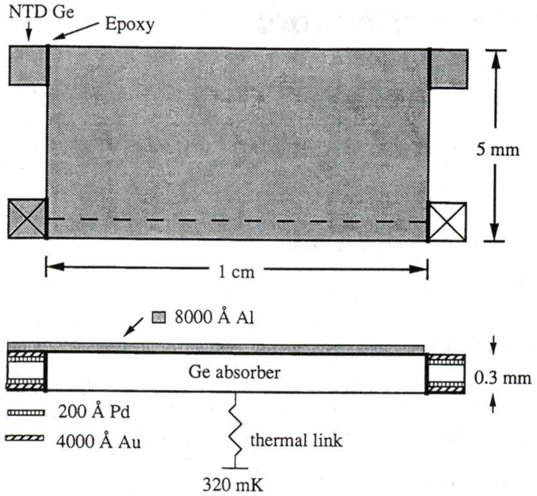

FIG. 1. Schematic diagram of the SLAPS device showing top and side views (not to scale). The two thermistors studied in this experiment are each denoted by X, and the axis scanned by the ^{241}Am alpha source is indicated by the dashed line.

mistors are attached. Due to the proximity effect the Al/Au/thermistor region has an energy gap several times smaller than the gap in the Al/Ge region. Quasiparticles moving into the smaller gap region scatter to lower energies by phonon emission and are then trapped because they have insufficient energy to return to the Al film. This process of phonon emission heats the attached thermistor and produces a voltage pulse as the thermistor resistance drops.

III. NTD GE THERMISTORS

The thermistor material used in the SLAPS device is neutron transmutation doped (NTD) germanium[6-8] with a net impurity concentration of 2.6×10^{16} cm^{-3}. This material was chosen for its low noise and high electrical responsivity at ^{3}He temperatures. Low-temperature electrical conduction in NTD Ge proceeds by variable range hopping[9] in which holes tunnel between impurity sites rather than enter the valence band. The electrical resistivity varies extremely rapidly with temperature, and is well described by $\rho=\rho_0 \exp(T_0/T)^{1/2}$. The NTD#14 Ge used in the SLAPS detector has a ρ_0 of $\sim$0.26 Ω cm and a T_0 of 51 K; thus at 360 mK the thermistor resistance R is $\sim$120 kΩ and the voltage noise $e_n = \sqrt{4kTR}$ is 1.4 nV/$\sqrt{\text{Hz}}$. Since this is less than the 7 nV/$\sqrt{\text{Hz}}$ noise of our read-out electronics, our experimental results are not thermistor noise limited.

The maximum voltage drop across a thermistor after an energy input E is $\Delta V=I(dR/dT)E/C_{\text{th}}$, where C_{th} is the heat capacity of the thermistor and I is the bias current.[10] Since the thermistor is connected to the surrounding environment at base temperature T_b by a link of thermal conductance C_{th}, over time the signal will decay with time constant $\tau_{\text{th}}\approx C_{\text{th}}/G_{\text{th}}$:

$$\Delta V(t)=I\cdot\frac{dR}{dT}\cdot\frac{E}{C_{\text{th}}}\exp\left(\frac{-t}{\tau_{\text{th}}}\right).$$

For the thermistors in this experiment, biased to 360 mK above a base temperature of 320 mK, the optimum bias current I is 0.5 μA, C_{th} is $\sim7\times10^{-11}$ J/K (see Sec. VI), dR/dT is $\sim-2\times10^6$ Ω/K, and $\Delta V/E\approx-2.3\times10^{-9}$ V/eV. Thus, when a thermistor absorbs a 60 keV γ-ray its initial temperature rise is $\sim$140 μK and the voltage drop is $\sim$140 μV.

IV. AL FILM PROPERTIES

The criteria we used to select aluminum as the superconducting film material on the SLAPS device were:

(1) we required a high purity film with minimal defects in order to minimize quasiparticle energy losses through processes other than phonon scattering,

(2) the lifetime for nonequilibrium quasiparticles created in the film, τ_{qp}, had to be long so that quasiparticles could diffuse over large distances, and

(3) T_c had to be several times greater than the operating temperature (320 mK) for a small population of thermally excited quasiparticles in the film.

Aluminum, with a measured T_c of 1.24 K in our 8000 Å Al film, is a material which has been well studied and is known to have a long quasiparticle lifetime.[11,12] Furthermore, techniques exist for making very high quality Al films with long electron mean-free-paths.

The mean-free-path λ for quasiparticle scattering in our dc-magnetron sputtered film was determined by measuring the residual resistance ratio $\mathscr{R}=R_{300}/R_{4.2}=27$ between 300 and 4.2 K. Since $\lambda_{4.2}=m^*\cdot v_F/(ne^2\rho_{4.2})=\mathscr{R}\cdot m^*\cdot v_F/(ne^2\rho_{300})$, where n is the concentration, m^* the effective mass of the electron, e the charge, and v_F the Fermi velocity of the conduction electrons, the low-temperature mean-free-path in aluminum is given by $\lambda\approx(149\text{ Å})\times\mathscr{R}=4000$ Å. As the temperature was lowered below 4.2 K, $\mathscr{R}$ remained constant indicating that λ had reached its maximum value. The quasiparticle diffusion length $\mathscr{L}$ in three dimensions[13] is related to λ by $\mathscr{L}=(2v_F\lambda\tau_{\text{qp}}/3)^{1/2}$, where v_F is the Fermi velocity. As discussed in Sec. VI, we assume that the quasiparticle lifetime τ_{qp} has the same order of magnitude as our signal risetimes (40 μs). Using this formula to obtain a rough estimate of the diffusion length $\mathscr{L}$ in our thin film, with $v_F=2\times10^8$ cm/s, $\lambda=4000$ Å, and $\tau_{\text{qp}}\sim40$ μs as we get:

$$\mathscr{L}\sim\sqrt{\frac{2}{3}v_F\lambda\,\tau_{\text{qp}}}\sim5\text{ mm}.$$

V. EXPERIMENTAL SETUP

To study the quasiparticle trapping mechanism and quasiparticle diffusion length, we mounted the SLAPS detector on a temperature-regulated stage thermally linked to a ^{3}He refrigerator. Electrical contacts were made to each thermistor by attaching two copper wires 5 mm long and 25 μm in diameter to the metallized thermistor contacts with a small amount of conductive epoxy. Resistances were measured using a dc bias voltage applied across the series combination of a 10 MΩ metal-film resistor at 1.6 K and the thermistor. The voltage drop across the thermistor was read through a cooled junction field-effect transistor (JFET) operating in source follower mode. We measured the resistance versus temperature curves of the thermistors for 310 mK$<T<$500 mK, and measured the thermal conductivities G_{th} and time constants τ_{th} of the epoxy bonds linking the thermistors to the germanium substrate at 320 mK$<T<$360 mK. We saw no significant difference between the values of G_{th} and τ_{th} measured in the three thermistors covered with an 8000 Å Al film versus the values measured in the thermistor with no Al film, and conclude that as expected the Al film does not significantly contribute to G_{th}. After characterizing the thermistors we installed a lead-collimated 0.7 μC ^{241}Am alpha source (spot size $\approx$1 mm) above the SLAPS device. An alpha particle striking the device deposits 0.4% of its energy (22 keV) into the 8000 Å Al film and travels an additional 20 μm into the 300-μm-thick Ge substrate, depositing the remainder of its energy in the form of athermal phonons which travel through the Ge substrate. We scanned the device with the alpha source along a line parallel to the 1-cm-long axis and centered on two NTD Ge thermistors, one with an Al/Au trap and one without. Successive source positions were separated by 1/2 mm, thus we were able to study the pulse-height spectrum observed in the two thermistors for 20 different source positions. In addition to emitting alpha particles, the ^{241}Am source emits 60 keV gamma rays which were not collimated with the alpha particles.

VI. SYSTEM TIME CONSTANTS

The voltage pulses observed in each thermistor are characterized by four major time constants: the response time of the readout electronics τ_{el}, the characteristic time for quasiparticles to deposit athermal phonon energy into the thermistor τ_{ath}, the time constant τ_{th} of the thermal link connecting the thermistor to the Ge substrate, and the time constant τ_{Ge} of the thermal link between the Ge substrate and the 320 mK stage. The magnitudes of these time constants are related to each other by $\tau_{\mathrm{el}} \ll \tau_{\mathrm{ath}} < \tau_{\mathrm{th}} < \tau_{\mathrm{Ge}}$. This is the optimum ordering for the following reasons: τ_{el} should be at least an order of magnitude smaller than the other system time constants so that the JFET output voltage can rapidly track voltage changes across the thermistor. The quasiparticle sensing time τ_{ath} must be shorter than the thermistor time constant τ_{th} in order for the additional phonon signal produced in the thermistor by quasiparticle trapping to produce a significant temperature rise before the thermistor reaches thermal equilibrium with the germanium absorber. (This requirement significantly constrains the design of future devices utilizing a quasiparticle trapping mechanism.) Similarly, τ_{th} should be several times shorter than τ_{Ge} so that the thermistor can respond to temperature changes in the absorber before the system returns to equilibrium.

We have measured these time constants in the SLAPS device by exponentially fitting the rise and fall times of the various pulses observed at different ^{241}Am source positions (see Sec. VII) and find that $\tau_{\mathrm{el}} \approx 4.2$ μs, $\tau_{\mathrm{ath}} \approx 40$ μs, $\tau_{\mathrm{th}} \approx 90$ μs, and $\tau_{\mathrm{Ge}} \approx 300$ μs. The value for τ_{el} is consistent with a thermistor resistance of 120 kΩ and a capacitance of 35 pF from the JFET input to ground, and agrees with the value $\tau_{\mathrm{el}} \sim 4$ μs we measured by biasing the thermistors with an ac square wave. The characteristic time τ_{ath} for athermal phonon sensing in the thermistor is a complicated function of the athermal phonon lifetime in the Ge substrate, the quasiparticle lifetime in the Al film, the trapping time for quasiparticles in the Al/Au/thermistor region, and the relaxation time for the hot electrons in the Au film. We have calculated that these characteristic times are considerably faster than our electronic response time of 4.2 μs except for the quasiparticle lifetime in the Al film, which we calculated to be $\sim$25 μs at T=320 mK using the theoretical approximation of Kaplan[11] assuming a superconductor with impurities and a near-equilibrium distribution of phonons and quasiparticles. It is also close to the quasiparticle lifetime $\tau_{\mathrm{qp}} \sim 35$ μs measured by Gray[12] in a much thinner (300 Å) Al film at the same value of $\Delta/kT \approx 6.4$. We conclude that τ_{ath} is primarily determined by the quasiparticle lifetime τ_{qp} and by the spread in diffusion times to the trap. The thermistor time constant τ_{th} agrees with the value of 90$\pm$10 μs measured electrically, and combined with our measurement of $G_{\mathrm{th}}=(8\pm1)\times10^{-7}$ W/K gives a total thermistor heat capacity C_{th} of 7×10^{-11} J/K.

VII. PULSE HEIGHT SPECTRA

Two types of signals were observed in each thermistor when the ^{241}Am source was positioned over the germanium absorber, each signal having a characteristic pulse shape and height: (1) 60 keV γ rays directly striking the thermistor, and (2) 5.5 MeV alpha particles depositing energy into the Ge substrate at a distance from the thermistor edge ranging from 0 to 10 mm. The γ-ray event rate was $\sim$1 s^{-1} and the alpha particle event rate was $\sim$2 s^{-1}. The γ-ray pulses were observed at all positions of the ^{241}Am source because the lead collimator was designed to stop stray alpha particles while not fully attenuating the γ rays. The γ-ray peak in each pulse height spectrum was used to calibrate the thermistor signal produced by alpha particles interacting in the germanium absorber and to determine the thermistor energy resolution (6 keV FWHM for a 60 keV energy input at 360 mK). For all source positions, the γ-ray pulses had an electronics limited rise time of about 4.2 μs and a decay time constant of 90 μs equal to τ_{th}. As expected, we observed no significant difference in the pulse height and shape produced by γ rays striking either thermistor.

The height and shape of the voltage pulses produced by 5.5 MeV alpha particles depositing energy in the germanium absorber showed a strong position dependence in the thermistor with an Al/Au quasiparticle trap (see Fig. 2) and were nearly position independent in the thermistor with no aluminum film. For all source positions further than 5 mm from the thermistor edge the pulse height spectra of the two thermistors were essentially identical: in both thermistors the 5.5 MeV peak center had a pulse height 2.2 times greater than the pulse height of the 60 keV (direct hit in the thermistor) peak center. Assuming that the germanium heat capacity per unit volume is comparable to that of the doped germanium thermistors, we expect a pulse height ratio of around two because an alpha particle interacting in the Ge absorber deposits ninety times more energy in a volume fifty times greater than that of a 60 keV γ ray interacting in a thermistor. These pulses from alpha particles absorbed far from the ther-

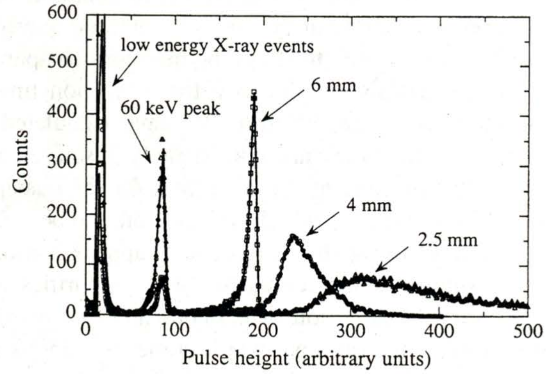

FIG. 2. Superimposed pulse-height spectra obtained with quasiparticle trapping thermistor for collimated alpha source located at 6, 4, and 2.5 mm from the thermistor edge.

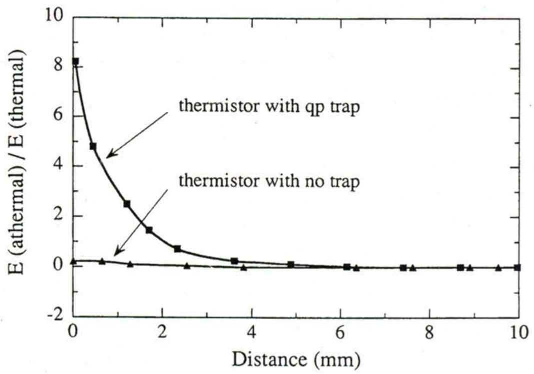

FIG. 3. Ratio of athermal to thermal phonon energy detected in each thermistor for various alpha source positions (measured relative to the respective thermistor edges).

mistor showed an exponential rise with time constant $\tau_{\rm th}$ of 90 μs in both thermistors as the thermistors reached equilibrium with the Ge absorber, and then an exponential decay with time constant $\tau_{\rm Ge}$ of 300 μs.

As the ^{241}Am source position was moved to the thermistor edge, the thermistor with no aluminum film showed a small increase in pulse height above the 60 keV peak from 2.2 to 2.65 (see Fig. 3). We attribute this 20% rise in energy detected in the thermistor to a small number of athermal phonons absorbed in the epoxy joint heating the thermistor above the equilibrium temperature of the Ge absorber. The time constants of the thermal rise and fall of the thermistor with no aluminum film were the same for all source positions to within the accuracy of our fit.

In contrast, the thermistor with an Al/Au quasiparticle trap began to show an increase in mean pulse height over the 60 keV peak at a source distance of 5 mm (see Fig. 2), indicating athermal phonon collection into the thermistor. As the ^{241}Am source was moved to the thermistor edge the mean pulse height of the 5.5 MeV peak rose dramatically to a value 20 times greater than the 60 keV peak, corresponding to a total energy input into the thermistor of 1.2 MeV. In other words, the use of a quasiparticle trapping mechanism allowed us to collect 20% of the energy deposited initially in the 80 mg Ge absorber into the 1.6 mg thermistor. At a source distance of 5 mm the athermal phonon energy deposited in the thermistor by quasiparticle trapping, determined by the mean pulse height, was 14% of the energy deposited by thermal phonons; at 2 mm the same ratio was 100%, and at the thermistor edge this ratio was 820% (see Fig. 3). We note that the nonlinearity of the quasiparticle trapping efficiency versus source distance produced increasingly non-Gaussian peaks in the pulse-height spectra as the alpha source was moved toward the thermistor edge, as shown in Fig. 2. The peak maximum, or mode, was therefore not equal to the mean pulse height.

As the ^{241}Am source was moved toward the thermistor with an Al/Au quasiparticle trap both the rise and fall times of the thermal pulse decreased, which is another indication that quasiparticle trapping into the Al/Au/thermistor region was dominating the energy input. At the thermistor edge the signal rise time $\tau_{\rm ath}$ was 40 μs. The initial decay time of this signal was 90 μs ($\tau_{\rm th}$), reflecting that the thermistor had heated significantly above the Ge absorber temperature. A second time constant of 300 μs ($\tau_{\rm Ge}$) was needed to fit the tail of this signal, indicating that the thermistor-absorber system had reached equilibrium. Thus, as the alpha source was moved toward the thermistor edge, the signal rise time decreased from 90 to 40 μs and the signal decay time decreased from a single time constant of 300 μs to two decay time constants of 90 and 300 μs. The dependence of the signal rise time on alpha source position has been measured; this data as well as further discussion of the pulse shapes will be published subsequently. We will show that the signal rise time gives position information for interaction distances of more than 6 mm from the quasiparticle trap. We note that the position sensitivity of the SLAPS device is related to but not equal to the quasiparticle diffusion length. Athermal phonons produced by an interaction in the Ge will excite quasiparticles throughout the Al film, with the highest quasiparticle density just above the interaction position. Thus, the range of interaction distances for which the thermistor signal is enhanced by quasiparticle trapping is a function of device geometry, athermal phonon lifetime, and the spread of quasiparticle diffusion times into the trap.

VIII. CONCLUSION

In conclusion, we have demonstrated with the SLAPS device that the quasiparticle trapping mechanism can be used to dramatically increase the sensitivity of a calorimetric detector to athermal phonons. The performance of this device could be improved by optimizing the film thickness and the ratio of film volume to trap volume, by using a superconducting film with a larger value of $v_F \cdot \lambda \cdot \tau_{\rm qp}$, and by operating at lower temperatures to reduce the quasiparticle energy loss from inelastic phonon scattering. Rather than relying on a random diffusion process to send quasiparticles into the trapping region a film could be devised with a decreasing energy gap gradient around the traps, thereby more efficiently funneling quasiparticles into the trapping regions. Finally, the position and energy resolution could be improved by separating the quasiparticle traps by distances on the order of the diffusion length and comparing pulse heights observed in neighboring traps to obtain curves of constant energy and position.[2]

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[1] *Low Temperature Detectors for Neutrinos and Dark Matter IV,* edited by N. E. Booth and G. L. Salmon (Editions Frontieres, Gif-Sur-Yvette, France, 1992).

[2] H. Kraus, F. von Feilitzsch, J. Jochum, R. L. Mossbauer, Th. Peterreins, and F. Probst, Phys. Lett. B **231**, 195 (1989).

[3] N. E. Booth, Appl. Phys. Lett. **50**, 293 (1987).

[4] D. J. Goldie, N. E. Booth, C. Patel, and G. L. Salmon, Phys. Rev. Lett **64**, 954 (1990).

[5] C. A. Mears, S. E. Labov, and A. T. Barfknecht, Appl. Phys. Lett. **63**, 2961 (1993).

[6] E. E. Haller, N. P. Palaio, W. L. Hansen, and E. Kreysa, IR Phys. **25**, 257 (1985).

[7] J. W. Beeman and E. E. Haller, Infrared Phys. Technol. **35**, 827 (1994).

[8] E. E. Haller, K. M. Itoh, J. W. Beeman, W. L. Hansen, and V. I. Ozhogin, SPIE Proc. **2198**, 630 (1994).

[9] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, Berlin, 1984).

[10] J. C. Mather, Appl. Opt. **21**, 1125 (1982).

[11] S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang, S. Jafarey, and D. J. Scalapino, Phys. Rev. B **14**, 4854 (1976).

[12] K. E. Gray, J. Phys. F **1**, 290 (1971).

[13] F. Reif, *Fundamentals of Statistical and Thermal Physics* (McGraw-Hill, New York, 1965).