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Recommended Citation

Irwin, K. D., Nam, S. W., Cabrera, B., Chugg, B., & Young, B. A. (1995). A quasiparticle-trap-assisted transition-edge sensor for phonon-mediated particle detection. *Review of Scientific Instruments*, 66(11), 5322–5326. <https://doi.org/10.1063/1.1146105>

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A quasiparticle-trap-assisted transition-edge sensor for phonon-mediated particle detection

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(Received 20 April 1995; accepted for publication 19 June 1995)

We have demonstrated the operation of composite superconducting tungsten and aluminum transition-edge sensors which take advantage of quasiparticle trapping and electrothermal feedback. We call these devices W/Al QETs (quasiparticle-trap-assisted electrothermal feedback transition-edge sensors). The quasiparticle trapping mechanism makes it possible to instrument large surface areas without increasing sensor heat capacity, thus allowing larger absorbers and reducing phonon collection times. The sensor consists of a 30-nm-thick superconducting tungsten thin film with $T_c \sim 80$ mK deposited on a high-purity silicon substrate. The W film is patterned into 200 parallel lines segments, each $2 \mu\text{m}$ wide and $800 \mu\text{m}$ long. Eight superconducting aluminum thin film pads are electrically connected to each segment, and cover a much larger surface area than the W. When phonons from particle interactions in the silicon crystal impinge on an aluminum pad, Cooper pairs are broken, forming quasiparticles which diffuse to the tungsten lines where they are rapidly thermalized. The W film is voltage biased, and self-regulates in temperature within its superconducting transition region by electrothermal feedback. Heat deposited in the film causes a current pulse of $\sim 100 \mu\text{s}$ duration, which is measured with a series array of dc superconducting quantum interference devices. We have demonstrated an energy resolution of < 350 eV full width at half-maximum for 6 keV x rays incident on the backside of a $1 \text{ cm} \times 1 \text{ cm} \times 1 \text{ mm}$ (0.25 g) silicon absorber, the highest resolution that has been reported for a fast (< 1 ms pulse duration) calorimetric detector with an absorber mass > 0.1 g. Applications of this technology include dark matter searches and neutrino detection. © 1995 American Institute of Physics.

I. INTRODUCTION

We are developing phonon-mediated cryogenic particle detectors for dark matter searches and neutrino detection.^{1,2} These detectors consist of a superconducting W thin-film transition-edge sensor (TES) deposited on a high-purity silicon absorber. The W film ($T_c \sim 80$ mK) is voltage biased in series with a dc superconducting quantum interference device (SQUID) array³ by putting a constant bias current through a parallel arrangement of the sensor and a small shunt resistor (Fig. 1). The substrate is cooled to well below T_c . When the film temperature is within the superconducting transition, the resistance goes down as the temperature decreases. Since the joule heating, $P = V^2/R$, increases as the resistance drops, the film stably self-regulates in temperature within its transition.⁴ This type of process is referred to as electrothermal feedback.

When a particle interaction occurs in the silicon, athermal phonons (~ 1 THz) propagate to the surface of the crystal, where they are absorbed in the superconducting film, thereby raising its temperature. The increase in film temperature causes an increase in the film resistance, and a corresponding decrease in the current through the film, which is measured with the SQUID array.

Since energy deposited in the film reduces the joule power dissipation in the film, the energy is removed both by

an increase in the heat flow to the substrate, and by a reduction in the joule heating. The energy removed by a reduction in the joule power is equal to the voltage bias multiplied by the integral of the SQUID current pulse, and can be measured with no free parameters. When the substrate temperature is reduced to well below the transition temperature of the film, the reduction in joule power is the dominant mechanism for the removal of heat by more than an order of magnitude. Since the measurement of energy removed by the reduction of joule power is relatively insensitive to imperfections such as transition nonlinearities and film nonuniformities, the best resolution is obtained by integrating the current pulse.⁴

Several different channels are instrumented on the surface of the silicon absorber. By observing the partitioning of energy between the channels, both event position and energy may be measured.⁵ The position information can be used to veto surface and multiple-scattering events, and will be used to reduce the background counts in dark matter and neutrino experiments.⁶ In order to scale these sensors up to a practical dark matter or neutrino detector, we must use a large mass absorber (~ 1 kg).¹ To scale up to a large absorber while maintaining good position and energy resolution, it is necessary to instrument a much larger detector surface area. Instrumenting large areas cannot be done simply by increasing the W film surface area without making the W heat capacity too large.

It is possible to collect phonon energy over large surface

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FIG. 1. Transition-edge sensor bias circuit.

areas using quasiparticle trapping, a technique first suggested by N. Booth for use with tunnel junction detectors.⁷ In Booth's devices, superconductors with two different energy gaps are used. The high gap superconductor, which is chosen to have a gap smaller than the incident phonon energy, is deposited as a large area pad. The lower gap superconductor is placed in intimate electrical contact with this pad. When phonons impinge on the high gap superconductor, they break Cooper pairs, forming quasiparticles. The quasiparticles relax to the gap edge, releasing phonons. If these phonons are also above the gap, they can create more quasiparticles, while any subgap phonons escape back into the substrate and are lost. The device geometry is chosen so that the time for quasiparticles to diffuse within the high gap superconductor to the low gap superconductor is short compared to the quasiparticle recombination time and the desired rise time. When a quasiparticle diffuses into the low gap superconductor, it relaxes to the new gap edge, releasing phonons, and is trapped in the potential well of the lower T_c material. The phonons released in this process can create new quasiparticles, or escape into the substrate if they are subgap. In Booth's devices, the quasiparticles trapped in the lower gap material are then measured when they cross a superconducting tunnel junction.⁷

Quasiparticle trapping can also be used with transition-edge sensors to increase the phonon collection area while keeping the heat capacity of the transition-edge sensor low.⁸ In the devices described in this work, Al is used as the high gap superconductor, and W is used as the low gap superconductor. Al pads are placed in electrical contact with the W TES. Since the gap of Al ($2\Delta \sim 0.3$ meV) is smaller than the mean athermal phonon energy ($E \sim 2$ meV), incident athermal phonons create quasiparticles in the Al, which diffuse to the TES on times that are short compared to the quasiparticle recombination time. Since the W TES is very near T_c , it has many thermally excited quasiparticles and behaves much like a normal metal. As a result, when quasiparticles diffuse from the Al into the W film, instead of emitting phonons as occurs for a two superconductor quasiparticle trap, electron-electron interactions with the quasiparticles in the W are the

dominant process, and the energy is rapidly thermalized within the electron system.⁹ Note that this thermal energy collection process is more efficient than the charge collection process through quasiparticle trapping with tunnel junctions. In the tunnel junction devices, the quasiparticles require many attempts before crossing the tunneling barrier, resulting in a relatively long tunneling time. Also, in the tunnel junction devices, the subgap phonons that are shed when the quasiparticles relax to the gap edge of the low T_c superconductor are lost into the substrate. In the quasiparticle-trap-assisted electrothermal feedback transition-edge sensors (QETs), more of the quasiparticle energy is thermalized directly into the electron system when it enters the W film. Note, however, that in both cases at least 43% of the energy is lost to subgap phonons when the quasiparticles are initially created in the high gap film.¹⁰

Our first large scale dark matter detector will be fabricated on 3-in.-diam Si wafers. In order to cover this large surface area while keeping quasiparticle trapping times short ($\sim 1 \mu\text{s}$) it is necessary to use many small area Al quasiparticle collection pads. In order to interface our W transition-edge sensor with many Al quasiparticle trapping pads, the W/Al QET is fabricated as an array of 200 W lines, each $2 \mu\text{m}$ wide and $800 \mu\text{m}$ long. The lines are connected in parallel by two narrow Al bars. When the aluminum bars are held at a constant potential difference, each W link individually self-biases on its transition. Each W line is placed in electrical contact with eight Al quasiparticle-trapping pads. Since the W lines are wired in parallel, they each have the same voltage bias, and the current through all lines is summed before being measured by the SQUID. Thus, the energy removed from the entire sensor by the reduction in joule heating is the voltage bias multiplied by the integral of the summed current pulse. Since the W lines self-bias, they may be spaced widely, allowing Al pads to be instrumented over a large surface area.

An additional benefit of using a parallel array of W lines is that, since each parallel W line self-regulates in temperature within its transition, the effect of any gradient in T_c across the absorber is reduced, thus eliminating the most important limiting factor in our previous W transition-edge sensors.⁵ Each parallel W line may be packed into a tight meander in order to minimize its area coverage and any variation in T_c across it. Since each element individually self-biases in temperature, only the T_c variation across an individual element is important. For the 200 element devices described in this work, the distance across one such meander is $\sim 60 \mu\text{m}$, instead of the ~ 3 cm length scale across one channel on a 3 in. wafer. The effect of any gradient in T_c is thus reduced by more than two orders of magnitude.

II. DEVICE FABRICATION

The W/Al QETs described in this work are fabricated on a double-polished, 1-mm-thick, $1 \text{ cm} \times 1 \text{ cm}$ absorber made of high purity magnetic Czochralski silicon (resistivity $\sim 2 \text{ k}\Omega \text{ cm}$). The silicon surface is instrumented with two W/Al QET channels, each covering a $2 \text{ mm} \times 4 \text{ mm}$ area, spaced 5 mm apart center to center, and centered on the chip [Fig. 3(b)]. Each channel is made of 200 parallel W lines $2 \mu\text{m}$

FIG. 2. Schematic of four elements of a W/Al QET. Eight Al quasiparticle trapping fins (light shading) are electrically connected along equal intervals to each W line (dark shading). The elements are connected in parallel by Al bars. Each channel is made up of 200 such elements.

wide, $800\ \mu\text{m}$ long, and $30\ \text{nm}$ thick, and has a normal resistance of $\sim 6\ \Omega$. The lines are packed into a tight meander in order to minimize any variation in T_c across a line. Eight Al quasiparticle trap pads $60\ \text{nm}$ thick and $\sim 80\ \mu\text{m}$ on a side are connected to each W line at equal intervals along its length in order to reduce the energy thermalization time (Fig. 2). The W lines are wired in parallel with $5\text{-}\mu\text{m}$ -wide Al bars connected to Al bonding pads. Al (with 1% Si) wire bonds are used to connect the chip to the electrical circuit.

The device is fabricated in two metallization steps, and two lithography steps. First, an Al film $60\ \text{nm}$ thick is deposited on a bare Si substrate in a Balzers 450 dc magnetron sputtering system. Without breaking vacuum, a protective W film $30\ \text{nm}$ thick is then deposited over the Al with a $-200\ \text{V}$ dc substrate bias. The composite film is photolithographically patterned and a two-step wet etch is used to define the Al quasiparticle trapping pads, which at this point are still covered with $30\ \text{nm}$ of W. The wafer is returned to the Balzers system for the second metallization. After the system is baked out, a rf backsputter is conducted to remove all of the surface oxide. Since the patterned Al film is covered by a thin layer of W, it is expected that little Al is backsputtered onto the Si surface during this process. A fresh W film $30\ \text{nm}$ thick is then deposited on the wafer, again using a $-200\ \text{V}$ dc substrate bias. The W meander lines and the connections to the Al quasiparticle traps are then photolithographically patterned, and all the excess W (including the initial protective layer on top of the quasiparticle trapping pads) is removed using a wet etch. The wafers are then diced into $1\ \text{cm} \times 1\ \text{cm}$ squares and mounted in a dilution refrigerator system with a $35\ \text{mK}$ base temperature.

FIG. 3. Detector geometry. (a) Cross-sectional view of the detector with a collimated ^{55}Fe source incident on the backside. (b) Top view of the detector. The line of collimation passes through the centers of both channels.

III. EXPERIMENTAL RESULTS

The W/Al QET was cooled to below T_c in a dilution refrigerator. Thermal contact was made to the backsurface of the Si crystal through four small gold plated beryllium-copper springs. An ^{55}Fe source of 5.89 and $6.49\ \text{keV}$ x rays was mounted on the backside of the crystal. The $1/e$ attenuation length of 5.89 and $6.49\ \text{keV}$ x rays in Si are ~ 29 and $\sim 38\ \mu\text{m}$, respectively, so most events occur near the back-surface of the 1-mm -thick Si crystal. In order to deconvolute event position and energy, it is necessary to compare the energy collected in several detector channels. Since the W/Al QET used in this work had only two channels, it was only possible to deconvolute position from energy in one of the two surface dimensions. To limit the events to this one dimension, the x rays were collimated through a slit across the centers of the two channels, as shown in Fig. 3. In future four channel experiments this collimation will be unnecessary.

In order to improve the energy resolution of the sensor, it was necessary to irradiate the silicon crystal with a photodiode for $\sim 10\ \text{min}$ before data were taken. When the crystal is initially cooled down, the minority (D^+) impurity sites are ionized, along with an equal number of majority (A^-) impurity sites.¹¹ When a particle interaction occurs in a silicon crystal, both phonons and electron-hole pairs are generated. The electrons and holes can recombine to produce additional phonons within the QET collection time, but electrons and holes can also be trapped at impurity sites within the crystal and prevented from recombining. Any statistical variations in this trapping, or spatial variation which is not fully deconvoluted, worsens the energy resolution. After sufficient exposure to a radiation source, however, all impurity sites are filled, and charge carriers can propagate all the way across the crystal. At our operating temperatures, thermal processes are insufficient to reionize the impurity sites.

FIG. 4. A set of coincident pulses in the W/Al QET. The event is a phonon signal from a 6 keV x ray interacting near the back of a 1-mm-thick Si crystal. 350 kHz low pass filters were used in both channels.

After diode irradiation, data were taken. The device was found to stably self-bias. All 6 keV pulses in the two independent W/Al QET channels were large and coincident (Fig. 4).

The total energy removed by the reduction of joule power is simply the voltage bias multiplied by the integral of the change in the SQUID current. If the entire pulse is integrated, however, substantial low frequency noise is introduced. In an effort to estimate the pulse integral while minimizing low frequency noise, the pulse was first integrated, and then run through a high pass filter with a knee at $\omega = 1/\tau_{\text{pulse}}$, where τ_{pulse} is the observed time constant of the pulse (neglecting a long, low amplitude pulse tail that may be due to the absorption of subgap phonons directly into the W film). The height of the filtered pulse integral was taken to be an estimate of the pulse integral. This estimate is somewhat low, since the tail of the pulse is not fully measured, but the resolution of the resulting energy measurement is improved.

In Fig. 5, the pulse integral in channel A is plotted

FIG. 5. Pulse integral A vs B plots for the W/Al QETs. The events are normalized to a peak at 6 keV in PHA+PHB.

FIG. 6. Pulse integral A vs B plot, with a cut excluding events near the edge of the crystal.

against the pulse integral in channel B. The pulses are normalized so that the sum of the integrals in A and B is centered on 6 keV. The 5.9 and 6.5 keV x-ray lines are clearly separated.

The data in Fig. 5 contain both position and energy information. For example, events that occur near the center of the crystal have equal energy deposition in both channels, and appear in the center of Fig. 5. As events occur nearer to channel A, and further from channel B, the pulse energy is shared more unequally, and the event appears near the bottom right-hand corner of the plotted data. The fact that the sum of the pulse energies near the center of the crystal is slightly less than that nearer one channel (the data do not quite fall on a line) indicates that a small fraction of the phonons is absorbed in a site other than the sensor channels (such as the Be-Cu springs used for heat sinking). It is thus necessary to deconvolute the position and energy to attain the best energy resolution.

In this set, deconvolution of the position and energy is complicated since the data fold back on itself. When a pulse occurs in the center of the crystal, the pulse integrals contain the same energy in both channels. Events that occur directly under one sensor lead to maximum pulse integral in one channel, and minimum pulse integral in the other. When events occur further towards the edge of the crystal, the energy is once again shared more equally between the two channels, and the data fold back on itself. As a result, a careful deconvolution of energy and position for events in this region of degeneracy requires implementation of a more complicated analysis which takes into account pulse timing. In order to simply estimate the resolution of this detector, the events nearer the edge of the crystal were excluded from the data set (Fig. 6). In the region of this cut, the data are approximately linear. The integral in channel A is added to the integral in channel B to derive the total energy. A histogram of the total normalized energy detected is plotted in Fig. 7. Two separate peaks are clearly seen. Both the separation of the peaks and the ratio of the number of events in the two peaks are consistent with the $k\text{-}\alpha$ (5.9 keV) and $k\text{-}\beta$ (6.5 keV) x rays from the ^{55}Fe source. The energy resolution is

FIG. 7. The energy histogram for the data in Fig. 6. The energy peak is normalized to 6 keV. The 5.9 keV $k\text{-}\alpha$ and 6.5 keV $k\text{-}\beta$ peaks are clearly distinguishable. The energy resolution is <350 eV FWHM.

measured to be <350 eV full width at half-maximum (FWHM), which is the highest resolution that has been reported for a fast (<1 ms pulse duration) calorimetric detector with an absorber mass >0.1 g. Comparable speed and energy resolution have been achieved at 100 mK using InSb with a series array of SIS tunnel junctions.¹² Slower transition-edge sensors operating at ~ 15 mK on larger mass Al_2O_3 devices have also been reported with higher energy resolution, but no position resolution.¹³

Our measured resolution is worse than what would be expected from the fluctuations in the transition-edge sensor alone. Accidental triggers are seen to have a resolution of ~ 120 eV FWHM (Fig. 7), indicating that statistical fluctua-

tions in the energy collection from the Si absorber into the W lines are currently limiting the energy resolution of the detector.

ACKNOWLEDGMENTS

We would like to thank P. Brink, B. Dougherty, and M. J. Penn for helpful discussions. This work was supported in part by the Department of Energy under Grant No. DE-FG03-90ER40569 and the office of Naval Research under Grant Nos. N00014-92-J-1464 and N00014-92-F-003.

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