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CALORIMETRIC PARTICLE DETECTORS WITH SUPERCONDUCTING TRANSITION EDGE THERMOMETERS

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Abstract. The cryogenic detector group at the MPI München, in collaboration with the Technische Universität München, develops calorimetric particle detectors utilizing large absorber crystals coupled to superconducting transition edge thermometers. At low temperature, high energy resolution results from the low detector heat capacity and the strong temperature dependence of the resistance of the thermometer at the normal/superconducting phase transition. The transition edge thermometer is a thin film of very low T_c superconductor deposited directly on the absorber. Measurements with iridium, tungsten, and iridium/gold proximity effect films are discussed. Detector performance, including thermal and nonthermal contributions to the radiation-induced signals, is described. Pulses from photon, muon, α particle, and heater induced events have been registered.

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1 Introduction

We are developing prototype calorimeters [1] for the detection of rare events in particle physics. Possible uses for such detectors are the detection of low energy neutrinos, searches for dark matter candidates, or rare decay events such as double-beta decay.

An idealized calorimeter consists of an absorber and thermometer in weak thermal contact with a heat bath. A scattering event deposits an energy δE into the absorber. In a naïve picture, the temperature of the detector rises by $\delta E/C$. It then decays back to the steady state temperature with the thermal relaxation time, C/g. Here, C is the heat capacity of the detector and g is the thermal conductance between the detector and the heat bath. For high energy resolution and a low energy threshold one needs a sensitive thermometer and low heat capacity.

Each of our detectors consists of a strip of superconducting film deposited directly on a dielectric crystal absorber. The detector is operated at a temperature within the normal/superconducting phase transition of the film. In this region the resistance of the film, as monitored with a dc-SQUID, strongly varies with temperature (large $\partial R/\partial T$). It is important for our purposes to use a film with a very low T_c and a sharp phase transition. To this end, we are concentrating our efforts on detectors with iridium films, tungsten films, and iridium/gold proximity effect films.

2 Performance of Two Detectors

We have performed extensive studies of two detectors. Each consists of a 19 gram Si crystal ($40 \times 20 \times 10$ mm^3) with a strip of superconducting film deposited on one face. The film area is 2×1 mm^2. It has additional contact pads overlayed on each end. The detector is supported within a copper housing by small spherical ruby tips. Thermal coupling of the detector is provided by ultrasonically bonded gold wires which connect one contact pad of the thermometer to the copper housing. This housing is weakly coupled to the mixing chamber of a dilution refrigerator. During detector operation the copper housing, which serves as the heat bath, is stabilized at the desired operation temperature.

Electrical connection is provided by aluminum wires ultrasonically bonded to the contact pads of the thermometer strip. Signal readout is performed with a parallel circuit driven by a constant current source. The strip thermometer comprises one branch of this parallel circuit. A reference resistor (50 mΩ) in series with a SQUID-coupled inductor makes up the other branch of this parallel circuit. An energy absorption event causes the resistance of the strip to briefly rise and then decay back to its steady state value. The SQUID measures the resulting change in current, δI(t), through the SQUID branch of the parallel circuit. For both of these detectors, the measured signal does not have the simple time dependence implied by the naïve picture of the introduction. The pulse induced by a particle absorption event is actually well characterized by one rise time and two, one fast and one slow, decay times.

$$\begin{aligned}\delta I(t) &= A_{fast}\exp\{-t/\tau_{fast}\} + A_{slow}\exp\{-t/\tau_{slow}\} \\ &\quad -(A_{fast}+A_{slow})\exp\{-t/\tau_{rise}\}\,. \qquad (1)\end{aligned}$$

The amplitude associated with the rise time must equal the sum of the decay amplitudes, $(A_{fast}+A_{slow})$, in order that the pulse start and relax to the same baseline. The operation point of these detectors (i. e., the position on the thermometer phase diagram) is determined by the value of the constant current, I_0, in the parallel circuit and the

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Table 1. Characteristics of two detectors.

Thermometer Material	T_c	Transition Width	Pulse Height δT	Energy Resolution	Operating Point
Iridium (200 nm thick)	220 mK	10 mK	$\approx 100\,\mu$K for 5.8 MeV α particles	50 keV (FWHM) for 5.8 MeV α particles	T_0=216 mK I_0=18 μA
Ir/Au bilayer (40 nm/40 nm, each)	105 mK (onset)	$\approx$ 100 mK	$\approx 120\,\mu$K for 60 keV photons	1 keV (FWHM) for 60 keV photons	T_0=17 mK I_0=100 μA

temperature, T_0, of the heat bath. The time constants and amplitudes of Equation 1 are found to depend on the operating point. Naturally, the amplitudes also depend on the energy deposition.

One of these detectors was fabricated with an Ir strip thermometer, and the other with an Ir/Au proximity effect bilayer. Some of the different characteristics of these two detectors, labelled by their thermometer structure, are listed in Table 1. The pulse data were taken at the indicated operating points of the detectors.

The Ir Detector

The thermometer strip of the Ir detector [2] had a sharp phase transition at a T_c of 220 mK, which is twice the transition temperature of bulk Ir. This enhancement of the transition temperature may be due to the formation of iridium-silicon compounds during the deposition process. This Ir detector was tested by irradiation with collimated α particles from a three line (5.16 MeV from ^{239}Pu, 5.49 MeV from ^{241}Am, and 5.81 MeV from ^{244}Cm) open source. For data taken with a single small collimation aperature the energy resolution for these α particle events was better than one percent. A second small collimation aperature was additionally opened. The position of this aperature was chosen such that the irradiated point on the crystal was separated from the thermometer along the [1 0 0] Si crystal axis. This is an axis for strong phonon focussing [3] in silicon. The pulse heights for these "focussed" events were about ten percent larger than for the other events. The rise time was nearly a factor of two faster for the "focussed" events than for the "nonfocussed" events.

The Ir/Au Detector

The thermometer strip of the Ir/Au detector [4,5] had a very broad phase transition as shown in Figure 1. This thermometer did not become fully superconducting down to the lowest accessible temperature. The extreme breadth may be due to problems at the iridium-gold interface. Even with such a broad transition, pulses from the α particles were very large and the threshhold of the detector could be lowered to approximately 10 keV at the more sensitive operating points.

The α particle source was subsequently removed and the detector was tested with γ radiation from ^{57}Co (major photon lines at 122 and 136 keV) and from ^{241}Am (major photon line at 59.5 keV) sources placed outside the dewar. Because of the low absorption cross section of the Si absorber for these radiations, essentially the whole volume of the detector is irradiated. Figure 2 shows a typical pulse registered from the absorption of a 59.5 keV photon. Figure 3 shows the pulse height spectrum obtained while irradiating the detector with the ^{241}Am source outside the dewar. If a strong position dependence were present in this detector it would show up as a broadening of the measured spectrum.

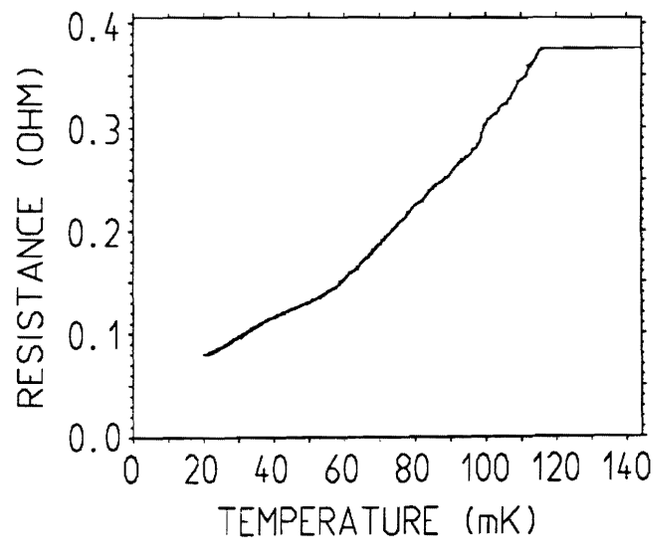

Figure 1: *Temperature dependence of the resistance of the Ir/Au proximity effect thermometer measured at the low current, $I_o = 4\mu A$.*

Natural background radiation was also measured by simply removing all other sources. In such measurements, events attributed to very high energy cosmic ray muons were identified. These muons are minimum ionizing particles which typically deposit 3-4 MeV into the detector.

The broad phase transition of this detector limited our temperature sensitivity and thus our energy sensitivity. But this breadth offered the opportunity of studying the temperature dependent performance of this detector over a wide temperature range. To study this the pulse am-

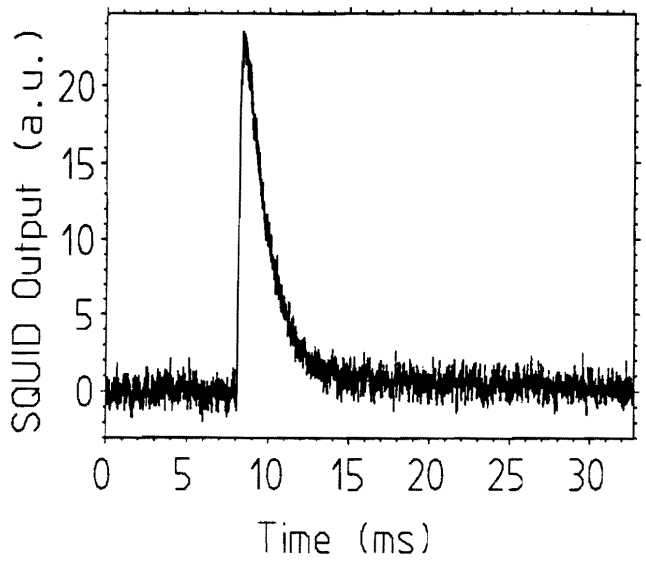

Figure 2: *A single 59.5 keV pulse from the Ir/Au detector recorded at 17 mK with a read-out current of 100 μA. The 59.5 keV photons were emitted from an ^{241}Am source placed outside the dewar. A pulse fit yields a rise time of 138 μs and two decay times of 1.53 ms and ~ 40 ms. The amplitude of the slow component, barely visible here, contributes less than 2% to the pulse height at this operating point.*

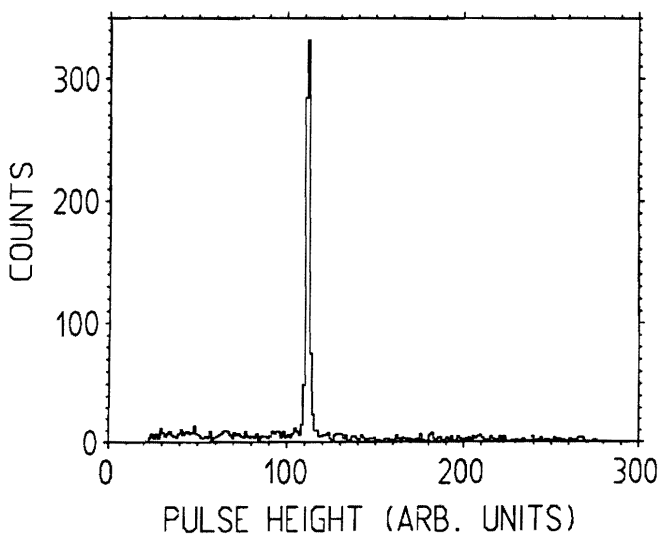

Figure 3: *Pulse height spectrum taken at 17 mK using an ^{241}Am 59.5 keV gamma source. The width of this peak corresponds to an energy resolution of ΔE=1.0 keV (FWHM).*

plitudes were expressed in units of temperature rise for a given energy deposition. The most important point revealed in this study was that the pulse height for a given energy deposition increased substantially as the temperature of the operating point decreased. But this increase was not as large as predicted by a simple Debye model Si heat capacity. The amplitude A_{fast}, which is the dominant component of the overall pulse height, increased as the temperature of the operating point decreased. Interestingly, the slow amplitude A_{slow} was not monotonic. Instead, the slow amplitude reached a maximum at approximately 40 mK. The rise time and the slow decay time increased (i. e., the pulses became slower) as the temperature of the operating point decreased. But the fast decay time remained essentially constant for all operating conditions.

3 A Model of our Detectors

These data on the temperature dependence of the pulse shape parameters have been used to develop a model [6] of our detectors. This model incorporates the scattering and thermalization of phonons in the absorber and the metal film, the Kapitza boundary thermal impedance at the film-absorber interface, the thermal impedance along the film and the gold wires, and the heat capacities of the thermometer and absorber. Central to this model is a consideration of the mechanism for thermal equilibration.

According to this model, the following things occur after a particle absorption event. Within a short time scale, a nonthermal population of high energy phonons is created from the absoption event and is uniformly distributed throughout the absorber. These phonons are not efficiently thermalized within the Si absorber crystal. But these phonons are efficiently down-converted and thermalized by the electron subsystem within the metal film. The electron subsystem of the film heats up from the influx of the high energy phonons whose population is thus steadily diminished. It is this temperature change of the electronic subsystem which we ultimately measure. The phonon subsystem of the film is heated by the electron subsystem via the electron-phonon interaction within the film. Some of the energy is then emitted, through the Kapitza boundary impedance, from the phonon subsystem of the film back into the Si absorber as thermal phonons. The rest of the energy directly escapes the electronic subsystem of the film out the gold wires to the bath. In this model the strong temperature dependence of the electron-phonon interaction in the metal film plays a key role. At the lowest operating temperatures, where this interaction is particular weak, only a small fraction of the energy is converted to thermal phonons.

The fast decaying part of the pulse reflects the extinction of the high energy phonon population and depends on th area of the film-absorber interface. The slowly decayir

part of the pulse represents the relaxation of the thermally equilibrated absorber-film system back to the bath temperature. The rise time depends on the heat capacity of the film.

Tests which involved cutting some of the gold thermal anchor wires support these conclusions. After the above tests, an additional platinum heater film was deposited on the Si surface opposite the thermometer of the Ir/Au detector. The heater tests also support the model qualitatively. But the heater results are complicated by the heat capacity, boundary impedance, and electron-phonon interaction in the heater film which are not measurable in our experiment.

4 Other Developments

To increase the sensitivity of this type of detector it is important to develop films with sharp transitions at low T_c. Therefore, we are systematically investigating Ir/Au proximity effect bilayers. We have found that the superconducting properties of these films sensitively depend on the presence of impurities incorporated during the deposition. We are especially concentrating on predictably tuning the T_c of the bilayer by adjusting the thicknesses of the iridium and gold layers. Ir/Au bilayers with T_c's as low as 70 mK and with transition widths of a few millikelvin have been produced. We are also trying other normal metals, such as copper, in place of the gold. These efforts are ongoing.

We are also working on tungsten film thermometers because bulk tungsten has the very low transition temperature of 15 mK. Solid tungsten exists in two phases. The α phase, stable in bulk tungsten, has the desirable low superconducting transition temperature. The β phase, which is often stabilized in thin films, has an undesirable high superconducting transition temperature of 4 K. We are concentrating on trying to produce clean α phase thin films. To this end we have built a special UHV deposition system dedicated to this tungsten effort. In order to be able to operate tungsten based detectors we have designed, constructed, and operated a new dilution refrigerator capable of continuous operation below 9 mK.

We have produced [7] epitaxial α phase thin films on sapphire substrates. Two of these were measured down to 9 mK but exhibited no superconducting transition. One of these films was subsequently analyzed and the tungsten-sapphire interface was found to have considerable iron impurities. These impurities may have been incorporated during the substrate preheating or heating phase of the deposition. Deposition for these two films was performed at a substrate temperature of 1000 °C with preheating at still higher temperatures. A third α phase film was grown on a sapphire substrate which was heated to only 500 °C during the deposition. This film did not grow epitaxially but exhibited a sharp (few millikelvin wide) superconducting transition at 14 mK. We are developing photolithography processes to sharply define the geometry of these tungsten films and the other films.

5 Summary

Results from two detectors yielding excellent energy resolution have been presented. Detailed studies have resulted in a model which will be used to optimize future detectors. To increase performance of this type of detector we are working on reliably producing thin films with a very low T_c. These efforts on iridium, tungsten, and Ir/Au are progressing.

References

[1] W. Seidel, G. Forster, W. Christen, F. von Feilitzsch, H. Göbel, F. Pröbst, and R. L. Mößbauer, "Phase Transition Thermometers with High Temperature Resolution for Calorimetric Particle Detectors Employing Dielectric Absorbers" Phys. Lett. **B 236**, pp. 483, March 1990.

[2] D. Dummer "A Calorimetric Particle Detector using a SQUID Monitored Transition Edge Thermometer," presented at the IVth International Conference on Superconducting and Quantum Effect Devices and their Applications, Berlin, Germany, June 18-21, 1991. *Springer Proceedings in Physics,* **64**, 1992 Springer-Verlag, Berlin.

[3] C. Elbaum, "Anisotropic Heat Conduction in Cubic Crystals," in *Proceedings of the International Conference on Phonon Scattering in Solids*, Paris, July 1972, pp 1-17.

[4] F. Pröbst, S. Cooper, D. Dummer, M. Frank, and W. Seidel, "Recent Progress in Calorimeters with Transition Edge Thermometers," in *Low Temperature Particle Detectors for Neutrinos and Dark Matter IV*, Oxford, UK, September 4-7, 1991, pp. 193

[5] W. Seidel, D. Dummer, and F. Pröbst, "Signal-to-Noise Ratio Expected for a Calorimeter with Transition Edge Thermometer," in *Low Temperature Particle Detectors for Neutrinos and Dark Matter IV*, Oxford, UK, September 4-7, 1991, pp. 203

[6] F. Pröbst, "Phonon Mediated Detection of Particles," in *Proceedings of the Seventh International Conference on Phonon Scattering in Condensed Matter,* Ithaca, New York, August 1992.

[7] W. Seidel "Superconducting Thin Film Thermometers for Calorimetric Particle Detectors," to be presented in *Twelvth International Vacuum Congress, Volume III,* The Hague, Netherlands, October, 1992.