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Characterization of photolithographically defined NIS tunnel junctions as X-ray sensors

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Abstract

We are developing normal-insulator–superconductor (NIS) tunnel junctions for use as X-ray detectors for astronomical purposes and as phonon sensors for dark matter detectors. We are using photolithographic techniques to produce structures in which aluminum is the superconductor, Al_2O_3 is the tunnel barrier, and copper is the normal metal. We describe microfabrication details and present X-ray pulse data.

1. Introduction

The motivation for the development of a new class of particle detector arises primarily from the search for dark matter, which requires the ability to sense small (~1 keV) energy depositions in large (~100 g) crystals, and from the rapidly evolving field of X-ray astrophysics, which requires high-resolution (<20 eV at 6 keV) and high quantum efficiency. Normal-insulator–superconductor (NIS) tunnel junctions, which function as extremely sensitive thermometers for the electrons in the normal electrode, are being investigated for use on these detectors [1,2]. The major advantage of this type of sensor is that there is no need to apply an external magnetic field to suppress Cooper pair tunneling as is the case for superconductor–insulator–superconductor (SIS) junctions. The major challenge associated with NIS junctions is that when they are biased for maximum sensitivity they dissipate a significant amount of heat. We believe that difficulties can be circumvented by using small-area NIS sensors coupled to large-area phonon or X-ray absorbers and to cooling fins or traps which prevent quasiparticles from recombining too close to the normal film. With these considerations in mind, we began a program to integrate these structures by applying photolithographic techniques which provide precise dimensional control, feature alignment, and topological flexibility. The first step in this effort is to develop a process for fabricating NIS junctions. This paper reports preliminary results.

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2. Device fabrication

During this exploratory phase we are using an existing mask set intended for SIS junction development which contains series-pair patterns suitable for NIS prototyping. Fig. 1 shows the required masking steps. We fabricate devices in the Thin Film Laboratory at San Francisco State University (SFSU). Our principal deposition system is a cryopumped UHV sputtering system having four magnetrons in the main chamber and an ion gun in the load lock. First we DC sputter a 50 Å titanium glue layer and a 1200 Å aluminum base layer onto a three inch silicon wafer. (The titanium reduces the aluminum superconducting transition temperature from 1.2 K to 950 mK but does not broaden the transition.) We then pattern the composite film and wet etch both layers. Next we RF sputter a 2100 Å SiO_2 film and pattern it as an edge mask to define the (70 μm)^2 tunneling regions. The purpose of the edge mask is to prevent the normal electrode from crossing directly over the border area of the superconducting film. This is important for three reasons. First, short circuits through the tunnel barrier are more likely to form where one film crosses directly over the sidewall of another film. Second, pulse height resolution will be degraded if the tunneling region includes the border area where the gap

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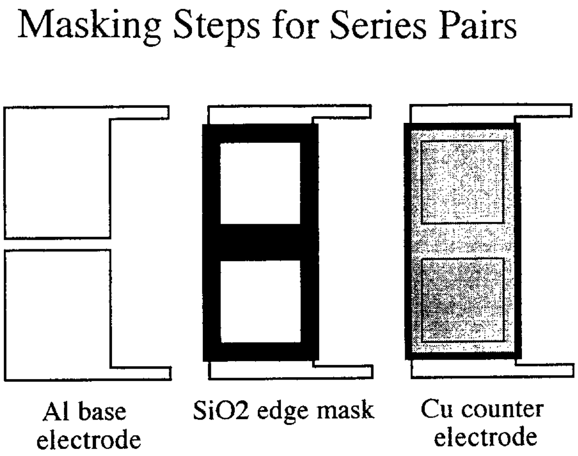

Fig. 1. Al base electrode is DC sputtered (with Ti glue layer) and wet etched. SiO_2 edge mask is RF sputtered and plasma etched. Tunneling windows are ion gun cleaned and oxidized to form tunneling barrier. Cu counter electrode is then DC sputtered and wet etched.

changes as the superconducting electrode tapers to zero thickness. Third, the tunneling region is set back from the edge of the normal electrode by the 10 μm overlap of the normal electrode on the edge mask. We believe that this feature protects the edges of the barrier region from environmental degradation. We etch the SiO_2 with a CHF_3/O_2 plasma in order to produce steeply sloped sidewalls which inhibit nucleation of copper crystallites during deposition of the counterelectrode. We clean the tunneling regions by ion bombardment with a 500 eV argon beam, expose the freshly cleaned aluminum surface to oxygen for thirty minutes at a fixed pressure in the range from 0.1 to 25 Torr, and then immediately DC sputter a 3000 Å copper film. Finally, we pattern and wet etch this layer to form the counterelectrode.

3. Device testing

This section summarizes the results of extensive testing of an NIS series pair in the Laboratory for Experimental Astrophysics at Lawrence Livermore National Laboratory (LLNL) in an adiabatic demagnetization refrigerator (ADR). First we measured the *IV* curve by biasing the device with a current source and reading out the voltage with a FET-input instrumentation amplifier. Fig. 2a shows an extended *IV* curve taken at a bath temperature of 80 mK. Data taken over a restricted range can be fitted by a 200 Ω shunt resistance R_d in parallel with an NIS pair at an effective temperature of 110 mK, a gap parameter $2\Delta \approx 270$ μV, and normal resistance $R_n \approx 0.71$ Ω. Usually a value of R_d/R_n of only ≈280 is a symptom of a leaky junction. Measurements between other contact pads on the chip indicated that most of this excess conductance may be due to a residual titanium film left over from incomplete etching of the glue layer.

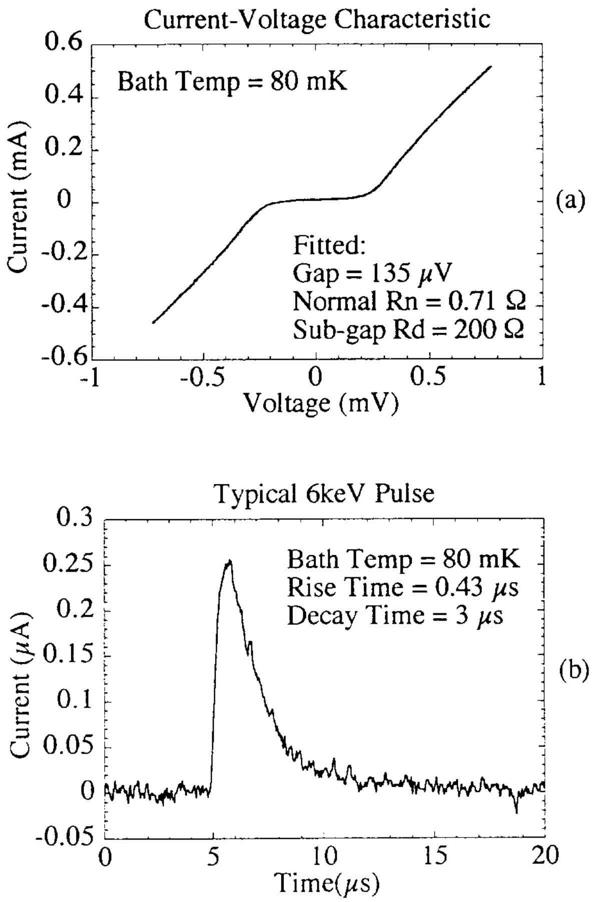

Fig. 2. (a) *IV* curve is measured at 80 mK. Fitting the curve indicates the junction temperature is at 250 mK, which is evidence of self-heating. For a lower current sweep, the fitted temperature is 110 mK. This is more representative of operating mode. Fitted energy gap is at 135 μV and normal resistance is 0.71 Ω. (b) Sample pulse taken at 80 mK with a bias of 315 μV. Rise time is limited by $L_{SQUID}/R_{dynamic}$ at bias voltage. Decay time is shorter than expected due to self-heating of the junction.

We irradiated this sensor with Mn Kα and Kβ X-rays from an uncollimated ^{55}Fe source located on the sample stage. We voltage biased the junction pair and measured X-ray induced current pulses by using a current amplifier based on a 200-SQUID series array manufactured by HYPRES, Inc. [3,4]. The SQUID was operated in an open-loop mode. In Fig. 2b we show a typical current pulse acquired at a bath temperature of 80 mK and a bias of 315 μV. The 0.43 μs 10%-to-90% rise time is limited by the response of the SQUID input circuit, which has a time constant τ_{SQ} given by the ratio of the input inductance of the SQUID ($L_{SQ} \approx 0.25$ μH) to the dynamic resistance of the series pair ($R_{dyn} \approx 0.9$ Ω). (The calculated value $\tau_{SQ} \approx$ 0.28 μ corresponds to a 10%-to-90% rise time of 0.61 μs.)

The 3 μs 80%-to-(1/e) × 80% decay time is determined by the electron cooling time in the copper film. In Figs. 3a and 3b we plot the pulse height and decay time as a function of bath temperature at three representative bias voltages. The pulse height depends on the product of the X-ray induced temperature rise ΔT and the current responsivity dI/dT. For bias voltages significantly below the gap voltage, as we sweep in temperature we expect dI/dT to pass through a maximum at relatively high temperatures, producing a maximum in pulse height as is evident in the curve measured at 202 μV. At higher bias voltages, this maximum occurs at lower temperatures. The pulse heights measured at 225 and 270 μV change much less than expected at bath temperatures below 180 mK indicating that the sensor itself may not reach lower temperatures due to self heating at these high bias points. This hypothesis is also supported by the measured decay times, which increase much more slowly (especially at high bias) than the T^{-3} dependence which would be expected if electron–phonon decoupling is the dominant factor. We suspect that our normal metal heats rather than cools as predicted [5] because excited quasiparticles produced by the tunneling process recombine into Cooper pairs in the aluminum film directly beneath the tunneling region. Phonons emitted during recombination can be absorbed by the normal metal and thus heat it. Excited quasiparticles are prevented from diffusing away by the narrow leads leaving the aluminum electrodes. (These narrow leads were intended to confine quasiparticles to the junction regions of the SIS pair for which the mask set was designed.) Future designs will include large superconducting radiators or normal metal thermalizers to remove these excited quasiparticles from the sensor region.

We took another set of pulse data in which we placed a copper collimator with a 70 μm × 300 μm slit 2 mm above the NIS device with the slit perpendicular to the longer side of the junction pair. We attached an ^{55}Fe source to a movable bracket on the outer wall of the dewar 11 cm from the NIS sensor. X-rays from this source could enter the dewar through thin aluminized-mylar windows. We stabilized the refrigerator temperature at 100 mK and biased the junction pair at 270 μV. In the pulse height spectrum shown in Fig. 4 the Mn Kα structure appears to consist of overlapping peaks having centers separated by ≈180 eV. The Kα feature can be fitted with a lower energy peak with 150 eV FWHM and a higher energy peak of similar width. The electronic noise contribution is estimated to be 110 eV. To look for position dependence in the response of the NIS pair, we varied the region illuminated on the sensor by moving the external source. Preliminary measurements suggest that this may have caused a change in the relative heights of the two Kα peaks. One explanation is that the junctions are not quite identical and thus are not biased at equivalent points. Another suggestion is that

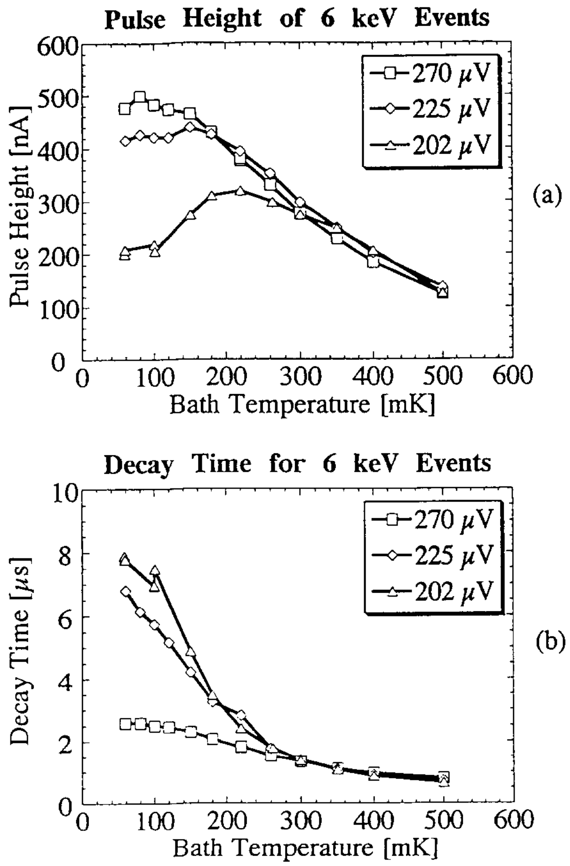

Fig. 3. (a) Plot of pulse heights vs. bath temperature at different bias voltages. Pulse heights leveling off below ~150 mK is indicative of junction self-heating. (b) Plot of decay time vs. bath temperature at different bias voltages. For low temperature, the decay time is less than expected. The limitation is indicative of self-heating.

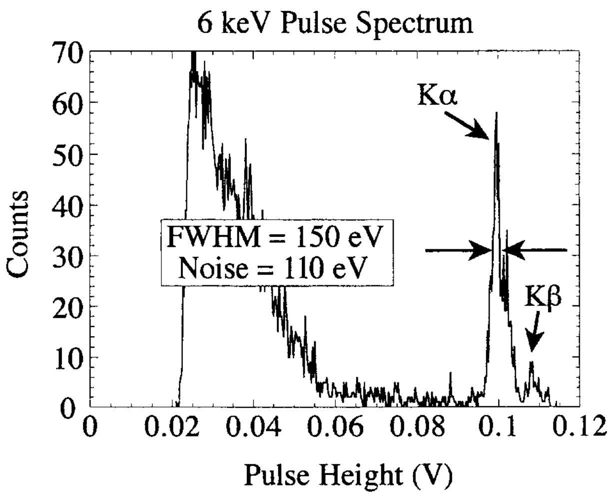

Fig. 4. Spectrum of 6 keV events taken at 100 mK with 270 μV bias. Fitted FWHM of primary peak is 150 eV. Noise is estimated at 110 eV.

the probability of phonon escape from the normal electrode may depend on whether the phonon is coupled from the copper film to the SiO_2 edge mask or to the aluminum film under the tunneling region. Thus during the initial localized cascade following the X-ray absorption event different numbers of high-energy phonons may be lost depending on the location of the interaction. Both hypotheses are under investigation.

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