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Superconducting transition edge sensor using dilute AlMn alloys

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We have fabricated a bolometer using a transition-edge sensor (TES) made of Al doped with Mn to suppress the superconducting critical temperature (T_c) of Al from ~1 K to ~100 mK. The resulting detector exhibits low-frequency noise consistent with theory, with a noise-equivalent power of 7.5×10^{-18} W/$\sqrt{\text{Hz}}$. The addition of Mn impurities did not significantly increase the heat capacity of the TES. In addition, the detector is surprisingly insensitive to applied magnetic fields. The use of AlMn alloy films in arrays of TES detectors has advantages in simplicity of fabrication when compared to traditional bilayer fabrication techniques. *© 2004 American Institute of Physics*. [DOI: 10.1063/1.1789575]

In this letter, we report the results from a superconducting transition-edge sensor (TES) bolometer fabricated using manganese impurities to reduce the T_c of an aluminum film from ~1 K to ~100 mK. We have found noise close to theoretical predictions, low noise-equivalent power, and a low sensitivity of the sensor to magnetic fields. These features, in addition to the ease of fabrication, make Al–Mn an attractive candidate for use in TES bolometers and microcalorimeters.

TES detectors have become an important detector technology for sensitive photon detection in submillimeter, optical, and x-ray regimes.[1–3] These detectors offer excellent sensitivity, despite having some unexplained noise. An important reason for their popularity has been a clear path toward large-format arrays. TES detectors can be multiplexed cryogenically,[4] and TES arrays with ~10 000 pixels are presently being fabricated.[3] Because of this success, there is ongoing interest in improving the noise performance and ease of fabrication of TES detectors.

An important parameter of TES sensors is the superconducting transition temperature, T_c. Because T_c strongly affects heat capacity, thermal conductivity, and thermal noise of the sensor, careful control of T_c is necessary to optimize a sensor for a given application and cryogenic platform. Since the transition temperatures of elemental superconductors are not usually optimal, T_c is often engineered by fabricating bilayers of superconducting and normal metals. The T_c of the superconducting metal is suppressed by the presence of the normal metal through the proximity effect.[5] Controlling the T_c of a bilayer is technically challenging, as the T_c is a sensitive function of the properties of both layers, as well as the interface transparency.

Another technique is to use doping with ferromagnetic impurities to adjust the T_c of an elemental superconductor. The impurity method is simpler and potentially more reproducible, as only one homogeneous layer of superconducting material is used in the TES. The leads can be made out of the nondoped elemental superconductor, eliminating the risk of chemical interactions between different materials during processing. In both proximity bilayers and ferromagnetic doping, the dominant operative effect depressing T_c is traditional pair-breaking, originally elucidated by Abrikosov and Gor'kov (AG),[6–8] lately modified to include antiferromagnetic coupling effects, the latter of which reduce pair breaking and raise T_c.[9]

While the T_c of tungsten has been adjusted for use in a TES by the implantation of ions of ferromagnetic species including iron and cobalt in the ~100 ppm range,[9] it is not ideal for many TES applications. Tungsten has a high resistivity and its T_c is strongly dependent on film morphology, making it difficult to fabricate. Aluminum is an attractive alternative for TES applications due to its lower resistivity and ease of deposition.

For many applications, it is desirable to reduce the T_c of Al to ~100 mK. However, as confirmed with ion implantation, doping with ferromagnetic metals does not produce a substantial decrease in the T_c of aluminum, even at relatively high concentrations.[10] Instead, we have developed a TES using Al doped with Mn. As we have previously reported,[11] Mn can drive the T_c of Al to below 50 mK. This occurs for Mn concentrations in the ~3000 ppm regime, suggesting that AG pair breaking is not the principal agent, and rather that T_c suppression in Al–Mn alloys is due to pair scattering from resonant impurity sites in the context of the Friedel–Anderson model,[12] as quantified by the Kaiser theory.[13] This conjecture is substantially reinforced by tunneling measurements in AlMn/I/AlMn tunnel junctions that show BCS-like tunneling characteristics with conductance characteristics exhibiting the complete absence of gap smearing from paramagnetic pair breaking.

To create these films, an Al–Mn alloy (99.7%/0.3%) sputter target is used in a co-sputter system with a pure aluminum target. By varying the deposition rate of each target as they are sputtered onto a rotating silicon wafer, Al films with different concentrations of Mn are produced. Al–Mn films have been fabricated with T_c of less than 58 mK up to

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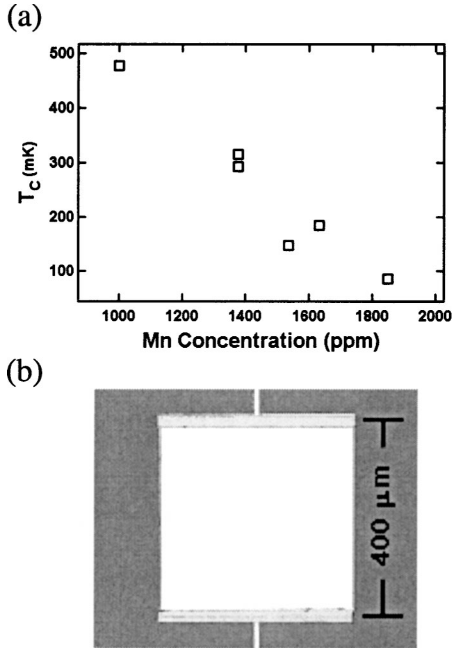

FIG. 1. (a) Dependence of T_c in Al on Mn concentration. (b) Optical micrograph of an Al–Mn TES.

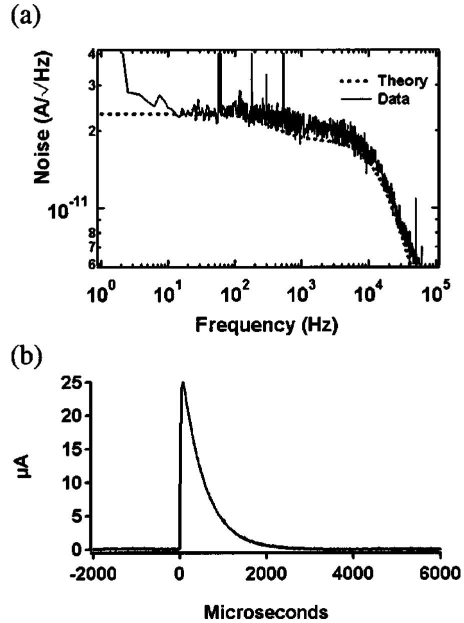

FIG. 2. (a) Noise of the Al–Mn TES detector. (b) Fe^{55} x-ray pulse in the detector.

the bulk T_c of the aluminum, ~1 K ([Fig. 1(a)). At a T_c of ~100 mK, the residual resistivity ratio of the films is ~1.5. The resistivity of these films at 100 mK (~2.4 $\mu\Omega$ cm) is fairly high, making it necessary to use thick films for applications requiring low sheet resistance.

A 400-nm-thick film of Al–Mn was patterned into a 400 μm square with an aluminum wet etch. Pure aluminum leads were evaporated through a photoresist liftoff stencil. The TES was deposited on a silicon wafer with a 350 nm coating of Si_3N_4. Silicon was removed from beneath the TES by a deep reactive-ion etch process, providing a free-standing nitride membrane for the necessary thermal isolation. Figure 1(b) shows a photomicrograph of a completed detector.

The detector was cooled in an adiabatic demagnetization refrigerator. The T_c of the detector is 112 mK, with a normal resistance R_N=72.4 mΩ. TES sensors are typically voltage-biased, and the resultant Joule heating combined with the thermal isolation of the sensor from a heat bath (with $T_{\text{bath}} \ll T_c$) produces a negative electrothermal feedback. This allows the detector to be stably biased at a given point in its superconducting transition.[1] The Al–Mn detector has a broad transition, as quantified by the unitless measure of transition steepness, $\alpha=(T/R)(dR/dT)\approx 31$ when biased at 0.25 R_N. Figure 2(a) shows the noise spectrum of the device at this bias, measured with a superconducting quantum interference device current amplifier. Superimposed is a noise model based on the measured properties of the detector. There are no free parameters in this model, and it is a good match in the low frequency, thermal fluctuation noise dominated part of the spectrum. At higher frequencies, where Johnson noise dominates, the measured excess noise for the Al–Mn TES is ~50%. This is substantially better noise performance than is typical for TES sensors, where excess noise of ~200% is often exhibited at these frequencies. The measured low-frequency noise-equivalent power is 7.5×10^{-18} W/$\sqrt{\text{Hz}}$, consistent with theoretical expectations.

The detector was exposed to 5.9 keV Fe^{55} x rays. Because no absorber was used, the detector had a low cross section to x rays, making it difficult to collect a spectrum. However, the x rays did produce pulses, as shown in Fig. 2(b). Comparing the noise of the device to the measured x-ray pulse heights, and assuming a linear detector response (which has generally been the case in our TES detectors) to a calculated energy resolution of ~2 eV, it is assumed no further sources of noise (e.g., position dependence) come into play. It is impossible, however, to determine the energy resolution of this system until it has been tested with an absorber. We calculate heat capacity C=2.6±0.3 pJ/K from the measured time constant, thermal conductivity, and α. This value is ~10% higher than the calculated heat capacity of a pure Al film, indicating that the presence of Mn has not significantly increased the Al heat capacity.

Typically, when a magnetic field is applied to a superconductor, the superconductor's T_c shifts. In a TES, this results in a shift of the bias resistance for a given bias voltage. The Al–Mn TES, however, showed very little change in T_c with magnetic field. The detector's resistance versus bias voltage was measured with zero applied field and again for an applied field of 2.21×10^{-5} T. The same was done for a Mo–Cu bilayer TES, with an applied field of 1.76×10^{-5} T. Figure 3 shows a plot of change in resistance versus the resistance of the device at bias (normalized to R_N, the normal

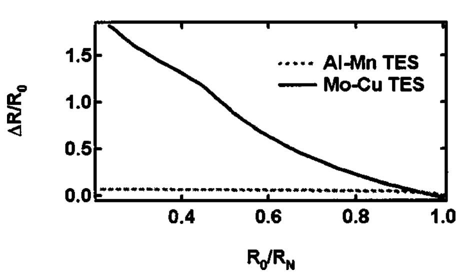

FIG. 3. The ratio of the change in TES resistance with field to resistance without ($\Delta R/R_0$) vs the resistance of the device at bias (normalized to R_N, the normal state resistance).

resistance of the TES) for both devices. At a bias voltage of 0.25 R_N, the Mo–Cu resistance changes by 175%, while the operating resistance of the Al–Mn TES changes by 6.8%. The noise performance of the Al–Mn device was unchanged before and after the field was applied.

The fabrication of Al–Mn TES detectors is simpler than that of bilayer detectors. However, there are two properties that must be considered when using Al–Mn in a TES detector. The resistivity of Al–Mn films is higher than that of Mo–Cu sensors, so thick films may be required to reduce internal thermal fluctuation noise,[14] as well as for good thermalization and low position dependence in x-ray microcalorimeters. The use of a semimetal absorber, (e.g., bismuth) incorporating a metallic layer may eliminate thermalization problems.[15] It may also be possible to produce a bilayer of Al–Mn and pure Al to improve sheet resistance. Further, because the α of the Al–Mn TES is low compared to that of Mo–Cu bilayers, a lower heat capacity will be needed for high count rate x-ray microcalorimeter applications.

Its low excess noise also makes the Al–Mn TES an interesting candidate for bolometric applications. It is unclear whether the low excess noise is caused by the magnetic impurities, or by the detector's low α. Previous measurements[16] indicate that low-α detectors have low excess noise, and this measurement seems to agree with the results from low-α Mo–Cu detectors.

The magnetic field sensitivity of TES detectors is the cause of some concern in instrument design, since they must be carefully shielded from fields produced by both the instrument and the observing environment. A small magnetic field gradient across a TES array could produce different bias resistance values within the array, producing inconsistent results from one pixel to the next. The low magnetic field sensitivity of this doped system may result in arrays that are much more stable in actual instruments.

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