T_c TUNING OF TUNGSTEN TRANSITION EDGE SENSORS USING IRON IMPLANTATION

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Abstract

We have developed a technique for precisely tuning the transition temperature of superconducting tungsten (W) films used in Quasiparticle trap-assisted Electrothermal-feedback Transition edge sensors (QETs). We have demonstrated our technique using several 350 Å-thick W films with "as-deposited" transition temperatures in the range of ≈ 90 mK to 150 mK. The accuracy of our tuning process is excellent, and T_c suppressions of prescribed amounts ranging from a few mK to 100 mK have been demonstrated. Our implantation method is highly reproducible and does not result in broadened transitions of the superconducting films. Our results represent an important breakthrough in the optimization of detectors used in the Cold Dark Matter Search (CDMS) experiments, where we prefer W phonon sensors with $T_c \approx$ 65 mK. In this paper, we describe in detail our T_c tuning technique and we present results from characterization experiments performed with the T_c - adjusted films.

1. Introduction

It is well known that even minute concentrations of magnetic impurities in an elemental superconductor can dramatically affect the temperature at which the sample's superconducting-to-normal state transition occurs. In general, the presence of magnetic impurities causes a suppression of T_c compared to the "pure" sample value, whereas nonmagnetic impurities typically have little effect on T_c. In this paper, we focus specifically on the effect of magnetic impurities on the T_c of one elemental superconductor, tungsten.

Our motivation for this work was a desire to develop a reliable technique for optimally "tuning" the T_c of tungsten transition edge sensors used by the Cold Dark Matter Search (CDMS) collaboration. The CDMS detectors (Ref. 1) simultaneously sense phonons and ionization created by a particle interaction in a 76 mm diameter x 10 mm thick single-crystal, high-purity Si or Ge substrate. The phonons generated by an event are detected using four independent arrays of W/Al Quasiparticle trap-assisted Electrothermal-feedback Transition edge sensors (QETs) on one face of the detector. A detailed description of the design and operation of QET sensors is presented in Ref. 2.

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2. The Experiments

Unpatterned tungsten, and patterned W/Al-QET test samples were fabricated at the Stanford Nanofabrication Facility, using a Balzers magnetron sputtering system operated at -100 V DC substrate bias during the tungsten depositions. All tungsten films were 350 Å thick and the deposited aluminum films were 3000 Å thick. Silicon was used for the substrate material.

Our tungsten target is 99.999% pure and our aluminum target is 99.9999% pure. Most importantly for this work, the concentrations of magnetic impurities in the tungsten target are low: [Fe] = 0.9 ppm; [Co] = 1.9 ppb; [Ni] = 0.10 ppm, and the sputtering chamber is carefully monitored to minimize contamination from unwanted impurities such as carbon (from photoresist) or stray metals.

The "as-deposited" T_c was measured for each of a set of W samples. Then, neighboring samples from each substrate were ion-implanted with either Fe, Co or Ni. Finally, the implanted samples were cooled using a dilution refrigerator, and the film T_c's were measured.

Below, we first present our T_c results obtained with unpatterned tungsten films, both before and after ion implantation. We then compare our results to a theoretical prediction of T_c suppression due to the presence of magnetic impurities in superconductors.

Finally, we summarize preliminary results obtained with patterned W/Al QET samples, and we briefly describe our continuing work in this area.

3. Samples and Results

In Fig. 1, we show the resistance vs. temperature plot for a typical patterned tungsten film used in this study. Curve (1a) corresponds to the sample "as deposited", and curve (1b) corresponds to the sample after implantation with $^{56}Fe^{+}$ (2e12 cm^{-2} @ 50 keV).

The implantation depth profile for 50 keV Fe in tungsten is roughly Gaussian, with the peak of the distribution located 130 Å into the W film. At the surface, the Fe concentration is ≈ 1/4 the peak concentration. The coherence length of our W films (≈ 0.3 μm) is significantly larger than the film thickness (350 Å), thus there is not a gradient in T_c throughout the film.

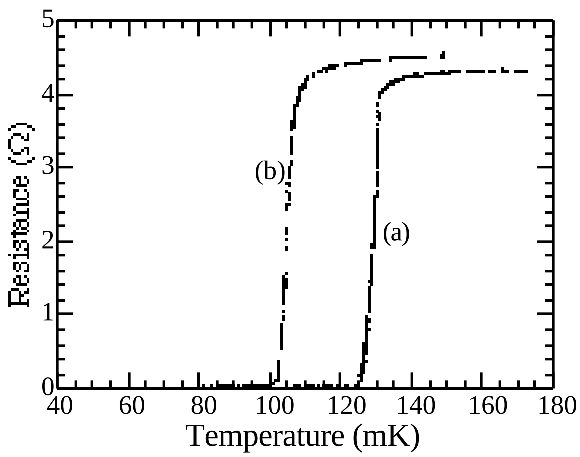

Figure 1. Superconducting transition curves for (a) an un-implanted W film and (b) the same film implanted with 2e12 cm^{-2} $^{56}Fe^{+}$ at 50 keV.

In Fig. 2, we plot T_c results for several implanted tungsten samples. The three distinct sets of points correspond to samples implanted at 50 keV with either $^{58}Ni^{+}$, $^{56}Fe^{+}$ or $^{59}Co^{+}$. The inset of Fig. 2 shows our results for one W film implanted separately at several different Fe doses. Our Fe data fit well a model for dilute concentrations of magnetic impurities in metals developed by Abrikosov and Gor'kov (AG) (Ref. 3), and extended by Roshen and Ruvalds (Ref. 4), and others. In the AG model, magnetic impurity atoms couple asymmetrically to individual Cooper pair (CP) electrons in the host metal. The interaction is asymmetric in that it acts oppositely on the two electrons (of opposite spin) within a given CP. The impurity atom - CP electron interaction alters the Hamiltonian for the superconductor such that T_c is suppressed. The AG model predicts a linear decrease in T_c with increasing impurity concentration, for dilute concentrations. The slope is determined by the spin of the magnetic impurity atoms, the Fermi energy of the host film, and the superconducting Exchange Coupling Constant for the given system.

Roshen and Ruvalds (RR) extended the AG model to account for the deviation from linearity of T_c vs. concentration for these magnetically and lightly-doped systems. The RR model incorporates into the AG Hamiltonian an additional term which represents coupling between the impurity atoms themselves, *e.g.*, Fe-Fe interactions. This extra coupling term can have either algebraic sign (+/-), representing either ferromagnetic coupling (impurity spins aligned; T_c suppression effect enhanced) or anti-ferromagnetic coupling (impurity spins anti-aligned; T_c suppression effect reduced). The upwards deviation of the T_c vs. [Fe] curve shown in Fig. 2 at the higher concentrations is quantitatively consistent with anti-ferromagnetic coupling between the Fe impurity atoms. (Ref. 5)

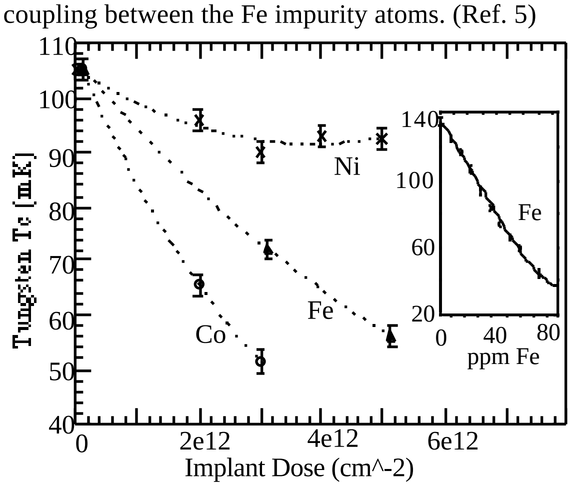

Figure 2. Tungsten T_c vs. implant dose for Ni, Fe and Co. The inset shows a wider range of Fe data, with a fit to the Abrikosov-Gor'kov model, modified to include antiferromagnetic ordering (see text and Ref. 5).

Several samples patterned in a QET geometry were also studied for T_c as a function of Fe atom doping. Three distinct fabrication sequences were tested: (1) fully-patterned QET samples were implanted using a hard-baked photoresist "mask" to protect the Al phonon-collection pads from the ion beam; (2) fully-patterned QET samples were implanted without using resist to protect the Al regions of the QETs; and (3) ion implantation of the active (top) W layer of QETs was performed immediately before photolithographic patterning of the active W film. We found that the T_C-shift for each implanted sample was independent of the choice of the three QET fabrication sequences described above. In addition, we confirmed that the effect of ion dose on T_C-shift was comparable for our patterned (QET) vs. unpatterned W films.

Using the ion implantation technique, we can easily control the T_c of our W films, while keeping the transitions sharp. For successful operation of QETs, however, it is important also that the implantation process does not appreciably affect the critical current or heat capacity of our superconducting films. To study these properties, we measured the current-voltage characteristics of several QETs both before and after implantation. The results were favorable, as can be seen, for example, in Fig. 3. We plan to complete a study of the critical current of our implanted films in the upcoming few months. Direct heat capacity measurements will be made using photons fed through an optical fiber already mounted to our fridge.

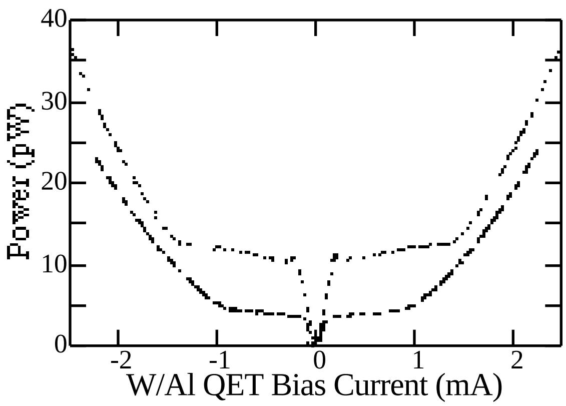

Figure 3. Diagnostic thermal characterization data obtained with (x) unimplanted and (--) implanted QET samples taken from the same patterned wafer. The y-offset between the two curves is consistent with the difference in T_C for the implanted vs. unimplanted samples. The flat region of the power dissipation curves corresponds to the electrothermal feedback region of operation. (See Ref. 6 for a discussion of P vs. I_b plots and other useful QET diagnostics.)

4. Reliability of Technique

The ion implantation technique we have developed for "tuning" superconducting films is reproducible and can be readily applied to films other than W. However, all magnetic species are NOT equivalent in their T_C - suppressing ability. This is evident in Fig. 2, where an equal ion dose of Co, Ni or Fe results in a well-defined, but very different, suppression of T_C.

Modern implanters provide exceptional control over ion species, with single isotope work common. This enables one to effectively "tune" the T_c of a cryogenic detector film while avoiding detrimental radioactive isotopes of a given element. Also, the atomic beam energy is exceptionally well controlled, and ion doses can be specified to 0.01 %.

Currently, the limiting factor in our ability to tune precisely the T_c of any given W film on the first try (± few mK) is our inherent uncertainty in the T_c of the starting material (*i.e.*, the unimplanted film). Over the past year, we have measured a range of T_C's of the as-deposited (un-implanted) films of ≈ 70 mK to 150 mK, although the transition width for any given film deposition is narrow (≈ few mK). Typically, the T_c of as-deposited films from one run to the next is fairly constant (± ≈ 5 mK) for several months at a time. We attribute the occasional variation in T_c of our as-deposited films from one deposition to the next to the sporadic appearance of impurities in our shared-facility sputtering system.

5. Summary

We have demonstrated a robust, yet simple, method for adjusting the T_c of superconducting W films using ion implantation of magnetic ions.

6. Acknowledgments

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7. References

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