Abstract

In the next decade, new ground-based Cosmic Microwave Background (CMB) experiments such as Simons Observatory (SO), CCAT-prime, and CMB-S4 will increase the number of detectors observing the CMB by an order of magnitude or more, dramatically improving our understanding of cosmology and astrophysics. These projects will deploy receivers with as many as hundreds of thousands of transition edge sensor (TES) bolometers coupled to Superconducting Quantum Interference Device (SQUID)-based readout systems. It is well known that superconducting devices such as TESes and SQUIDs are sensitive to magnetic fields. However, the effects of magnetic fields on TESes are not easily predicted due to the complex behavior of the superconducting transition, which motivates direct measurements of the magnetic sensitivity of these devices. We present comparative four-lead measurements of the critical temperature versus applied magnetic field of AlMn TESes varying in geometry, doping, and leg length, including Advanced ACT (AdvACT) and POLARBEAR-2/Simons Array bolometers. Molybdenum-copper bilayer ACTPol TESes are also tested and are found to be more sensitive to magnetic fields than the AlMn devices. We present an observation of weak-link-like behavior in AlMn TESes at low critical currents. We also compare measurements of magnetic sensitivity for time division multiplexing SQUIDs and frequency division multiplexing microwave rf-SQUIDs. We discuss the implications of our measurements on the magnetic shielding required for future experiments that aim to map the CMB to near-fundamental limits.

Keywords
Superconducting detectors, Transition Edge Sensors, Bolometers, SQUIDs, Weak-link, Proximity Effect, Magnetic field dependence

1 Introduction

Current Cosmic Microwave Background (CMB) experiments depend on arrays of superconducting transition edge sensor (TES) bolometers coupled to Su-
perconducting Quantum Interference Device (SQUID)-based readout systems to make measurements of microwave wavelength photons. New generations of these technologies are being developed for upcoming experiments, including CCAT-prime, a 6-meter aperture off-axis submillimeter telescope that will be located at 5,600 m elevation on Cerro Chanjnantor in Chile [1], and Simons Observatory [2], an array of new CMB telescopes that will be located at 5,200 m elevation on Cerro Toco in Chile, near the Atacama Cosmology Telescope (ACT) [3], CLASS [4], and Simons Array [5]. These technologies are also relevant for CMB “Stage-4” (CMB-S4), the next generation ground-based CMB project [6] which will enable tests of inflation and provide constraints on dark energy and fundamental particle physics.

The superconducting devices on which current and future CMB surveys depend are sensitive to magnetic fields, and the response of the devices to external magnetic fields needs to be understood. When a magnetic field is applied to the plane of the superconducting film of a TES, for example, the critical temperature of the device shifts, which can affect the performance of the device in multiple ways. Sources of magnetic fields that can interfere with TESes and SQUIDs include Earth’s DC field as well as AC fields produced by nearby instrumentation and the telescope’s motion through Earth’s field. If the devices are not shielded sufficiently, exposure to magnetic fields could result in the presence of artifacts in the CMB temperature and polarization maps that could negatively impact science goals and are difficult to remove. Device performance in the presence of magnetic fields is difficult to compute analytically, rendering direct measurements necessary to understand the behavior of these devices. Information about SQUID and TES magnetic sensitivity will motivate magnetic shielding design considerations for future CMB experiments.

One technique of fabricating TES bolometers uses thin films of aluminum doped with manganese impurities to reduce the $T_c$ of the film from $\sim$1K to $\sim$100 mK. This approach has advantages in the simplicity of fabrication and appears to result in reduced sensitivity to magnetic fields when compared to Mo-Cu bi-layer fabrication techniques [7]. AlMn TESes can also be fabricated on single wafers with high uniformity, as are currently being used for Advanced ACTPol (AdvACT) and POLARBEAR-2/Simons Array [8, 9]. These features along with demonstrated performance in the field make AlMn TESes an attractive choice for next generation CMB experiments. Multiplexing readout of TESes is currently achieved with either time division multiplexing (TDM) using DC SQUIDs [10] or frequency division multiplexing (FDM) using DC SQUIDs, MHz LC resonators [11] or inductive coupling to rf-SQUIDs (μMUX) [10] [12] [13]. In this work, AlMn TESes and molybdenum copper bi-layer TESes (from ACTPol), TDM DC SQUIDs, and FDM μMUX rf-SQUIDs are tested for magnetic sensitivity.

The treatment of magnetic shielding currently varies for CMB experiments. Instruments for ACT rely on TDM readout and have used multiple layers of Cryoperm and Amunetal 4K7 in combination with individual niobium shields for SQUID series arrays [14] [15]. Experiments using MHz FDM readout systems, like POLARBEAR and SPT-3G, have mounted SQUIDs on Nb foil surrounded by a small cryoperm sleeve [16]. Appropriate shielding factors will be motivated by experimental testing of these SQUIDs and TESes combined with simulated telescope observations. This information will be combined with simulations of
shield geometries in order to develop mechanical designs for the cryogenic receivers currently under development.

2 Magnetic sensitivity of TES critical temperatures

We take resistance measurements of TESes varying in geometry, material, doping, manufacturer, and leg length using four-lead measurements, which precisely read out the low resistance values and critical temperatures by eliminating the lead and contact resistances from the measurements. TES chips were wire bonded and affixed with rubber cement to a printed circuit board stripped of solder and mounted to the coldest (100mK) stage of a dilution refrigerator (DR). A set of 1 m diameter Helmholtz coils applied DC magnetic fields up to 10.5 Gauss to the outside of the DR. The fields were attenuated by a 30 cm diameter, 85 cm long half-open cylindrical room temperature mu-metal magnetic shield inside the DR. Shielding factors were measured by using a gaussmeter to measure the field between the coils with and without the shield in place, and were determined to be $380 \pm 20$ in the horizontal direction (for the SQUID and weak-link-like behavior measurements) and $2.9 \pm 0.2$ in the vertical direction (for the four-lead measurements) at the locations of our detectors. The series array modules used for TDM readout are additionally shielded in a niobium box. Resistance vs. temperature data was acquired for each TES at various values of applied magnetic field, using a lakeshore AC resistance bridge with a low-noise preamplifier and ruthenium oxide thermometry with low magnetic field-induced errors.

We tested TESes from ACTPol chips [17], AdvACT 150 GHz (HF) chips, AdvACT 30 GHz (LF) chips [9], TES test chips with AlMn films of varying geometries, and POLARBEAR TES test chips [18] with varying leg lengths for magnetic sensitivity. We chose excitation currents for the four-lead measurements to balance noise reduction in the measurements with minimizing power dissipation through the TES bolometers (Table 1). For each device and at each applied magnetic field value, we took $T_c$ to be the temperature value at 50% $R_N$, where $R_N$ is the resistance value measured 2 mK above the last superconducting datapoint in the resistance vs. temperature curve at zero applied magnetic field. A plot of $T_c$
Fig. 2: $T_c$ vs. $B$ for tested TESes (AdvACT (AA), ACTPol (AP), POLARBEAR (PB), AdvACT LF (LF)) and parabolic fits to the data points. Dashed and solid lines indicate measurements of different devices of the same type. Coefficients from parabolic fits are listed in Table 1.

| TES     | Leg w x l [µm] | AlMn Area  | Ex. Curr. | $T_{C,B=0}$ [K] | $w \frac{dI}{dB}$ [µA/G] | $\frac{dI}{dB}$ [µA/G] |
|---------|----------------|-------------|-----------|-----------------|--------------------------|--------------------------|
| PB5     | 4, 10 x 500    | 610 µm²     | 100 nA    | 0.423           | 7.3e-6                   | 4e-5                     |
| PB7     | 4, 10 x 700    | 610 µm²     | 100 nA    | 0.423           | 9.7e-6                   | 5e-5                     |
| PB15    | 4, 10 x 1500   | 610 µm²     | 100 nA    | 0.416           | 1.3e-4                   | 5e-4                     |
| AdvACT  | 15 x 61        | 6200 µm²    | 10 µA     | 0.211           | 1.2e-3                   | 1e-1                     |
| AA16    | 20 x 61        | 3300 µm²    | 10 µA     | 0.214           | 1.1e-3                   | 1e-1                     |
| AA37    | 20 x 61        | 11250 µm²   | 10 µA     | 0.208           | 0.6e-3                   | 1e-1                     |
| ACTPol  | 20 x 61        | 9000 µm²    | 10 µA     | 0.171           | 4.2e-3                   | 5e-1                     |
| AA LF   | 10 x 1000      | 6200 µm²    | 10 µA     | 0.159           | 1.0e-3                   | 2e-2                     |
| AA LF   | 10 x 500       | 6200 µm²    | 10 µA     | 0.171           | 0.9e-3                   | 3e-2                     |
| AA LF   | 10 x 220       | 6200 µm²    | 10 µA     | 0.173           | 0.9e-3                   | 5e-2                     |

Table 1: AdvACT (AA), ACTPol (AP), and POLARBEAR (PB) TESes, leg lengths, AlMn (or MoCu for ACTPol) areas, and excitation currents, with parabolic fits in the form of $y = T_{C,B=0} - wx^2$ to $T_c$ vs. $B$ data for each type of tested TES. AA16 indicates an AdvACT test TES with a width of 16.5 µm, and AA37 indicates a width of 37.5 µm. PB TESes have one leg which is 4 µm wide and one which is 10 µm wide. Errors on parameters are taken to be 1.3 mK due to scatter in otherwise identical data points during separate cooldowns, and 20% of sensitivity fit $mK/G^2$ due to fitting error. Estimates of $dI_0/dB$ should be regarded as comparative figures only and are based on an approximation of the sensitivity at $B = 0.05$ G as described in Section 5.

3 Weak-link-like behavior in AlMn TESes

A theoretical model of the physics governing the superconducting phase transition of TES bolometers has yet to be constructed. Experiments have shown that the critical current of square thin-film TESes depends upon the TES geometry vs. applied magnetic field for the tested bolometers is shown in Figure 2 along with parabolic fits to the points. Parameters from the parabolic fits are listed in Table 1. The error bars on $T_c$ are chosen to be 1.3 mK, the standard deviation of a Gaussian fit to the differences in recorded $T_c$ between 18 otherwise identical data points taken over the course of two separate cooldowns for the AdvACT LF chips.
and temperature which can be described in terms of longitudinal proximity effects in the weak-link model of TES films [19]. The critical current of these TESes has been observed to show Fraunhofer-like oscillations in applied magnetic fields, similar to those observed in Josephson junctions [19, 20]. A Ginzburg Landau model can be used to explain measurements of $I_c(T)$ for TESes considered to be SN’S proximity induced weak-links, measured in bath temperatures near $T_c$ [19–21]. These measurements have previously been made for MoAu and MoCu bilayers, among others [22]. In this work, we present observations of weak-link-like behavior in AlMn TESes.

Using the same experimental field setup described in Section 1, magnetic fields are applied perpendicular to the plane of the TES films. The TES devices tested were most similar to the AdvACT HF TESes (B. in Figure 1). The TESes are read out using the same TDM readout system used in AdvACT with NIST SQUIDs similar to those in [23]. At each value of applied magnetic field or each value of temperature, we perform voltage ramps to get a reading of the critical current $I_c$ at which the TES transitions from superconducting to normal.

Plots of $I_c$ vs. $B$ are shown for three devices in Figure 3. This data was acquired for the TESes at bath temperatures near $T_c$ where the Ginzburg Landau model would apply for the AlMn films. A plot of $I_c$ vs. $T$ for the three devices is shown in Figure 3 along with fits to the data where the Ginzburg Landau model applies. The fits take the form $I_c(T) = a\sqrt{T/T_c} – Te^{-b\sqrt{T/T_c}}$, where $a$ is proportional to the width of the device film and $b$ is proportional to the length [19]. We observe a trend in $a$ consistent with the theory, with $a = 0.50 \pm 0.01 \times 10^6$ µA for the 16.5 µm wide AlMn device (“TES 2”) and $a = 1.00 \pm 0.05 \times 10^6$ µA for the 25 µm wide devices (“TES 1” and “TES 3”).

We observe Fraunhofer-like oscillations in all three tested devices, though the observed oscillations are not consistent in period or decay. The absence of the central peak in the oscillations requires further study. The ability of the Ginzburg Landau model to describe the high temperature data suggests that the behavior observed in these devices agrees with the weak-link model.
Fig. 4: (a): An example of shifts in the V-φ curve of a single TDM SQUID under the influence of applied magnetic field. (b): φ₀/Gauss for resonances on the μMUX chip display a gradient in response across the chip for the Run 1 orientation (red) but not for the Run 2 orientation (black). The top view schematic diagram shows the position of the μMUX chip within the magnetic shield for the two runs along with the applied field directions outside the shield. An upper limit on the magnetic sensitivities of these rf-SQUIDs is taken to be 0.3 φ₀/Gauss.

4 Magnetic sensitivity of μMUX and TDM SQUIDs

To measure the magnetic sensitivity of the TDM SQUIDs described in Section 1, magnetic fields were applied perpendicular to the planes of the SQUIDs. The SQUIDs were mounted in the same MUX board used to read out AdvACT single pixels on the DR’s coldest stage. V-φ curves were acquired for applied various field values using the MCE readout electronics. The shift in the V-φ curves due to the presence of applied fields was averaged for 72 readout channels (Figure 4) and for two applied directions of fields (positive and negative normal). We determine the upper bound on measured sensitivities to be 1.2 φ₀/Gauss.

To estimate the magnetic sensitivity of μMUX rf-SQUIDs, magnetic fields were applied perpendicular to the planes of 33 rf-SQUIDs on a single NIST μMUX 14a chip and time-ordered data was taken on each rf-SQUID using a ROACH readout system, returning an average phase response of the μMUX channel in radians as a function of applied magnetic field. Data was taken for two different orientations of the chip within the magnetic shield (Figure 4). A gradient in response to the magnetic field was seen across the μMUX chip in the first orientation, with a minimum in sensitivity at the central rf-SQUIDs and maxima at the ends of the chip (Figure 4). This slope is thought to be due to the sensitivity of the gradiometric winding of the SQUID coils to gradients in magnetic field as a function of position inside the DR, since the same response was not observed in the second orientation of the chip within the shield. We place an upper limit on magnetic sensitivities of 0.3 φ₀/Gauss for the μMUX rf-SQUIDs.

5 Shielding considerations for future CMB experiments

Magnetic shielding designs for upcoming CMB experiments should be driven by device sensitivities such as those presented in this work in order to minimize cost and extent of mechanical design. Using the measurements obtained for our tested TESes and SQUIDs, we can convert detector and readout magnetic sensitivities into estimates of the change in detector bias current per applied magnetic field by using \( \frac{\delta I_0}{\delta B} \approx \frac{G(T,\omega_B)}{V_0} \), where \( w \) is our parameter fit listed in Table 1, \( B \) is
a magnetic field value offset from zero (taken to be 0.05G, or \(\sim 1/10\) Earth’s magnetic field) and \(G\) is the thermal conductance of the TES \([24]\). Using appropriate values for the types of TESes tested, we obtain sensitivity estimates in detector bias current and list them in Table 1 \([25, 28]\). Because these sensitivities are estimated at an arbitrary value of magnetic field, and the true relationship between \(dB\) and \(dI_0\) is more complex than fully represented in this estimate, these numbers should be treated as a comparative guide to relative sensitivities.

A similar calculation can be done to convert the TDM SQUID sensitivity estimate into a predicted detector current response as a function of magnetic fields inside the shielding, using conversion factors particular to our readout setup \([24]\). For our upper limit sensitivity, 1.2 \(\phi_0/\text{Gauss}\), we estimate \(\delta I_{0\text{ eff}}/\delta B \approx 100 \mu\text{A}/\text{G}\), three orders of magnitude larger than the estimates for our TESes. For the \(\mu\text{MUX}\) rf-SQUIDS, with an upper limit sensitivity of 0.3 \(\phi_0/\text{Gauss}\) due to the gradiometric response of the rf-SQUIDS, \(\delta I_{0\text{ eff}}/\delta B \approx 4 \mu\text{A}/\text{G}\).

Based on these measurements, we consider order of magnitude estimates for required shielding factors. These factors would ideally take into account several phenomena that are not considered here, including the rate at which the instrument is rotated through Earth’s field, whether gradients inside the shields result in significantly different pickup levels on different SQUIDs, and how non-common mode magnetic pickup could generate spurious systematics; however, those phenomena are beyond the scope of this study. In this study we consider that the detector white noise level for TDM and \(\mu\text{MUX}\) readout is roughly \(10^{-10}\) A/\(\sqrt{\text{Hz}}\) \([23]\).

If we aim to maintain pickup below this noise level and the instrument sweeps through 1/10 of Earth’s field (0.05 G) in one second, this would require a shielding factor of roughly 50,000 for TDM and 2,000 for \(\mu\text{MUX}\). If we use a similar scaling approach for the TES pickup in a background DC field comparable to Earth’s field, we find smaller required shielding factors for the TESes; however, as described above, the true \(\delta I_0/\delta B\) relationship is more complex for TESes than SQUIDs and warrants further study.

6 Conclusion

We have made measurements of the magnetic sensitivity of AlMn and MoCu TESes, varying in geometry, leg length and doping, TDM SQUIDs, and \(\mu\text{MUX}\) rf-SQUIDs. The MoCu ACTPol TESes are the most sensitive to magnetic fields, followed by the AdvACT AlMn TESes, with the POLARBEAR AlMn TESes being the least sensitive. The primary source of the differences between the sensitivities of the AlMn TESes is not yet clear, though we note that the POLARBEAR and AdvACT TESes do have significantly different areas, critical temperatures, doping, and thicknesses. An observation of weak-link like behavior in AlMn TESes at low critical currents was made. Further study could help inform how this behavior impacts detector parameters. We used order of magnitude pickup and noise estimates for AlMn TESes, TDM SQUIDs, and \(\mu\text{MUX}\) SQUIDs to motivate shielding factors that would suppress a 0.05 G field excursion for TDM and \(\mu\text{MUX}\) readout to below the detector white noise level. These results will inform the design of magnetic shielding for upcoming CMB experiment receivers such as those for CCAT-prime, Simons Observatory, and CMB-S4 and thereby help enable precision measurements of the CMB sky.
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