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Antenna-coupled transition-edge hot-electron microbolometer

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Abstract

We are developing a new type of antenna-coupled superconducting bolometric detector for millimeterwave and sub-millimeterwave astrophysics. In this design, a planar antenna couples radiation from free space to the electron system in a small absorber. The absorber is in thermal contact with a small Transition-Edge Sensor (TES), which serves as a thermistor. At sub-Kelvin temperatures the thermal isolation between the electrons and the lattice in metals causes the incoming radiation to heat the normal electrons in the absorber and the TES without the need for micromachined thermal isolation structures. We call these detectors Transition-edge Hot-electron Microbolometers and are optimizing them for observations of the cosmic microwave background. The small volume ($\sim 5\ \mu m^3$) of the absorber and TES produces a short thermal time constant that facilitates rapid scanning of the sky. These devices can be coupled to arrays of dual-polarization antennas in large format focal planes and other optical systems. We have constructed a scale model of a candidate planar antenna and tested a Mo/Cu proximity effect TES and Cu absorbers.

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Keywords: Microbolometer; Hot-electron; Superconducting sensors

1. Introduction

The anisotropy in the temperature and polarization of the cosmic microwave background (CMB) can tell us a lot about the evolution of the early universe. Recently the WMAP satellite [1] has mapped the anisotropy of the CMB with exceptional precision over the full sky. WMAP [2] and DASI [3] have detected the long-anticipated faint polarization signal as well. Further measurements of the CMB polarization promise to improve our knowledge of the cosmological parameters and directly probe the era of inflation. Since the polarization signals are so much smaller than the temperature anisotropy of the CMB, large numbers ($\sim$1000' s) of detectors operating near the background limit from space, balloons, or good ground-based sites are required.

2. Hot-electron Microbolometer

Promising candidates for this application include bolometers that use a Transition-Edge Sensor (TES) as a thermistor [4,5]. Here we

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describe a type of TES bolometer called a Transition-edge Hot-electron Microbolometer (THM). In the THM the electrons in a small volume of normal metal absorber are heated by radiation. The weak coupling between the electrons and the phonons in metals at low temperature produces a large temperature rise in the electrons for a small rise in incident power [6]. Antenna coupling [7] allows the thermally active region to be much smaller than a wavelength. Hot-electron Microbolometers have been made in which a TES simultaneously acts as the absorber and detector; Gershenson et al. [8] have demonstrated the hot electron phenomenon in ultrathin films and call this a Hot-electron direct Detector (HEDD). The THM [9] is similar but separates the absorber from the TES (Fig. 1). This separation allows flexibility in optimizing the design. In particular, the absorber resistance can be varied to match the impedance of transmission line or antenna (10's of Ω) and the TES impedance can match the SQUID amplifier readout ($<1\Omega$).

An optimization of the THM with optical efficiency of 0.5 and 30% bandwidth at 90 GHz for low-background CMB observations gives $\mathrm{NEP} = 5.8 \times 10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ and a time constant $\tau \approx 5\ \mu\mathrm{s}$ [9]. The sensitivity to a 2.7 K Planck spectrum is $\mathrm{NET} = 25\ \mu\mathrm{K}\sqrt{s}$. Advantages of TES

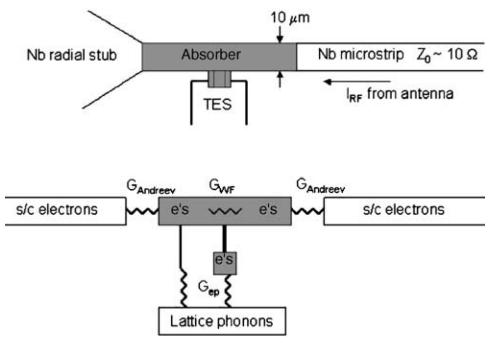

Fig. 1. Top shows a resistive normal metal film terminating a microstrip transmission line with an impedance of ~10 Ω. The film overlaps an adjacent TES to form electrical and thermal contact with it. Bottom is the thermal circuit for the THM. To treat the electrons as isothermal, we require the internal thermal conductivity of the absorber (and TES) to be much greater than the electron–phonon conductivity. $G_{\mathrm{e-ph}}$ is chosen so that the thermal fluctuations in the thermal link are small compared to the photon noise from the observed source.

microbolometers include: (1) Lithographic fabrication, suitable for large arrays of matched detectors, (2) Small size, (3) Speed, which is required for rapid scans, and (4) Focal plane processing: the devices are easily coupled to a variety of planar antennas and transmission line circuits.

3. Fabrication

We have been fabricating [10] TES devices by depositing bilayers of Mo/Cu on Si wafers coated with a thin silicon nitride layer. The thicknesses of the Mo and Cu layers determine the T_c [11] of the superconducting bilayer by the proximity effect. Both Mo and Cu layers are deposited by e-beam evaporation: a 40 nm layer of Mo is first deposited at a temperature of ~500°C, and a 170 nm, Cu layer is then deposited over it at about 100°C, without breaking vacuum. The bilayer is then etched with both dry and wet methods to produce TES devices (Fig. 2). The Cu layer is wet etched to define the two sides of a square TES device. Then by using the Cu layer as a mask the exposed Mo layer is plasma etched. In subsequent steps Cu and Mo layers are wet etched to define the remaining sides of the device and the superconducting leads to the device. A Cu absorber that terminates a Nb transmission line is then deposited to overlap the TES thermistor. We are testing other absorber materials (Bi) as well.

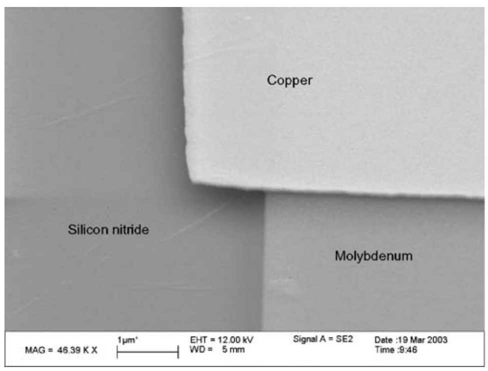

Fig. 2. SEM of the Mo/Cu edge of a test TES. Plasma etching undercuts the Mo layer by ~300 nm, and produces a Cu overhang which eliminates superconducting shorts along the sides of the device.

4. Planar antenna

A planar antenna couples radiation from free space, through a superconducting transmission line, to the absorber of the bolometer. Planar dual-slot antennas are particularly useful because they produce nearly Gaussian beams. A pair of dual-slot antennas oriented at 90° to each other will couple to two orthogonal polarizations, ideal for polarization measurements. Several groups [12,13] have developed designs to couple TES devices to polarization-sensitive planar antennas. We plan to fabricate the slot antenna on a Si wafer coated with thin layers of superconducting Nb. The groundplane and the microstrip transmission lines are separated by a layer of insulator (SiO). The beam width of the planar antenna can be adjusted by placing the antenna on a thick hyperhemispherical silicon lens [14]. We simulated a single slot antenna operating at 100 GHz coupled to a microstrip line and built a scale model that operates around 8.7 GHz.

5. Applications

Planar antenna-coupled THMs are good candidates for measuring the polarization of the CMB. By coupling radiation from two orthogonal slot antennas to two THMs one can measure the polarization signal in one pixel in a focal plane array. Another application of the THM is for interferometry. For example, the Millimeter-wave Bolometric Interferometer (MBI) [15] is a short-baseline ($\sim$15 cm) adding interferometer designed to search for CMB "B-modes" from the ground (Fig. 3). Interferometers can measure the CMB power spectrum directly without scanning the sky, or differencing signals from different detectors.

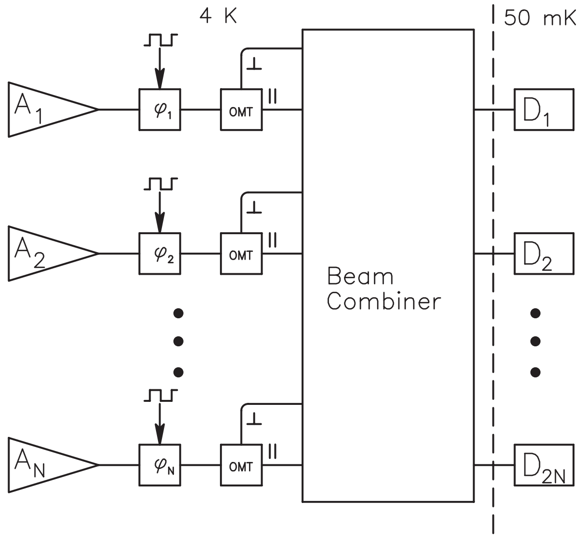

Fig. 3. Bolometric interferometer schematic. The signal from each antenna in an array is phase modulated and split into two orthogonal components by an orthomode transducer (OMT). The resultant signal amplitudes are then combined (beam combiner) and detected by THMs. Signal amplitudes from all of the N horns appear at the $2N$ combiner outputs. The detection process forms products of amplitudes from all possible baselines. The beam combiner, phase modulator, and OMT can be formed with superconducting microstrip transmission lines that couple naturally to the THM.

Acknowledgements

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