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Design, fabrication, and testing of a TiN/Ti/TiN trilayer KID array for 3 mm CMB observations

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Abstract Kinetic inductance detectors (KIDs) are a promising technology for astronomical observations over a wide range of wavelengths in the mm and sub-mm regime. Simple fabrication, in as little as one lithographic layer, and passive frequency-domain multiplexing, with readout of up to $\sim$1000 pixels on a single line with a single cold amplifier, make KIDs an attractive solution for high pixel-count detector arrays. We are developing an array that optimizes KIDs for optical frequencies near 100 GHz to expand their usefulness in mm-wave applications, with a particular focus on CMB B-mode measurement efforts in association with the QUBIC telescope. We have designed, fabricated, and tested a 20-pixel prototype array using a simple quasi-lumped microstrip design and pulsed DC reactive magnetron sputtered TiN/Ti/TiN trilayer resonators, optimized for detecting 100 GHz (3 mm) signals. Here we present a discussion of design considerations for the array, as well as preliminary detector characterization measurements and results from a study of TiN trilayer properties.

Keywords Kinetic Inductance Detector, CMB, Titanium Nitride, Trilayer

1 Introduction

Kinetic Inductance Detectors (KIDs) [1] are a highly-scalable, highly-multiplexable superconducting detector technology which shows promise as a transition edge sensor (TES)-alternative in very high-pixel-count arrays for mm and sub-mm astronomy. KIDs work on the following principle: Light is absorbed into a high-kinetic inductance superconducting planar resonant LC circuit. Incident photons of sufficient energy break Cooper pairs in the superconductor, increasing the kinetic inductance, which shifts the resonance frequency, phase, and magnitude.

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Passive frequency domain multiplexing of up to $\sim$1000 detectors[2] on a single line with a single cold amplifier can be achieved by tuning each resonator in the array to a slightly different resonant frequency, creating a "comb" of resonances within the readout band. In contrast to TESs, no SQUIDs are required and complete arrays can be fabricated with as little as a single lithographic layer. We have shown previously[3] that KIDs and TESs have comparable noise limits at 100 GHz with practical assumptions for optical loading, TES bias power, and bath temperature.

Cosmic microwave background B-mode polarimetry is one area in which KIDs may provide a benefit over other types of detector arrays. Because of the small expected signal size, large arrays of highly sensitive detectors will be required to either discover or rule out primordial B-modes. Next-generation focal planes in this field will require as many as 100,000 pixels. However, as pixel counts rise, TES arrays pose an increasing logistical and financial burden as a result of their limited SQUID-based multiplexibility and large number of lithographic layers, which are complex and costly to build. Because of the ability to easily multiplex KIDs in the frequency domain, there are substantial cost and throughput advantages over TES for large-format architectures. As part of determining whether KIDs are a good alternative to TESs for CMB and other mm-wave applications, we are developing a prototype 100 GHz KID array using a simple titanium nitride / titanium / titanium nitride (TiN/Ti/TiN) trilayer quasi-lumped element direct-absorbing design. Due to bath temperature constraints, we require the resonator material to have a critical temperature (T_c) greater than about 0.8 K. The signal photons must have $h\nu > 2\Delta$, where Δ is the superconducting gap energy, requiring a T_c below 1.3 K. There are few materials with T_c in this range, and even fewer that meet other requirements for a sensitive KID, such as high normal-state resistivity and long quasiparticle recombination time constant, τ. Molybdenum was considered[4], but was ruled out due to low internal quality factor. Titanium nitride is a material that has been popular in the KID community for some time, due to its high resistivity, large value of τ, and tunable T_c. Moving forward from the Mo devices, monolayer TiN was investigated as a candidate material, however in order to engineer the T_c, a TiN/Ti/TiN trilayer technique, similar to recent work at NIST[5], was used.

In the sections that follow, we summarize the results of our efforts to develop a TiN/Ti/TiN trilayer material suitable to this application. Additionally, we discuss the design of a prototype 100 GHz detector array using the trilayer material, and finally we present preliminary results of tests of the prototype trilayer detector array under both dark and 100 GHz-illuminated conditions.

2 Measurement technique

Measurements were conducted using an ADR pre-cooled with a pumped LHe bath. The system has a typical base temperature of 150 mK. Detectors are illuminated with W-band (75-110 GHz) radiation using a room-temperature microwave source which is coupled to the detectors via a novel Stycast-epoxied coaxial vacuum feedthrough. The signal is carried via 68.5 cm of cupronickel coaxial cable through the vacuum wall of the dewar, to heatsinking clamps on the liquid nitrogen and liquid helium stages, and couples to a coax-waveguide transition which powers a horn antenna. The horn antenna illuminates a rexolite lens which focuses the radiation on the bare focal plane. The coaxial cable provides 34 dB of broadband attenuation. The coaxial line provides sufficient attenuation to harmonic frequencies generated by the multiplier chain that generates the W-band signal. A room temperature vane attenuator is used to make fine (up to several dB) adjustments to the W-band signal to control the optical power at the detector.

A Stycast epoxy hermetic feedthrough similar to that used for the microwave line is also used for the coaxial cables used for the RF readout. NbTi coaxial cables in conjunction with bias tees are used for thermal isolation and heat-sinking, respectively, to carry the signal onto and off of the 150 mK stage and cold amplification is provided by a SiGe amplifier on the liquid helium stage. The primary components of the room temperature readout electronics are a vector network analyzer, a chain of room temperature low-noise amplifiers, and an IQ demodulator. The VNA is used to provide the carrier power and either the VNA or the IQ demodulator is used to detect the response. This configuration is used for measurements of both the TiN trilayer test resonators and the prototype detector array.

3 TiN Material Study

In an effort to better understand the properties of the TiN/Ti/TiN trilayer films being produced at NASA Goddard, and to identify a specific recipe suitable for our detector application, we undertook a brief study of several trilayer recipes. For each recipe, two samples were tested: a DC 4-wire test structure used to check normal state sheet resistance and critical temperature, and a 16-element resonator test array. The 16-resonator test array is made from a mask developed and regularly used for materials testing by the detector development group at GSFC. It features 16 blind RF resonators, each with a different coupling quality factor. The single-side, single-layer fabrication limits confounding effects on film properties from processing steps. Both the 4-wire test structure and 16-resonator test array chips were photolithographically patterned on TiN/Ti/TiN-coated Si(001) substrates. The TiN/Ti/TiN trilayers were etched with an inductively coupled Cl-based plasma, which etches a small amount of underlying Si. Wet, Cl-containing etchants were also explored. However, whereas the TiN/Ti/TiN was removed with these techniques, a resistive surface layer which prevented microwave characterization of the trilayer always remained.

Recipe TiN/Ti/TiN	T_c [K]	RRR	R_s [Ω /sq]	Highest Q observed
3/8/3 nm	1.22	1.3	68.0	
3/8/3 nm *	1.26	1.3	58.7	
3/10/3 nm	1.18	1.4	53.7	$\sim$10,000
3/10/3 nm *	1.16	1.2	44.7	$\sim$50,000
3/12/3 nm *	1.16	1.3	34.4	

Table 1: Test results from various TiN trilayer recipes. Asterisks (*) indicate recipes in which the Si was nitridized prior to deposition of the first TiN layer.

All trilayer samples studied were prepared with 3 nm thick stoichiometric TiN top and bottom layers. Pulsed DC reactive magnetron sputtered samples were prepared at room temperature with 8, 10, and 12 nm thick Ti center layers inside a chamber with base pressure $\sim 2 \times 10^{-9}$ Torr and an O_2 partial pressure $< 1 \times 10^{-10}$ Torr. The substrates were reversed biased during deposition. Additionally, samples were prepared both with and without a Si surface nitridization step, in which the H-terminated Si(001) substrates were RF plasma cleaned in a Ar+N2 atmosphere, prior to deposition of the first TiN layer. 5 samples were studied (Tab. 1). For these samples, Si surface nitridization appears to have a minimal effect on the critical temperature and RRR, and a small effect on sheet resistance. However sample size was extremely small and more work is required to draw any conclusions. Unexpectedly, the thickness of the center Ti layer had an insignificant effect on the critical temperature. This suggests that the trilayer may not be fully proximitized, perhaps due to extremely small grain size (<50 nm) of the materials. While the film properties of the final array appear to be broadly stable on the scale of months, with the arrays stored in a nitrogen-purged dry box with excursions in air, we have observed oxidization of 5 nm samples of similar TiN recipes during standard processing steps such as O_2 ashing, and it is possible that rather than a TiN/Ti/TiN trilayer, we actually have a Ti/TiN bilayer capped with titanium oxynitride, which could explain the incomplete proximitization. Future work will more thoroughly investigate the reason for incomplete proximitization. Only resonator chips from the samples with 10 nm Ti layers were tested for quality factor because of limited RF testing capacity and because they had sheet resistances near the target for our existing photolithography mask. Of the two, the nitridized sample exhibited much higher internal quality factor. Sample size was too small to draw conclusions, however if this trend continues with a larger data set, this would suggest that the surface layer at the Si/TiN interface may contribute to the loss in the resonator. The nitridized 3/10/3 nm TiN/Ti/TiN recipe was selected for detector fabrication.

4 Detector Design and Fabrication

Detectors were designed in an effort to create a proof-of-concept prototype for KIDs as detectors for CMB polarimetry observations in the 3 mm (100 GHz) band. We are specifically motivated by the design constraints for the QUBIC telescope[6], however we have made an effort to keep the design as simple and as broadly applicable as possible.

The pixels are superconducting resonators consisting of an interdigitated microstrip capacitor coupled to a microstrip meandered inductor with filling fraction designed to match efficiently to free space (Fig. 1, left). The resonator sits on the front (illuminated) side of a silicon wafer with custom thickness chosen to be 1/4 λ. The back side of the wafer is coated with a thick unpatterned layer of niobium which serves three purposes: it is an integrated quarterwave backshort for optical coupling, a groundplane for the microstrip resonators and readout line, and provides isolation from the lossy copper chip holder. We have calculated that the optical coupling design should give about 70% peak absorption efficiency near 110 GHz, with a FWHM of about 20 GHz, based on the Mattis-Bardeen formula for surface impedance and our measured T_c of 1.16 K. The detectors are read out between 385 MHz and 475 MHz. We estimate the expected sensitivity of these detectors to be about $5 \times 10^{-18} W/\sqrt{Hz}$ at optical load < 10 fW, and less than a factor of 2 above the photon noise limit of $1 \times 10^{-17} W/\sqrt{Hz}$ with a 1 pW load. A measurement of the actual sensitivity of our devices will be presented in a future publication.

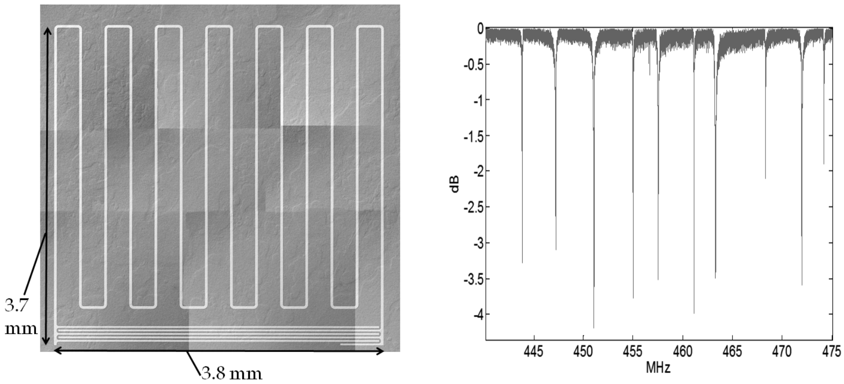

Fig. 1: **Left:** Composite micrograph of one resonator from the prototype detector array. **Right:** S_{21} measurements of several un-illuminated resonators at a bath temperature of 155 mK, with -90 dBm carrier power at the input to the chip.

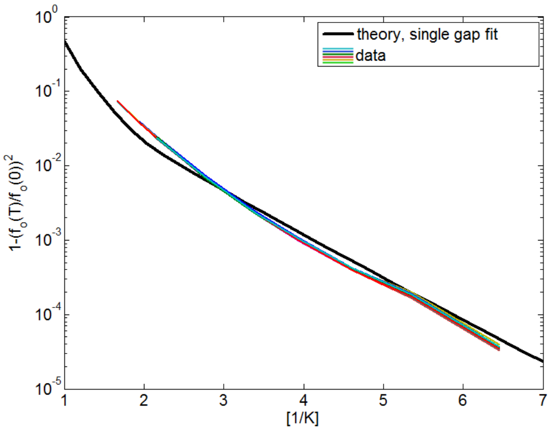

Fig. 2: (Color online) Dependence of resonator center frequencies on bath temperature. Heavy black line is a fit from a single-gap Mattis-Bardeen model with a kinetic inductance fraction α=0.5 and a gap of Δ=105 μeV, significantly lower than the 176 μeV expected from a simple BCS model. The single gap model is a poor fit to the data; additional measurements will be required to determine whether a double-gap, broadened gap, or other model is the best fit.

Fabrication was carried out in the NASA Goddard Detector Development Laboratory. Processing includes three photolithographic layers: TiN/Ti/TiN resonators, Au heatsinking pads, and an Nb layer which comprises the readout microstrip line and a single pixel with the same geometry as the trilayer pixels, which serves as a blind diagnostic resonator. Additionally, there is an un-patterned layer of Nb on the backside of the wafer.

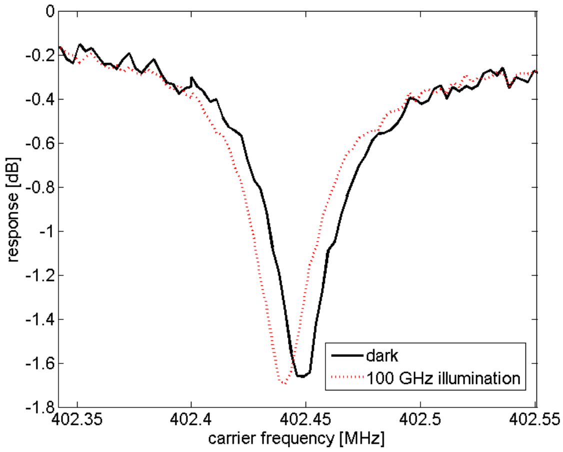

Fig. 3: (Color online) Response of resonator 5 to 100 GHz illumination of roughly -60 dBm (uncalibrated source). Resonance is under-coupled due to limitations on the number of fabrication iterations. Ongoing work will study lower illumination powers more consistent with what the detectors would see in an actual CMB-observing instrument.

5 Measurements

The detector array was cooled to a 155 mK base temperature. Resonator center frequencies and quality factors were measured at several temperatures between 155 mK and 600 mK (Fig. 1, right). Internal quality factors up to 193,000 were observed at base temperature, however order-of-magnitude variations in internal quality factor across the chip remain unexplained. A readout power of about 1 pW was used for these measurements. As expected for TiN-based resonators, the response of resonator center frequency to changes in bath temperature does not match a basic single-gap Mattis-Bardeen model (Fig. 2). Further work will be required to determine whether the bath temperature response behavior is consistent with a double-gap, broadened gap, or other model.

Initial optical measurements show a response to W-band illumination (Fig. 3). Ongoing work seeks to calibrate the actual illumination power and to understand the response in detail.

6 Conclusions

We have produced TiN/Ti/TiN trilayer material with high enough sheet resistance and low enough T_c to permit efficient coupling to W-band radiation using a solid silicon substrate as a quarter-wave backshort spacer. The measured Q_i for our material and resonator design is sufficiently high for application to CMB polarimetry at 100 GHz, based on theoretical expectations, and we have observed a photoresponse at 100 GHz. Analysis and calibration of the photoresponse data is ongoing.

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