Photon-noise limited sensitivity in titanium nitride kinetic inductance detectors

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We demonstrate photon-noise limited performance at sub-millimeter wavelengths in feedhorn-coupled, microwave kinetic inductance detectors (MKIDs) made of a TiN/Ti/TiN trilayer superconducting film, tuned to have a transition temperature of 1.4 K. The lumped-element detector design enables dual-polarization sensitivity. The devices are fabricated on a silicon-on-insulator (SOI) wafer. Micro-machining of the SOI wafer backside creates a quarter-wavelength backshort optimized for efficient coupling at 250 μm. Using frequency read out and when viewing a variable temperature thermal source, we measure device noise consistent with photon noise when the incident optical power is >1 pW, corresponding to noise equivalent powers > 4×10⁻¹⁷ W/√Hz. This sensitivity makes these devices suitable for broadband photometric applications at these wavelengths.

Keywords: kinetic inductance detector, MKID, TiN, sub-millimeter, polarimeter, photon-noise

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Microwave kinetic inductance detectors (MKIDs) are superconducting pair breaking devices currently in development for a broad range of applications. Making use of high quality factor resonators, MKIDs multiplex in the frequency domain and thus scale to large-format arrays. MKIDs are the implemented or planned detector technology for several sub-millimeter instruments.

The fundamental limit of the sensitivity of a sub-millimeter photon integrating detector is set by the photon fluctuations from the source under observation, which is referred to as the photon-noise limit or background limit. The noise equivalent power (NEP) of photon fluctuations from a narrow bandwidth source can be expressed as

\[ \text{NEP}_{\text{photon}} = \sqrt{2P\Phi \nu (1 + m\eta)}. \] (1)

The first term describes Poisson shot noise. \( P \) is the optical power, \( h \) is Planck’s constant, and \( \nu \) is the observation center frequency. The second term describes photon bunching. \( m \) is the occupation number per mode, and \( \eta \) is the efficiency from transmission to detection of one electro-magnetic mode. MKID detectors are also limited by generation-recombination noise \(^9,10\). In the limit of photon dominated quasiparticle production \(^11\),

\[ \text{NEP}_{\text{GR}} = \sqrt{2P\Delta/\eta_{ph}}. \] (2)

Here \( \Delta \) is the superconducting energy gap and \( \eta_{ph} = 0.57 \) is the efficiency of converting photons to quasiparticles \(^12\). Under optical loading, generation-recombination noise is negligible so long as \( \xi \equiv \Delta/\eta_{ph}h\nu \ll 1 \), which for this work \( \xi = 0.09 \).

In recent years, the sensitivity of MKIDs has increased. Photon-noise limited performance has been achieved in aluminum MKIDs at 1.5 THz \(^{13}\) and 350 GHz \(^{14}\) at optical power levels suitable for spectroscopy (\( P < 1 \) pW ), and at 150 GHz \(^{15}\) at optical powers relevant for ground-based photometry. Photon shot noise has been detected \(^{16}\) at 857 GHz in devices made of titanium nitride \(^{17}\) at \( P \sim 120 \) pW, suited to ground-based photometry.

As the superconducting material in kinetic inductance detectors, TiN has a number of potential advantages including low loss \(^{17,18}\), high resistivity, large kinetic inductance fraction and a tunable transition temperature. Recently, the spatial non-uniformity of TiN films with \( T_c < 4 \) K has been solved by use of a new superconducting film, a TiN/Ti/TiN trilayer \(^{19}\). These films show \(< 1\% T_c \) variation across a 75 mm diameter wafer.

In this work, we report a measurement of photon-noise limited sensitivity in kinetic inductance detectors fabricated from TiN/Ti/TiN films and at power loads relevant for balloon-
borne or satellite-based photometry ($1 < P < 20 \text{ pW}$). The devices are feedhorn-coupled to a variable temperature blackbody source. Feedhorn-coupling is a standard approach at sub-millimeter wavelengths, but until now has not been demonstrated with MKIDs. Our measurements show the two traits associated with photon-noise limited detection in MKIDs: the noise spectra are well-described by a Lorentzian function, and the NEP scales as $\sqrt{P}$.

Figure 1 shows the detector array package, detector design and feedhorn-coupled mounting scheme. We grow a 4/10/4 nm thick trilayer film of TiN/Ti/TiN as described in\textsuperscript{20} on a silicon-on-insulator (SOI) wafer. The film is patterned into five $f \sim 1 \text{ GHz}$ lumped-element resonators each comprised of a 5 $\mu\text{m}$ width and spacing interdigitated capacitor (IDC) of total area 0.9 mm$^2$ in parallel with a one-turn inductor. The width of the inductor strip is 8 $\mu\text{m}$, and has a total volume $V = 86 \text{ $\mu$m}^3$. The resonators on the chip couple to a 50 $\Omega$ cross-wafer microstrip feedline, also made of the trilayer. We measure $T_c = 1.4 \text{ K}$ ($\Delta = 1.76k_bT_c = 0.21 \text{ meV}$ is assumed for the generation-recombination noise calculation)},
internal quality factors of 200,000 to 400,000 at bath temperature $T_{bath} = 75$ mK, and coupling quality factors $\sim 30,000$.

The inductor element also acts as the absorber of incident sub-millimeter radiation. It is located $\sim 50$ µm below the 200 µm diameter waveguide output of the feedhorn. The sheet impedance of the inductor is matched to the waveguide impedance and absorbs radiation polarized along the long axis of the inductor. Future designs will include an orthogonal MKID to achieve dual-polarization sensitivity within one spatial pixel. Modeling indicates that dual-polarization versions of the single-polarization device tested here can be designed to have low crosstalk, as long as the two polarization channels have widely separate resonance frequency$^{21}$. Ten micron alignment precision is set by dowel pins and machining tolerance. To ensure high absorption efficiency, we place the absorbing inductor element at one quarter-wavelength distance away from a backshort in silicon. The silicon behind the inductor and capacitor is removed with deep reactive ion etch up to the buried insulator layer of the SOI wafer. This produces a 19 µm thick silicon membrane. The oxide beneath the inductor and capacitor is removed with a CHF$_3$/O$_2$ plasma etch. RF sputter deposition of a 500 nm thick layer of Nb on the backside of the wafer creates a reflective backshort as well as a continuous ground plane.

We mount this package to the 50 mK temperature-controlled stage of a commercial ADR cryostat. The feedhorns view a temperature controlled THz tessellating tile$^{22}$ that has $< -30$ dB reflection at 600 GHz$^{23}$. Using the simulated beam profile of the feedhorns, we calculate $> 99\%$ of the optical throughput goes to the blackbody. The tile is glued into a copper block that is weakly linked to the 3 K stage of the cryostat. We control the load temperature between 3 K and 25 K to $\sim 1$ mK stability by use of a heater and calibrated thermometer.

The optical passband is defined by the 1 THz waveguide cut-off in the feedhorn and a well-characterized 1.4 THz low-pass filter$^{24}$ mounted to the feedhorn array. The in-band power emitted from the load is,

$$P = \int_{\nu_1}^{\nu_2} d\nu \left( \frac{c}{\nu} \right)^2 B(\nu, T) F(\nu),$$  \hspace{1cm} (3)

where we have assumed the single-mode optical throughput $A\Omega = \lambda^2$. $B(\nu, T)$ is the Planck function, and $F(\nu)$ is the measured filter transmission. Metal-mesh filters are known to have harmonic leaks at frequencies above cut-off$^{25}$. However, the integrated power above the
FIG. 2. **a)** Resonant frequency versus blackbody power. **b)** Noise spectra for blackbody loads between 5 K and 21 K taken at a bath temperature of 75 mK. The solid lines are fits to the Lorentzian model described in the text. **c)** The blue points show the low frequency white noise converted to a NEP via the responsivity $\delta f/\delta P$ as a function of blackbody load. The red, dashed line is the photon noise NEP prediction. The black, dashed line is the best fit NEP model described in the text.

passband is $< 2\%$ of the total in-band power, even at the highest blackbody temperatures.

We perform a frequency sweep and characterize noise with a homodyne measurement and a SiGe amplifier at thermal loads ranging from $P = 5$ fW to 21 pW and at $T_{\text{bath}} = 75$ mK. A fit to the complex transmission $S_{21}(f)$ yields the resonant frequency as a function of thermal power. The detector response for one device is shown in Fig. 2a. The frequency responsivity $\delta f/\delta P$ varies by $< 10\%$ at loading powers $> 2$ pW. The significance of this linearity is discussed below.

For each thermal load, we measure noise at the microwave frequency that maximizes $\delta S_{21}/\delta f$. The approximate power on the feedline is -85 dBm, which is $\sim 13$ dB below bifurcation\textsuperscript{26,27}. This choice ensures negligible non-linear effects in the resonator. We project the raw in-phase and quadrature components of the data into the frequency and dissipation quadratures\textsuperscript{26} and examine the noise in the frequency quadrature. Example spectra at various thermal loads are shown in Fig. 2b. Each spectrum is well described by a Lorentzian function of white noise level $A$ and time constant $\tau$, associated with quasiparticle recombination, that is summed with an amplifier limiting background noise floor $B$,

$$S_{\delta f/f}(\omega) = \frac{A}{1 + \omega^2\tau^2} + B.$$ (4)

The amplifier noise limit can be seen above 100 kHz. Fits to this model are shown as black...
lines in the figure. Above 1 pW, the quasiparticle lifetime scales as \( \tau \sim P^{-0.5} \), as expected in the limit of photon dominated quasiparticle generation\(^{13}\).

We determine the measured NEP referred to the front of the horn with a combination of the responsivity \( \delta f / \delta P \) (slope in Fig. 2a) and the fit parameters \( A \) and \( B \),

\[
NEP_m = \frac{\sqrt{A + B}}{\delta f / \delta P}.
\]  

These values are plotted as a function of thermal load power \( P \) in the Fig. 2c, which is the main result of this letter. Above 1 pW the measured NEP scales as \( \sqrt{P} \), demonstrating the second signature of photon-noise limited detection in MKIDs. Furthermore, the red, dashed line of Fig. 2c is the photon noise prediction, calculated using Eq. 1 (\( \nu = 1.2 \) THz and \( m < 0.1 \) for all blackbody temperatures). For photon loads \( \geq 1 \) pW, the data match the prediction indicating background limited sensitivity.

The full data set fits the model (dashed-black line of Fig. 2c)

\[
NEP_m^2 = NEP^2_\alpha + \frac{NEP^2_{\text{photon}} + NEP^2_{GR}}{\eta_{\text{opt}}}.
\]  

\( NEP^2_\alpha \) is a constant noise term that is independent of \( P \), which we discuss below. \( \eta_{\text{opt}} \) is the single-polarization optical efficiency, the band-averaged fraction of power detected in the MKID that is emitted by the load. Fitting to this model has become a standard technique in order to determine the optical efficiency of a MKID\(^{11}\). The fit yields \( \eta_{\text{opt}} = 0.97 \). However, electro-magnetic simulations indicate 16% cross-polar coupling for this absorber geometry, including a \( \Delta z = 50 \) \( \mu \)m air gap between the absorber and waveguide. Subtracting this level of cross-polar coupling from the fit determined \( \eta_{\text{opt}} \) yields a more reliable value of the true single-polarization optical efficiency, \( \eta_{\text{opt}} = 0.81 \pm 0.20 \). The stated error is dominated by systematic error due in part to the uncertainty in \( \Delta z \), which changes the cross-polar coupling prediction. This value agrees with simulations, which show 62% co-polar coupling. We note that for future devices, we expect \( < 0.2\% \) cross-polar coupling as well as improvements in co-polar coupling by decreasing \( \Delta z \), including a waveguide choke, and decreasing the width of the absorbing strip to 2 \( \mu \)m. The reduction of absorber width mandates the use of several absorber strips in parallel to maintain the effective sheet impedance of the absorber, required for high co-polar coupling.

At \( P < 1 \) pW, we find that the NEP saturates to \( NEP_\alpha = 4 \times 10^{-17} \) W/\( \sqrt{\text{Hz}} \). Initial measurements suggest that the source of this noise is from a background of excess quasiparticles due to stray light absorption. We will conduct future tests in a carefully designed
light-tight box to confirm that $NEP_\alpha$ decreases when stray light is reduced. However, the currently measured level of $NEP_\alpha$ has a small effect on the sensitivity for many potential applications. The sensitivity relative to the photon noise level degrades by 20% for 3 pW thermal loads, and even less for higher loads.

Lastly, we discuss the implication of constant responsivity to increased optical power (Fig. 2a). This phenomenon has previously been observed in TiN films\textsuperscript{28} and departs from the behavior of MKIDs fabricated from conventional superconducting materials, which show $\delta f/\delta P \sim P^{-0.5}$ as a consequence of $\delta f \propto \delta n_{qp}$ and $P \propto n_{qp}^2$. Here $n_{qp}$ is the quasiparticle number density. Our linear responsivity measurement suggests that $P \propto n_{qp}$. However, the observed scaling of quasiparticle lifetime with optical power may be inconsistent with this picture. Anomalous quasiparticle behavior in TiN films has already been reported\textsuperscript{29}. Sub-gap states or quasiparticle traps may play a role in these TiN trilayer films as well.

In conclusion, we have demonstrated photon-noise limited sensitivity with high coupling efficiency in feedhorn-coupled microwave kinetic inductance detectors fabricated from a superconducting TiN/Ti/TiN trilayer film. This work represents a significant step towards realizing high sensitivity, large-format kinetic inductance detector arrays suitable for broadband photometry and with polarimetric sensing capability. Further work is planned to explore the origin of $NEP_\alpha$ and to better understand the anomalous quasiparticle behavior in our TiN/Ti/TiN films.

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