

Final Technical Report

submitted to:

Keck Institute for Space Studies

for

Development of Ultrasensitive Photon Detectors and Microwave Amplifiers Using Superconducting Nitride Thin Films

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1 Introduction

This is the final technical report for the KISS Technical Development program entitled “Development of Ultrasensitive Photon Detectors and Microwave Amplifiers Using Superconducting Nitride Thin Films”. The Technical Development phase started in January 2011 and concluded in December 2012. The overall goal of this program was to explore the application of high-resistivity superconductors, particularly titanium nitride (TiN), for sensitive photon detection at millimeter through optical/ultraviolet wavelengths. The program was focused on research activities at Caltech and JPL but included participation by our collaborators at Cardiff (Mauskopf/Doyle), NASA/GSFC (Moseley), NIST Boulder (Gao/Irwin), TU Delft (Klapwijk), and UC Santa Barbara (Mazin). Progress reports were given by our collaborators during a KISS-sponsored workshop held at Caltech on February 21-22, 2012. For further details, see [1].

2 Technical Accomplishments - Campus

Graduate student *Omid Noroozian* completed his thesis on far-infrared direct-absorption TiN MKID arrays and received his Ph.D. in Electrical Engineering in 2012. Omid’s work focused primarily on the issue of electromagnetic crosstalk between pixels, a basic engineering issue that needs to be addressed before sensitive arrays can be developed. Omid described how this problem was tackled and solved in his thesis and his 2012 IEEE paper [2]. Omid is currently a postdoctoral fellow at NIST Boulder.

In 2011, postdoctoral fellow *Loren Swenson* focused his effort on understanding the response of TiN MKIDs to far-infrared radiation. One of the key issues for TiN MKIDs is the

effect of the nonlinear kinetic inductance on detector performance. A basic theory of detector performance in this regime was developed and compared to measurements obtained in collaboration with JPL; these results were published in the Journal of Applied Physics [3]. The good agreement between theory and experiment demonstrated that the kinetic inductance nonlinearity is benign and does not add noise.

For 2012, Swenson shifted his focus to full-system demonstration of TiN arrays for sub-millimeter wavelengths ($\lambda = 350 \mu\text{m}$). This involved construction and commissioning of a test cryostat, integration of a 432-pixel TiN array into the cryostat, and testing of the system using an FPGA-based readout system developed at JPL. The full system, named MAKO [4], was deployed at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, HI, and very recently produced the first-light image shown in Fig. 1. The very high dynamic range evident in this image was obtained in a 9-minute measurement, despite poor weather conditions that gave only 2.5% atmospheric transmission.

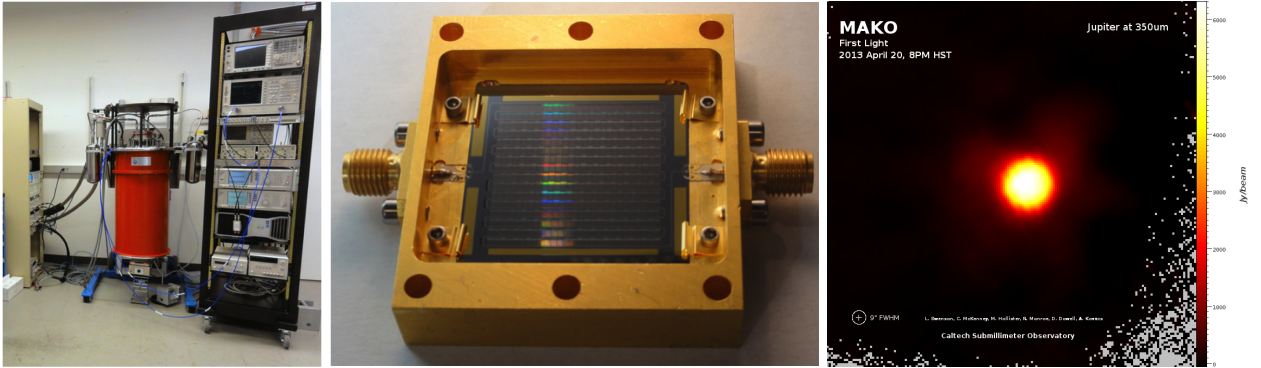


Figure 1: Left: MAKO cryostat and laboratory test electronics. Center: 432-pixel TiN $\lambda = 350 \mu\text{m}$ array used in MAKO. Right: MAKO's first-light image of Jupiter at the Caltech Submillimeter Observatory, obtained on April 20, 2013.

Postdoctoral fellow *Chris McKenney* was a key contributor to MAKO's success. Chris designed the MAKO array shown in Fig. 1 [5], relying on the experience he gained from testing of earlier prototypes at JPL at $\lambda = 215 \mu\text{m}$. The MAKO arrays achieved a high multiplexing density (all 432 pixels are read out on a single line) as well as photon noise limited operation for 300 K scenes. The successful demonstration of these arrays at the CSO validates the laboratory measurements, provides a foundation for development of much more sensitive arrays in the near future, and strongly motivates the use of TiN MKIDs in other instruments and projects in the near future.

KISS prize postdoctoral fellow *Erik Shirokoff* has developed an integrated-chip submillimeter spectrometer using TiN MKIDs, named "Superspec" [6]. The idea is to shrink the size of the current machined-metal grating spectrometer used in the CSO Z-spec instrument from $\sim 0.6 \times 0.5 \text{ m}^2$ down to a 2 cm^2 chip (see Fig. 2). SuperSpec will provide a revolutionary new capability for submillimeter astronomy and will enable imaging spectroscopic array instruments; one of the key goals is to study the epoch of reionization using the redshifted $\lambda = 157 \mu\text{m}$ fine-structure line of ionized carbon. Each chip will provide a 500-channel spectrum across the 200-300 GHz frequency band for a single beam on the sky. Successful laboratory tests of the mm-wave optical response of the first-generation Super-

spec chip design were obtained in late 2012, demonstrating the concept and showing that the required spectral resolution could be obtained. This is an example of an application that requires fairly sensitive TiN detectors, about two orders of magnitude more sensitive than for MAKO. For comparison, a cold far-infrared telescope in space will require detectors that are still another order of magnitude more sensitive.

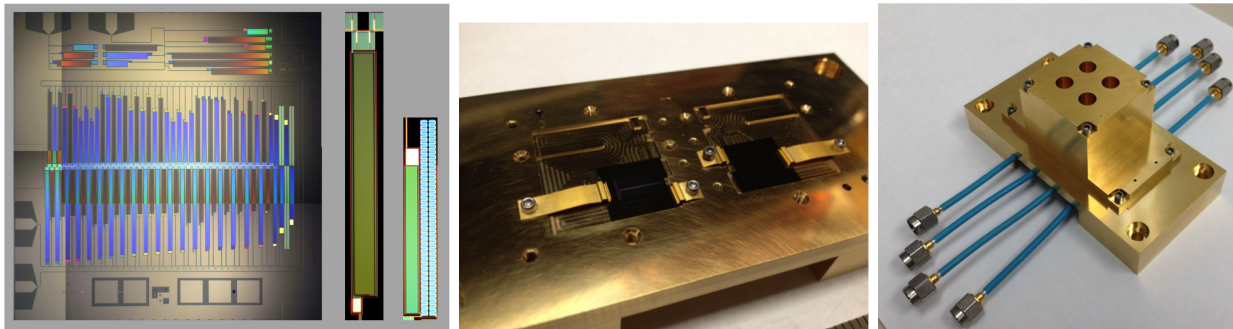


Figure 2: Left: Microscope image of the SuperSpec millimeter-wave spectrometer chip. The millimeter-wave radiation is coupled from a waveguide to the chip using a small probe (not visible). The radiation travels from left to right on a thin-film superconducting microstrip feed line at the center of the photograph. Superconducting half-wave resonators are used to couple the mm-wave radiation in narrow spectral channels from the feed line to a series of 80 TiN MKID detectors. These detectors are visible as the vertical stripes above and below the feed line, and also in the detail image to the right. Center: This image shows two cm-scale Superspec chips mounted in a waveguide block; the block can carry up to four chips. Right: The waveguide mounting block contains smooth-wall drilled feed horns that are used to couple the mm-wave radiation from a free space beam to the Superspec chips. The four pairs of RF coaxial cables visible at the bottom of the block are used for frequency-multiplexed readout of the TiN MKIDs contained on the four Superspec chips (one chip per feed horn).

Graduate student *Aditya Kher* joined the group in fall 2011 and was awarded a NASA Space Technology Research Fellowship in summer 2012. Aditya's Ph.D. thesis research is a spinoff of our KISS work on TiN photon detectors: he is studying a variety of novel devices that exploit the kinetic inductance nonlinearity of TiN nanoinductors. One example is a current sensor, basically a nanoinductor in a resonant circuit that serves as a current to frequency transducer. Recent measurements performed at JPL have shown that the noise of our device is comparable to the extremely sensitive Superconducting Quantum Interference Devices (SQUIDs). However, our device is easier to fabricate and is compatible with the same frequency-multiplexed technique used for MKIDs, and therefore provides a simple route to hundreds or thousands of measurement channels. These exciting, very recent results are being prepared for publication.

Caltech undergraduate and SURF student *Saptarshi Chaudhuri* worked on the development of a detailed and sophisticated numerical model for predicting the performance of a traveling-wave NbTiN parametric amplifier (see section 3 below). The agreement between Saptarshi's simulation and the experimental results (see Fig. 3) is remarkable, and provides us with a very strong foundation for continued development of this technology. This work

constitutes Saptarshi’s senior thesis; Saptarshi will be joining Stanford’s Ph.D. program in physics in fall 2013.

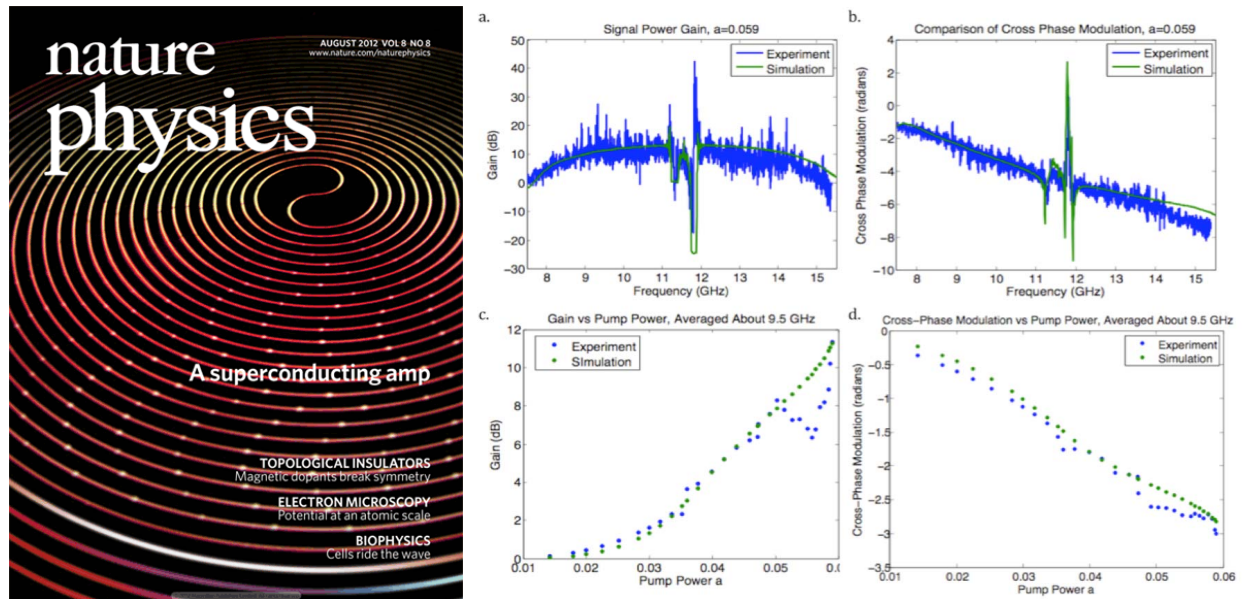


Figure 3: Left: NbTiN traveling-wave nonlinear kinetic inductance parametric amplifier featured on the cover of Nature Physics in August 2012. Right: Comparison of Saptarshi Chaudhuri’s simulation with the experimental results for a traveling-wave kinetic inductance parametric amplifier.[7]

Another undergraduate, *Rebecca Wernis*, studied the use of NbTiN resonators for read-out of a new type of detector that is a hybrid between an MKID and a bolometer, which we call the “resonator bolometer”. This device is useful for for 1-4 K operation, a temperature range that is too high for standard MKIDs because the thermal contact between the electron system in the superconductor and the phonon bath becomes quite strong, leading to low responsivity. This problem is solved by use of micromachining techniques to introduce a thermal suspension for the inductor/absorber, similar to what is done in standard bolometers (see Fig. 4). Rebecca’s senior thesis will describe laboratory tests of this concept, demonstrating that the performance of this device reaches the fundamental limits set by thermal fluctuations and photon noise. Rebecca will pursue her Ph.D. at U.C. Berkeley starting in fall 2013.

Finally, an extensive review paper focusing on superconducting microresonators and MKIDs has been published in Annual Reviews of Condensed Matter Physics [8].

3 JPL Accomplishments

The foundation for this program rests solidly at JPL’s Microdevices Laboratory. JPL’s activities have focused on the fabrication of all of the TiN films and devices for the program as well as testing the performance of far-infrared detectors and nonlinear kinetic inductance

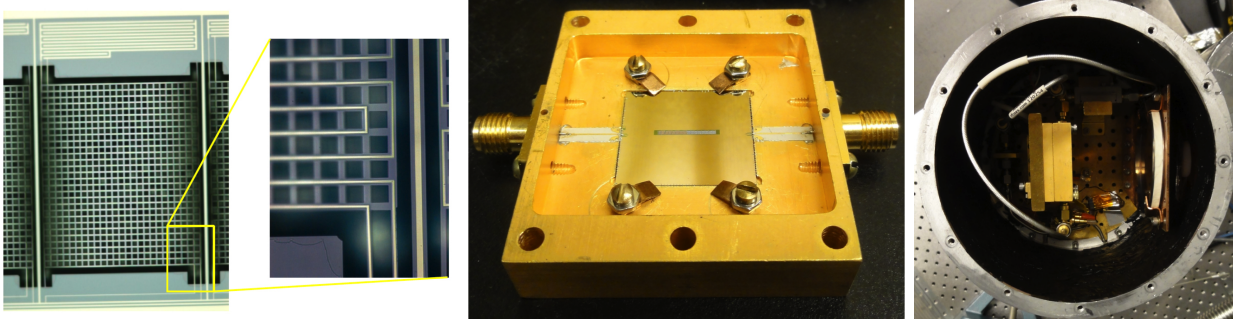


Figure 4: Left: The resonator bolometer consists of a NbTiN kinetic inductor that is thermally suspended on a silicon nitride micromesh structure. The inductor serves double-duty as a far-infrared radiation absorber. The interdigitated capacitor at the top of the image forms a microwave resonant circuit with the inductor. Center: the resonator-bolometer chip is mounted in a standard package with coaxial input and output for the readout signal. Right: the resonator-bolometer package is mounted in a LHe cryostat for far-infrared optical testing.

devices. Co-lead Rick Leduc successfully rebuilt his TiN deposition system to allow more uniform films to be produced on larger substrates. JPL’s films were provided to other collaboration members for testing, including Cardiff, GSFC, NIST, and TU Delft. JPL’s Peter Day has assisted with testing of the far-infrared detectors, providing guidance to Caltech postdocs Swenson and McKenney as well as access to Day’s dilution refrigerators. In addition, Caltech research staff member Byeong-Ho Eom has been working closely with Day on demonstrating the TiN/NbTiN microwave traveling-wave parametric amplifier (see Fig. 3). This work has led to the demonstration of the first superconducting amplifier with low noise, wide bandwidth, and high dynamic range [7]. Finally, Day and Eom work closely with Caltech graduate student Kher on the development of nonlinear kinetic inductance devices for other applications.

4 UCSB

Postdoctoral fellow *Danica Marsden* started her KISS-supported appointment in August 2011, working with Ben Mazin’s group at UCSB. UCSB’s primary accomplishment was to successfully demonstrate a single-photon, energy resolving camera (ARCONS) using KISS-supported TiN detectors [9]. The group recently completed its third field campaign using a new 2024 (44x46) pixel MKID array at the Palomar 200 telescope. Improvements over past year include a doubling of the pixel count, improvement of the optical fill factor from 67% to 92%, and most importantly elimination of a problem related to incomplete absorption of the photon energy through the use of thicker TiN films. Marsden is devoting significant effort to improving the energy resolution and quantum efficiency of the detectors [10]. Membrane-suspended designs, similar in principle to the far-infrared resonator bolometers, should provide better energy resolution; current designs appear limited by geometry and positional effects and not detector or amplifier noise. These significant advances are stimulating

new ideas for astronomical instrumentation and applications [11].

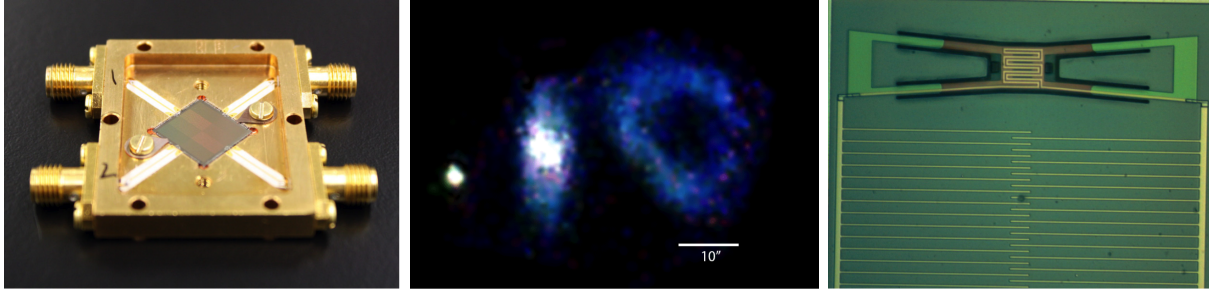


Figure 5: Left: A 2040-pixel, visible wavelength, energy-resolving TiN MKID array demonstrated at the Palomar 200" telescope by the UCSB group. Center: TiN MKID images of the interacting galaxies Arp 147 taken at the Palomar 200. Right: The first membrane-suspended UVOIR TiN Kinetic Inductance Detector, recently fabricated at JPL.

5 TU Delft

Teun Klapwijk, our KISS-supported visitor in 2011, returned to the Netherlands in summer 2011 and motivated by our work, held a week-long scientific workshop in August at the Lorentz Center, entitled "Strongly Disordered Superconductors and Electronic Segregation". Klapwijk has focused his attention on understanding the electrodynamic properties of the nitride superconductors, whose behavior does not fit the standard BCS-derived Mattis-Bardeen theory. Klapwijk proposed that the behavior could be understood by assuming that the density of states in resistive superconductors was broadened. This workshop stimulated theoretical and experimental work in Europe on the physics of highly resistive superconductors, with a focus on TiN, that has been very useful for our program (see Related Publications, below).

6 NIST

NIST has studied single-photon detection with TiN MKIDs in the near-infrared, at the 1550 nm telecom wavelength. Their results, reported in our 2012 February workshop and in [12], are very intriguing. Each photon produces a pulse in the reactive (frequency) response that is about as expected, provided that one uses a somewhat smaller value for the electronic density of states. However, the dissipative response is both smaller and expected, and has a decay time much shorter than for the reactive response. This result is in broad agreement with our far-infrared measurements, which indicated that the dissipative response was suppressed. The physical interpretation of the NIST results is not yet clear. It may be that in a resistive superconductor, quasiparticles may be trapped into localized states close to the gap, where they sit for some time before finally recombining to produce Cooper pairs. The short decay time observed with the dissipative response may be related to the time required for the quasiparticles to get "stuck" into a localized state. Meanwhile, the longer

decay time observed in the frequency response may be the recombination time. Other work at NIST has focused on studying the deposition conditions and microstructure for TiN films (see Related Publications, below).

7 GSFC

GSFC's goal is to produce MKIDs capable of single-photon detection in the far-IR, and to include them in their version of a single-chip spectrometer. GSFC has been developing the fabrication methods for MKIDs that use a related material, molybdenum nitride (see Patel *et al.*, in Related Publications), and studying their optical response.

8 Postdoctoral Scholars and Students

Name	Position	Role/Project
Saptarshi Chaudhuri	Undergraduate student (SURF)	Paramp - simulation
Aditya Kher	Graduate student	Nonlinear kinetic inductance devices
Danica Marsden	Postdoctoral scholar	UCSB - Optical detectors
Chris McKenney	Postdoctoral scholar	Submm/far-IR detectors
Omid Noroozian	Graduate student	Submm/far-IR detectors
Erik Shirokoff	KISS Postdoctoral Scholar	Superspec - design/measurement
Loren Swenson	Postdoctoral Scholar	Submm/far-IR detectors
Rebecca Wernis	Undergraduate student (SURF)	Resonator bolometer

TiN MKIDs are now baselined for two out of the four first-light facility instruments being considered for the CCAT 25 m submillimeter telescope. These are SWCAM, the short-wavelength ($\lambda = 350\,\mu\text{m}$) camera, and X-spec, the multiobject spectrometer. TiN MKIDs are also a very strong candidate for LWcam, the long-wavelength camera. Our KISS-supported research has also stimulated two proposals to NASA for balloon payloads:

- SKIP, an MKID-based instrument for searching for B-mode polarization of the cosmic microwave background (PI: Amber Miller, Columbia; Zmuidzinas is a co-I)
- STARFIRE, an MKID-based far-IR spectrometer for intensity mapping of redshifted ionized carbon (CII) emission (PI: James Aguirre, Penn; Bradford is co-I and Zmuidzinas is a collaborator)

Publications and Presentations

- [1] URL: <http://www.kiss.caltech.edu/workshops/photon2011b/index.html>.
- [2] Omid Noroozian, Peter K Day, Byeong Ho Eom, Henry G Leduc, and Jonas Zmuidzinas. “Crosstalk reduction for superconducting microwave resonator arrays”. In: *IEEE Transactions on Microwave Theory and Techniques* 60.5 (2012), pp. 1235–1243.
- [3] LJ Swenson, PK Day, BH Eom, HG Leduc, N Llombart, CM McKenney, O Noroozian, and J Zmuidzinas. “Operation of a titanium nitride superconducting microresonator detector in the nonlinear regime”. In: *Journal of Applied Physics* 113.10 (2013), pp. 104501–104501.
- [4] Loren J Swenson, Peter K Day, Charles D Dowell, Byeong H Eom, Matthew I Hollister, Robert Jarnot, Attila Kovács, Henry G Leduc, Christopher M McKenney, Ryan Monroe, et al. “MAKO: A pathfinder instrument for on-sky demonstration of low-cost 350 micron imaging arrays”. In: *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics. 2012, 84520P–84520P.
- [5] Christopher M McKenney, Henry G Leduc, Loren J Swenson, Peter K Day, Byeong H Eom, and Jonas Zmuidzinas. “Design considerations for a background limited 350 micron pixel array using lumped element superconducting microresonators”. In: *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics. 2012, 84520S–84520S.
- [6] Erik Shirokoff, Peter S Barry, Charles M Bradford, Goutam Chattopadhyay, Peter Day, Simon Doyle, Steve Hailey-Dunsheath, Matthew I Hollister, Attila Kovács, Christopher McKenney, et al. “MKID development for SuperSpec: an on-chip, mm-wave, filter-bank spectrometer”. In: *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics. 2012, 84520R–84520R.
- [7] Byeong Ho Eom, Peter K Day, Henry G LeDuc, and Jonas Zmuidzinas. “A wideband, low-noise superconducting amplifier with high dynamic range”. In: *Nature Physics* (2012).
- [8] Jonas Zmuidzinas. “Superconducting microresonators: Physics and applications”. In: *Annu. Rev. Condens. Matter Phys.* 3.1 (2012), pp. 169–214.

- [9] Benjamin A Mazin, Bruce Bumble, Seth R Meeker, Kieran O’Brien, Sean McHugh, and Eric Langman. “A superconducting focal plane array for ultraviolet, optical, and near-infrared astrophysics”. In: *Optics Express* 20.2 (2012), pp. 1503–1511.
- [10] Danica Marsden, Benjamin A Mazin, Bruce Bumble, Seth Meeker, Kieran O’Brien, Sean McHugh, Matthew Strader, and Eric Langman. “Optical lumped element microwave kinetic inductance detectors”. In: *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics. 2012, 84530B–84530B.
- [11] Benjamin A Mazin, Danica Marsden, and Kieran O’Brien. “SuperMOS: A new class of low resolution multiobject spectrographs”. In: *SPIE Astronomical Telescopes+ Instrumentation*. International Society for Optics and Photonics. 2012, 84460O–84460O.
- [12] J Gao, MR Vissers, MO Sandberg, FCS da Silva, SW Nam, DP Pappas, DS Wisbey, EC Langman, SR Meeker, BA Mazin, et al. “A titanium-nitride near-infrared kinetic inductance photon-counting detector and its anomalous electrodynamics”. In: *Applied Physics Letters* 101.14 (2012), pp. 142602–142602.
- [13] Jonas Zmuidzinas et al. *Dispersion-engineered traveling wave kinetic inductance parametric amplifier*. US Patent App. 13/277,214. Oct. 2011.

Related Publications

- [1] J Chang, MR Vissers, AD Corcoles, M Sandberg, J Gao, David W Abraham, Jerry M Chow, Jay M Gambetta, MB Rothwell, GA Keefe, et al. “Improved superconducting qubit coherence using titanium nitride”. In: *arXiv preprint arXiv:1303.4071* (2013).
- [2] B Chiaro, S Ohya, A Megrant, C Neill, R Barends, B Campbell, Y Chen, J Kelly, M Mariantoni, J Mutus, et al. “Superconducting Titanium Nitride Coplanar Resonators: Relationships between performance and deposition parameters”. In: *Bulletin of the American Physical Society* 58 (2013).
- [3] P.C.J.J. Coumou, M.R. Zuddam, E.F.C. Driessen, P.J. de Visser, J.J.A. Baselmans, and T.M. Klapwijk. “Microwave Properties of Superconducting Atomic-Layer Deposited TiN Films”. In: *Applied Superconductivity, IEEE Transactions on* 23.3 (2013), pp. 7500404–7500404. ISSN: 1051-8223. DOI: 10.1109/TASC.2012.2236603.
- [4] P Diener, HG Leduc, SJC Yates, YJY Lankwarden, and JJA Baselmans. “Design and Testing of Kinetic Inductance Detectors Made of Titanium Nitride”. In: *Journal of Low Temperature Physics* 167.3-4 (2012), pp. 305–310.
- [5] P Diener, H Schellevis, and JJA Baselmans. “Homogeneous superconducting phase in TiN film: A complex impedance study”. In: *Applied Physics Letters* 101.25 (2012), pp. 252601–252601.
- [6] EFC Driessen, PCJJ Coumou, RR Tromp, PJ De Visser, and TM Klapwijk. “Strongly disordered TiN and NbTiN s-wave superconductors probed by microwave electrodynamics”. In: *Physical Review Letters* 109.10 (2012), p. 107003.
- [7] URL: <http://www.lorentzcenter.nl/lc/web/2011/449/info.php3?wsid=449>.

- [8] A. Patel, A.-D. Brown, W.-T. Hsieh, T. Stevenson, S.H. Moseley, K. U-yen, N. Ehsan, E. Barrentine, G. Manos, and E.J. Wollack. “Fabrication of MKIDS for the MicroSpec Spectrometer”. In: *IEEE Trans. Appl. Supercond.* 23.3 (2013), pp. 2400404–2400404. ISSN: 1051-8223. DOI: 10.1109/TASC.2013.2240152.
- [9] Martin Sandberg, Michael R Vissers, Jeffrey S Kline, Martin Weides, Jiansong Gao, David S Wisbey, and David P Pappas. “Etch induced microwave losses in titanium nitride superconducting resonators”. In: *Applied Physics Letters* 100.26 (2012), pp. 262605–262605.
- [10] Martin Sandberg, Michael R Vissers, Thomas A Ohki, Jiansong Gao, José Aumentado, Martin Weides, and David P Pappas. “Radiation-suppressed superconducting quantum bit in a planar geometry”. In: *Applied Physics Letters* 102.7 (2013), pp. 072601–072601.
- [11] Michael R Vissers, Martin P Weides, Jeffrey S Kline, Martin Sandberg, and David P Pappas. “Identifying capacitive and inductive loss in lumped element superconducting hybrid titanium nitride/aluminum resonators”. In: *Applied Physics Letters* 101.2 (2012), pp. 022601–022601.
- [12] Michael Vissers, Jiansong Gao, Suptarshi Chaudhuri, Clint Bockstiegel, Martin Sandberg, and David P Pappas. “Non-linear processes in thin titanium nitride transmission lines for parametric amplification”. In: *Bulletin of the American Physical Society* 58 (2013).
- [13] Martin Weides, Philipp Mayer, Fengbin Song, Sebastian Probst, Hannes Rotzinger, and Alexey Ustinov. “Large kinetic inductance microwave resonators in magnetic field”. In: *Bulletin of the American Physical Society* (2013).