National Aeronautics and Space Administration

Atomic Layer Deposition (ALD) of Superconducting Films for Through-Silicon-Via Structures and Photon Detectors

John Femi-Oyetoro (389W)* , JPL Postdoctoral Fellow
Henry LeDuc (389I)*, Peter Day (389I)* and Frank Greer (389L)*

***Microdevices Laboratory**
Jet Propulsion Laboratory, California Institute of Technology

Abstract

Superconductors traverse to normal metal behavior in the millimeter-far-IR wavelength range as consistently described in the Bardeen-Cooper-Schrieffer (BCS) theory. This property has been explored and leveraged upon in Astrophysics for detecting the early universe. The first light emitted after the Big Bang can still be detected in form of cosmic microwave background (CMB) with the aid of superconducting (SC) devices. To buttress, at the Microdevices Laboratory (MDL), SC devices have been deployed at the South Pole, including the Background Imaging of Cosmic Extragalactic Polarization (BICEP) telescopes and the Keck Array. These instruments have performed CMB polarization measurements with great sensitivity to the signatures of the early universe. In this work, we demonstrate the atomic layer deposition (ALD) of high-quality SC transition nitride films such as titanium nitride (TiN) with high transition temperature. These films will be used for high-density SC through-silicon-via (TSV) structures in large photon detector arrays. SC films provide outstanding sensitivity, mature fabrication, and large array sizes, for hybridization and 3D integration techniques. However, while conventional sputtering technique have been useful in fabricating SC detectors, ALD has provided an advantage of spatial uniformity and conformality which are difficult and/or absent in sputtering techniques. In addition, we employed ALD to control the repeatability, composition and thickness, which plays a role in the transition temperature (Tc) of SC films. We believe that these possibilities will assist in exploring different SC materials for specific detection in future science observations.

Background

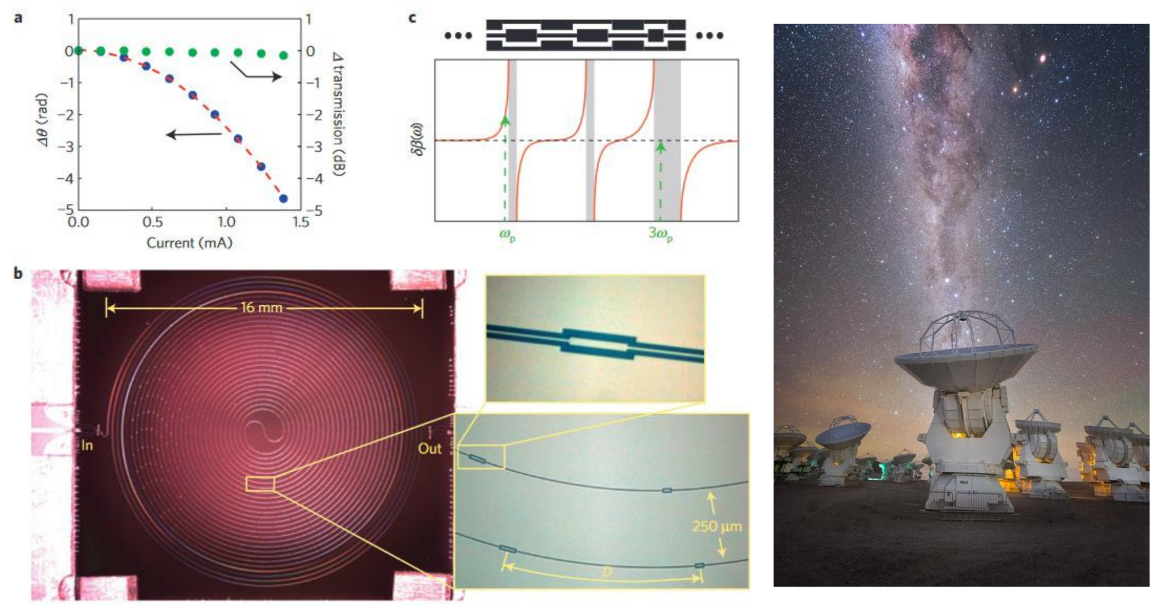

Figure 1. Superconducting (SC) films have been used for cosmic microwave background (CMB) experiments at the Atacama Large Millimeter. The SC films are used for fabriacting parametric amplifiers with quantum limited sensitivity ~ ½ hv better than HEMT amplifiers [1-3].

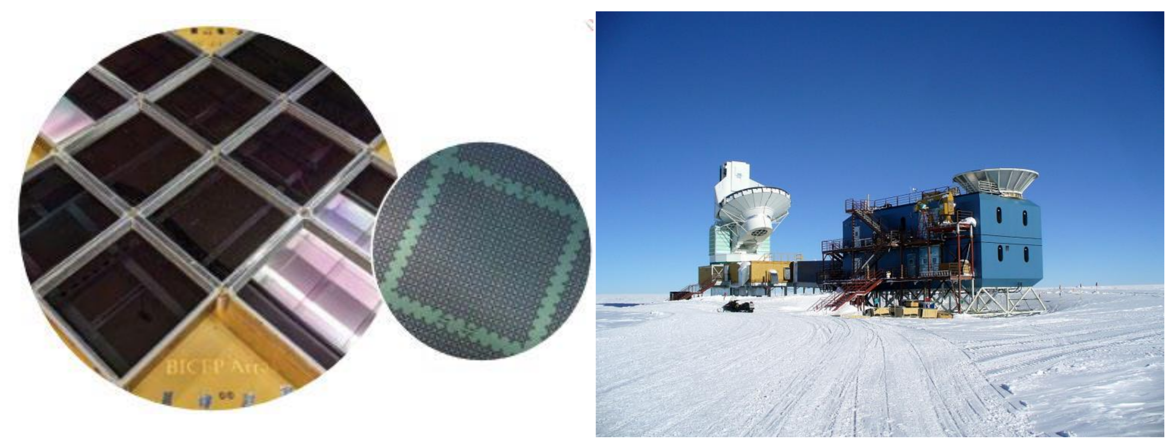

Figure 2. Transition edge sensor (TES) have utilized SC films for the Background Imaging of Cosmic Extragalactic Polarization (BICEP) telescopes. TES have high detection efficiency that can be tuned from millimeter wave to gamma ray [2, 4].

Potential Concept

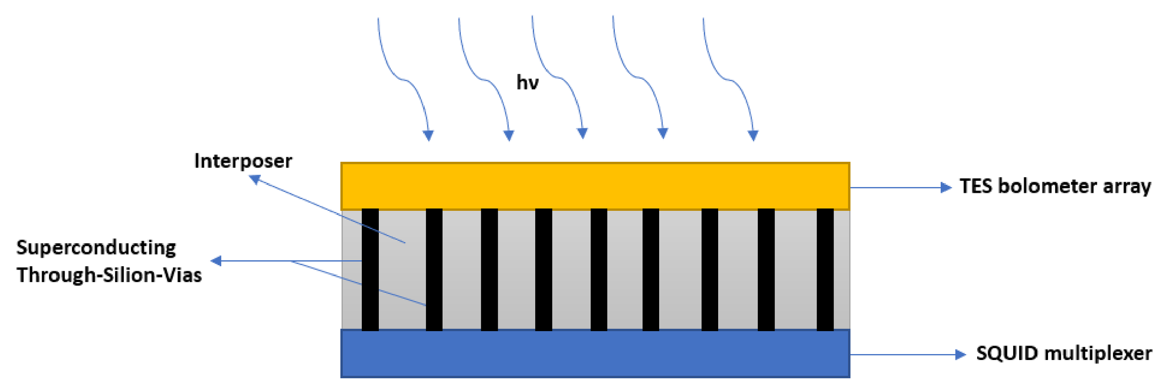

Figure 3. A three-tier SC system for low SWaP: TES bolometer array and SQUID multiplexer integrated using SC TSVs. The TSVs will be coated with TiN using ALD (Not to scale).

Materials Development

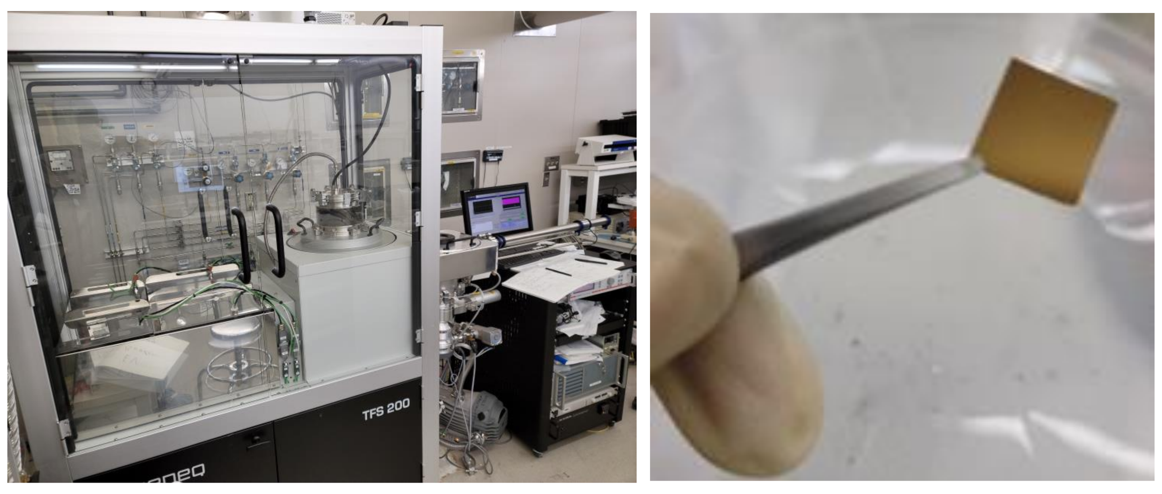

Figure 4. (a) Growth peformed in Beneq TFS 200 plasma-enchaced ALD (PEALD) at MDL Cleanroom. $TiCl_4$ and Tetrakis(dimethylamido) titanium (TDMAT) precusors at 400° C and 270° C respectively. (b) $TiCl_4$ TiN films have good normal state $R_{\square}$ = 0.85Ω at 2490 cycles and ρ = 0.73 μΩcm. TDMAT films have good $R_{\square}$ = 4.7 Ω at 1250 cycles, and at comparable thickness, with $R_{\square}$ = 5.6 Ω. Need to confirm the T_c [5].

Structural Charaterization

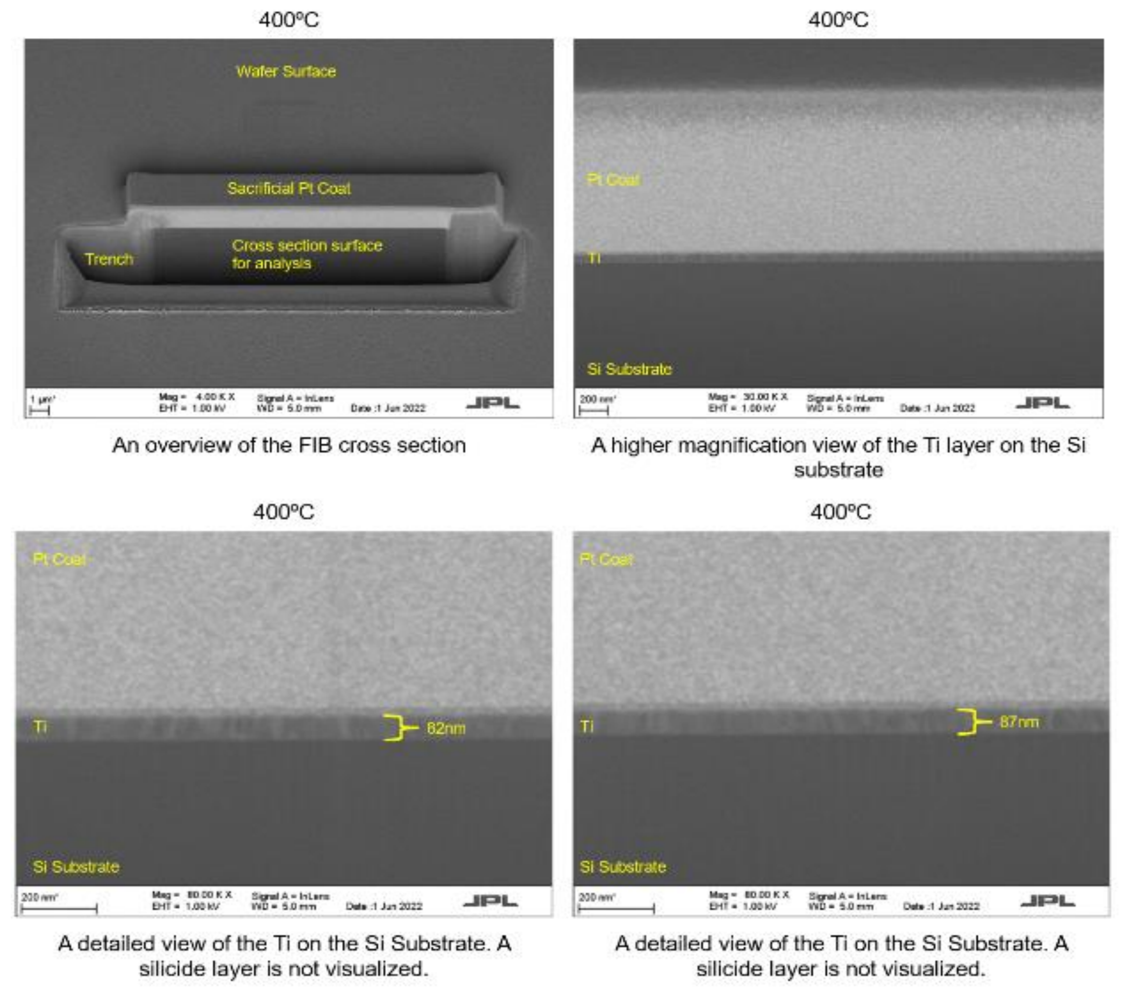

Figure 5. FIB SEM determines silicide layers were not present after growth. Silicides layers are responsible for TLS induced losses, and occurs at high temperatures.

Cryogenic DC Charaterization

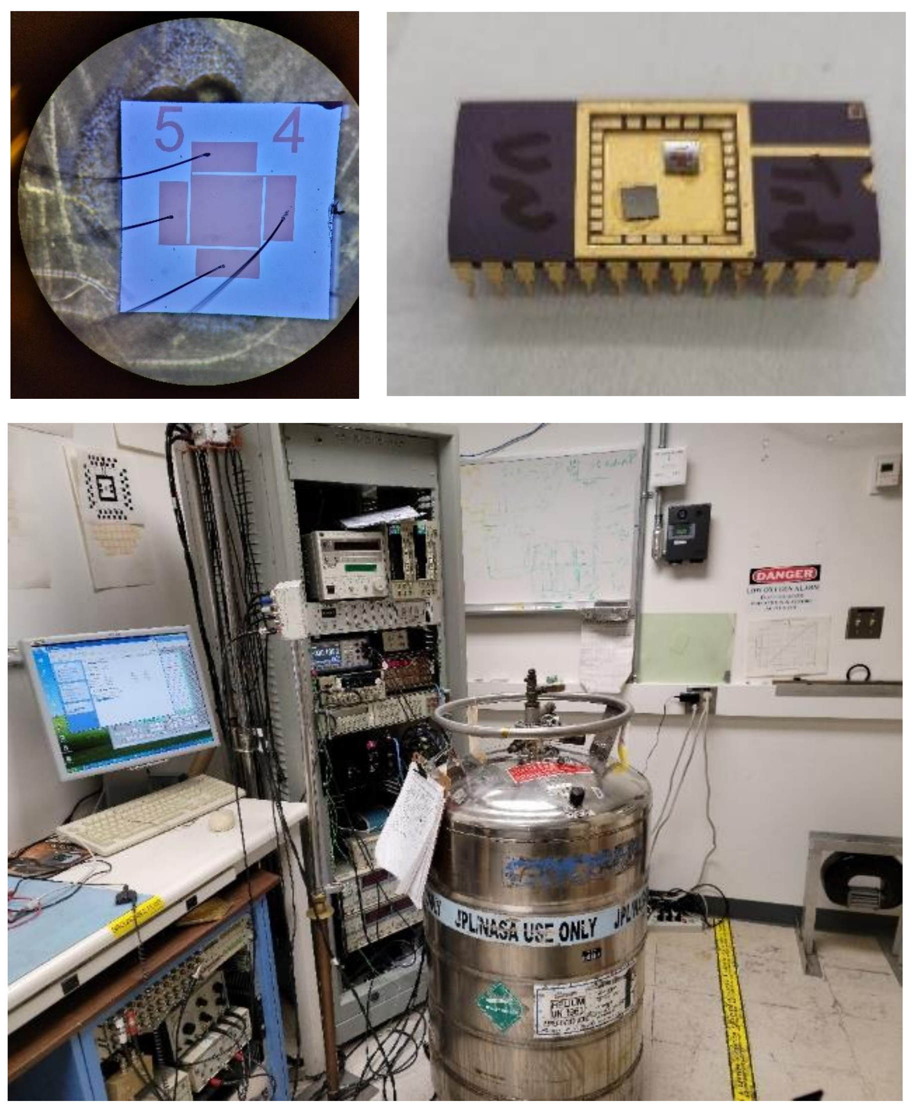

Figure 6. The $TiCl_4$ TiN films were patterened, wire-bonded and packaged for testing. DC characterization at cryogenic temperatures demonstrate a T_c = 4.59 K, and was carried out using the LHe RvT test apparatus in the Microdevices Laboratory.

Resistance Vs Temperature

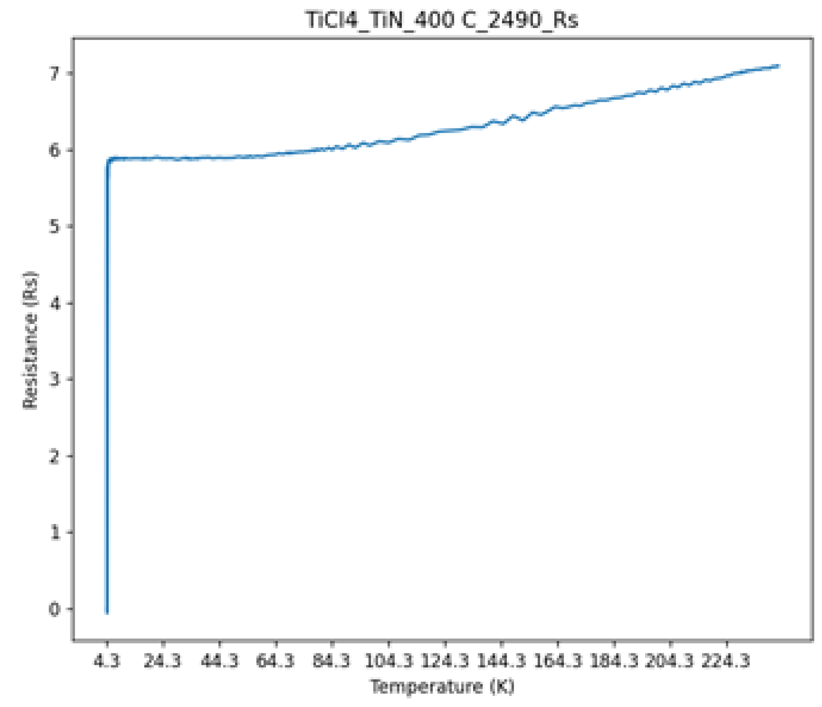

Figure 7. Four point probe measurements of $TiCl_4$ TiN film. Resistance as a function of temperature showing a T_c = 4.59 K.

Conclusions

- We have developed a plasma-enchaced ALD process for TiN from $TiCl_4$ and TDMAT precurcors. $TiCl_4$ has produced the highest quality film with decent metallic behavior.
- TDMAT has excellent $R_{\square}$. However, we need to test for T_c and/or contaminations.
- Current TiN samples don't have silicide layer as observed with FIB SEM. However, we need to do TEM to confirm these observations.
- We will fabricate and coat trenches with the high quality SC films, and test for Tc. We are interested in superconducting through-silicon-vias that will help in the hybridization and 3D integration of superconducting devices.
- Initial results have been accepted at the 68th AVS International Symposium and Exhibition scheduled for November 2022.

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Poster Number: PRD-T#015

References:

1. Ho Eom, B., Day, P.K., LeDuc, H.G. and Zmuidzinas, J., 2012. A wideband, low-noise superconducting amplifier with high dynamic range. Nature Physics, 8(8), pp.623-627.
2. https://microdevices.jpl.nasa.gov/interactivepdfs/index.html?pdf=2020-MDL-Annual-report.pdf
3. Wikimedia Foundation. (2022, September 26). Atacama large millimeter array. Wikipedia. Retrieved October 6, 2022, from https://en.wikipedia.org/wiki/Atacama_Large_Millimeter_Array
4. "Bicep and Keck Array." Wikipedia, Wikimedia Foundation, 26 Aug. 2022, https://en.wikipedia.org/wiki/BICEP_and_Keck_Array.
5. Shearrow, A., Koolstra, G., Whiteley, S.J., Earnest, N., Barry, P.S., Heremans, F.J., Awschalom, D.D., Shirokoff, E. and Schuster, D.I., 2018. Atomic layer deposition of titanium nitride for quantum circuits. Applied Physics Letters, 113(21), p.212601.

Contact Information:

Phone:(626) 314-4229, Email: john.femi-oyetoro@jpl.nasa.gov