National Aeronautics and Space Administration

Quantum Limited Terahertz MgB2 SIS Detector Technology Development

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Program: FY21 R&TD Innovative Spontaneous Concepts

Objectives

The objective was to address the need for THz sensitivity (up to a factor five improvement over HEB devices below 2 THz), the need for increased intermediate (IF) bandwidth of up to 20 GHz (as opposed to HEB devices with just a few GHz of If bandwidth), and enhanced system stability (important for flight). We proposed to utilize recent deposition advances in high critical temperature MgB2 superconducting film, which offers for the first time the unique possibility to extend the quantum limited performance of Niobium (Nb) based Superconductor-Insulator-Superconductor (SIS) mixers to 2 THz!

Background

Understanding the water trail, from the interstellar medium (ISM) to habitable planets, has been identified as one of the key science goals for the Origins Flagship mission proposed to the 2020 Astrophysics Decadal Survey. One of the key questions of modern astrophysics and planetary science concerns the development of the conditions of habitability in a planetary system, starting with the early protosolar nebula. Water, an essential ingredient for carbon-based life as we know it, is formed primarily via surface reactions in icy mantles of dust grains in interstellar clouds (the gas-phase chemistry only becomes efficient at temperatures above ~ 300 K).

Due to presence of two identical hydrogen atoms, water molecules come in two distinct spin modifications, ortho-H_2O with spins parallel, and para-H_2O with spins antiparallel. This results in effectively two distinct classes of molecules with completely different, complex rotational spectra in the 600 – 180 µm wavelength (500 –1700 GHz frequency) range. Outstanding detector sensitivity is required, as the abundance of, for instance, rare isotopologues (e.g. HDO) can be as little as 1/10,000 of that of the most abundant isotopologue ($H_2{}^{16}O$).

Approach and Results

The proposed Spontaneous task builds on recent development of 40 nm thick MgB_2 films on 3" SiNx/Si wafers with a critical temperature (Tc) around 37 K and resistivity of ~ 25 µΩ-cm. The critical temperature of the MgB2 film is expected to go up for thicker films while the resistivity will go down, both due to a reduction of surface scattering when the film gets thicker than the mean free path of electrons. The Spontaneous task will utilize thicker films (greater than multiple penetration depths).

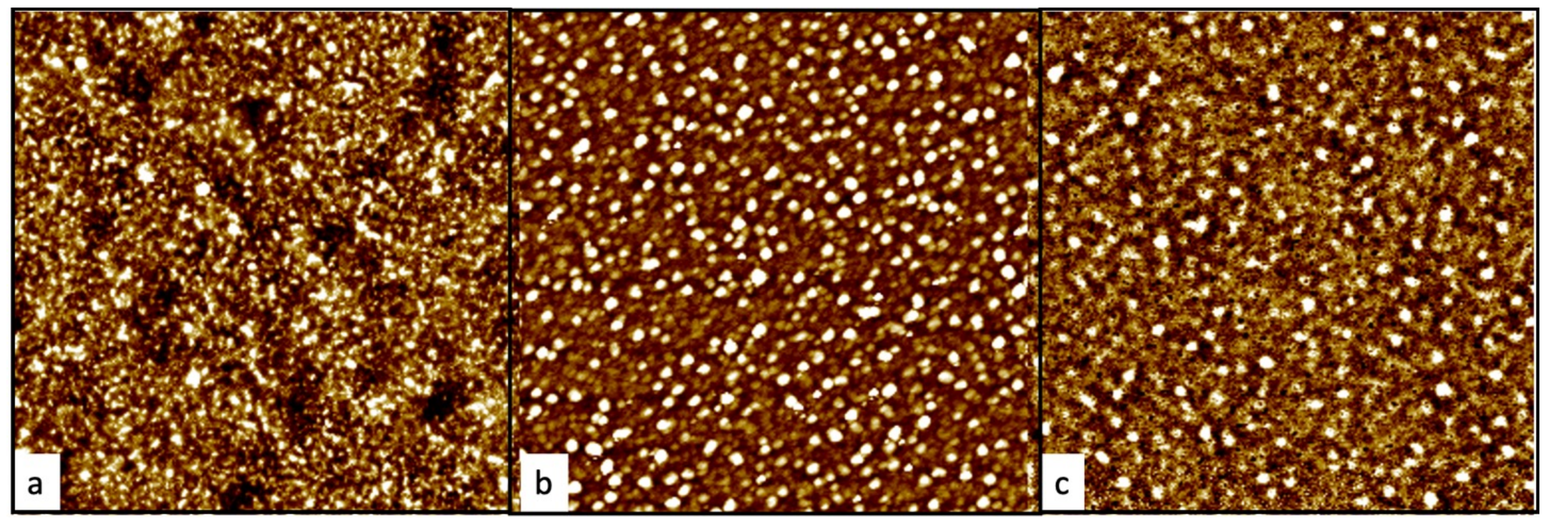

Figure 1. *Atomic Force Microscope (AFM) MgB2 images of MgB2 films fabricated at Caltech a). 210726-33nm on SiNx. 2.54 nm rms but some non-uniformity in the film (bumps/pores). This is the junction Bruce made and measured b) 210915-bc20s on sapphire, 3.83 nm rms with good uniformity and no bumps/pores c) 210915-bc20s on sapphire with SF6 ICP etch 1.78 nm rms. Surface getting smoother with experience.*

The MgB_2 surface roughness is already less than 2 nm rms, which should easily accommodate low leakage Nb junction tunnel barriers. Compared to previously available MgB_2 thin films, the films at JPL were developed with device fabrication in mind in that the utilized sputtering technique is widely used in micro-fabrication because of its reproducibility and uniformity.

The following is an outline of the step taken to address the objectives of the Spontaneous task:

1 - Proposal and WAM (6/21/2021)

2 - Test Nb films on MgB2 (6/29). The Nb films were all on 50 nm MgB2 / SiNx/Si which Chang Sub (JPL) ion milled before being giving to MDL. The first attempt at 3 different Nb thickness on MgB2 was to see if the proximity effect of Nb decreased the Tc of MgB2 - which it did not, so either penetration into MgB2 is much less than 50 nm or our interface is poorly constructed:
- In-situ 60 second ion mill on each to remove ~ 1 nm of the surface. - Sample 1 Nb, 30 sec ~ 22 nm , measured 9.23 Ohm / sq.
- Sample 2 Nb, 60 sec ~ 45 nm , measured 4.64 Ohm/sq.
- Sample 3 Nb, 2 min., ~ 90 nm, measured 2.29 Ohm/sq.3 - Test thin Nb (20 nm) base layer Nb/Al-Ox/ Nb structure using MLA lithography and simple mask design by Dan Cunnane. (#B210715)

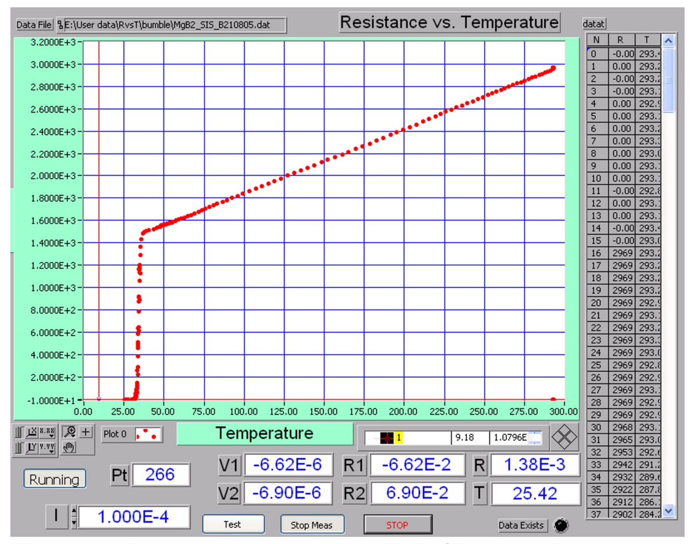

Figure 2. *Measured MgB2 film critical Temperature (Tc = 39K). B210805*

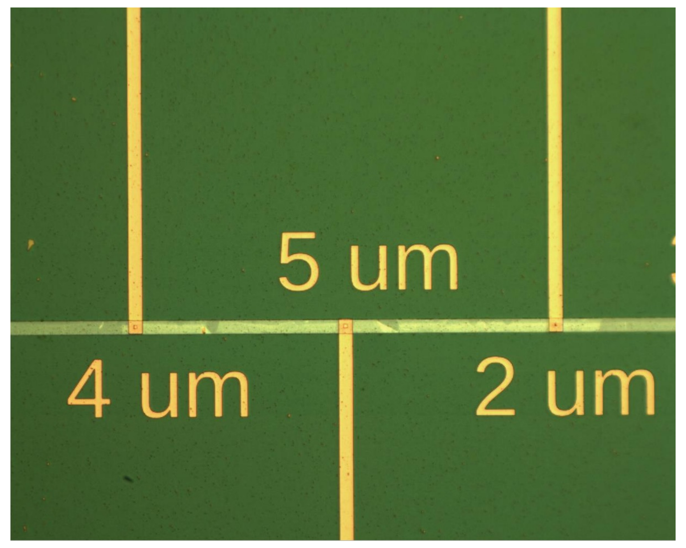

Figure 3. *Test mask layout with different size SIS junctions.*

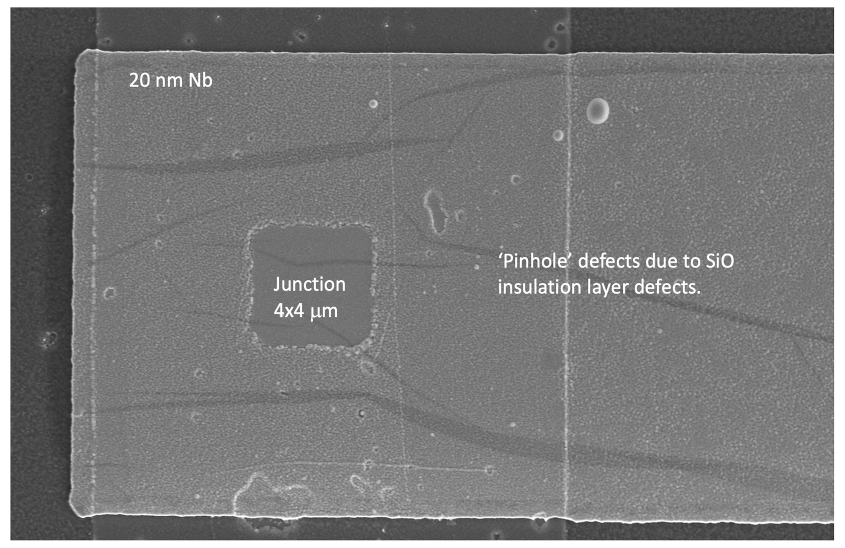

Figure 4. SiO insulation layer which shows a variety of pinholes, giving rise to 'micro' shorts, possibly being due to the interface with the underlying MgB2 or SiO (The SiO2 sputter target was down). The MgB2/SiNx/Si seems to also transfer roughness to the structure.

The gap was slightly reduced to 2.6 mV with the thin Nb base showing a broad transition from 8.54 K to 8.89 K.

4 - Use 26 nm thick MgB2 on SiNx for proximity SIS device Nb (10 nm)/Al-Ox/Nb. Fabri
- MgB2(33 nm) / SiNx / Si
- Air transfer - Ion mill surface instu (mild - < nm removed)
- Nb (10 nm) \ Al (8 nm) - Ox (500 mTorr min.) \ Nb (80 nm) ;
- Pattern etch layers [There is a question about etching through the MgB2 with BCL3 + Cl2 as used for the Nb trilayer] -SiOx (100 nm)
- Nb (150 nm) pattern wire and etch
- Dice & test (8/11/2021)

5 - Use thick MgB2 (>100 nm?) on SiNx with thicker SIS Nb (100 nm) / Al-Ox /Nb (#B210831) Pattern with new lithography for stub resonators.
Abort after ground plane etch showing unusable surface in SEM images.(9/8/2021)

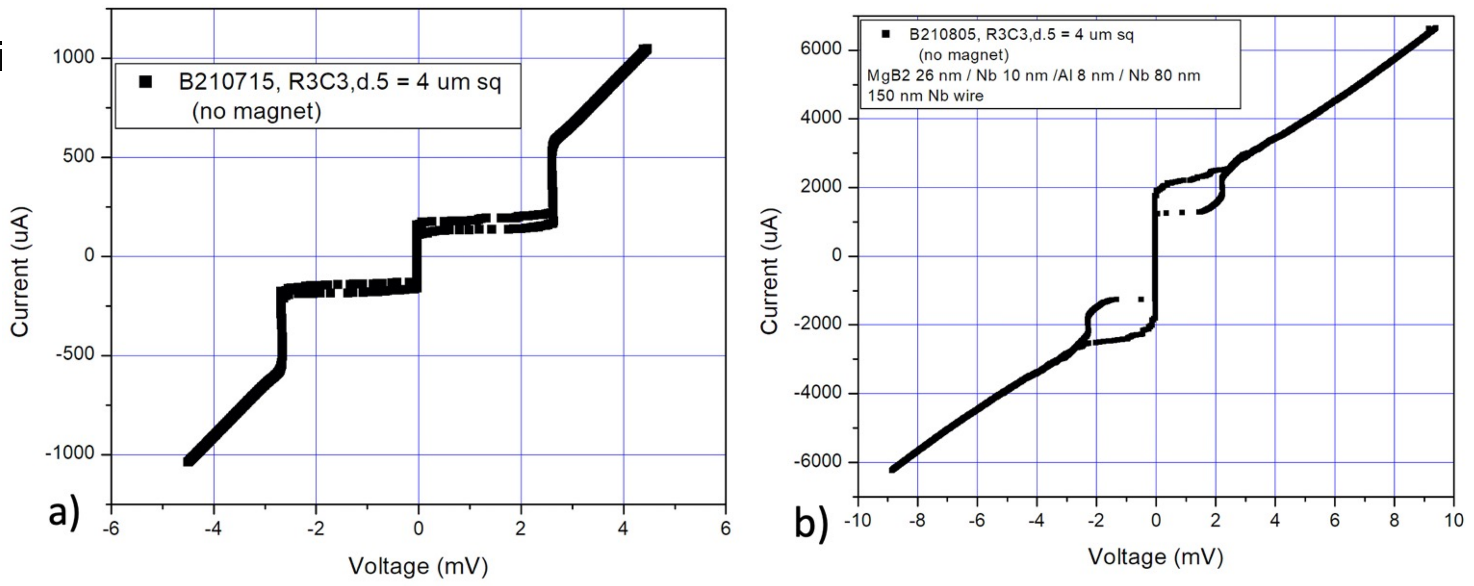

Figure 5. a) 4x4 mm Nb/AlOx/Nb SIS junction on Oxidized Silicon. b) 4x4 µm Nb/AlOx/Nb SIS junction on MgB2/SiNx/Si. The Base Nb is 20 nm.

Significance/Benefits to JPL and NASA

The goal of the Spontaneous task was to fabricate Nb SIS mixers with varying base thickness on a relatively thick, yet better than 2 nm rms surface roughness MgB_2 ground layer. By systematically lowering the Nb SIS junction base layer on the MgB2 ground plane the superconducting energy gap of the Nb contact will increase through what is known as the proximity effect. By studying the SIS junction energy gap as a function of base thickness on the much thicker and higher Tc MgB2 ground plane the MgB2 coherence length can be assessed. Furthermore, building for the first time a Nb SIS tunnel junction on MgB2, the 'quality' can be addresses.

Significantly, the main focus of the task ended up improving the etch recipe of making smooth (~ 1.5 nm RMS) MgB2 ~50nm thick film on SiNx as the time allotted was not adequate for the entire scope of the work, given constrains related to other tasks and equipment repair. This work was done at Caltech by Chang Sub Kim. The use of SiNx wafers is an important technology development as future detection devices will most certainly utilize 'Silicon-on-insulator' (SIO) technology. With additional funding continued progress will be made.

References / Publications

Dependence of penetration depth, microwave surface resistance and energy gap of MgB2 thin films on their normal-state resistivity, B B Jin, T Dahm, C Iniotakis, A I Gubin, Eun-Mi Choi, Hyun Jung Kim, Sung-IK Lee, W N Kang, S F Wang, Y L Zhou, A V Pogrebnyakov, J M Redwing, X X Xi and N Klein, Supercond. Sci. Technol. 18 (2005) L1–L4

Terahertz surface impedance of epitaxial MgB2 thin film, B. B. Jin, P. Kuzel and F. Kadlec, T. Dahm, A. V. Pogrebnyakov and X. X. Xi, N. Klein, APPLIED PHYSICS LETTERS 87, 092503, 2005.

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