National Aeronautics and Space Administration

Device Design/Prototyping for In-House MgB2 Superconducting Thin Films

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Objectives

The objective of this task was the fabrication of prototype devices using MgB2 thin films. Two applications of the thin films were outlined in the proposal. These applications are signal transmission and non-linear kinetic inductance (KI) devices, both of which hope to utilize the material to move into the THz frequency range. Though both of these applications require low RF losses in the material, for signal transmission KI is an undesirable perturbation of the geometric inductance that must be accommodated for in the design. Alternatively, for non-linear KI devices such as quantum limited amplifiers and frequency multipliers, the fraction of total inductance made up by this superconducting phenomenon is ideal when maximized. In the most basic assumption, the KI scales with the square of the resistivity in the films. NbTiN and TiN which are used in existing KI devices have resistivities around 100 μΩ·cm and Nb, which is used for transmission lines has resistivity on the order of a few μΩ·cm. MgB2 is highly tunable from <10 μΩ·cm to > 200 μΩ·cm by adjusting the Mg/B ratio in the films. The demonstration of device fabrication and performance metrics established in this effort were used to submit a ROSES APRA proposal.

Background

The material Magnesium Diboride was discovered to be superconducting in 2001, with a bulk transition temperature of 39 K. Since then many different techniques have been attempted in order to synthesize practical MgB$_2$ thin films for electronics and detector applications. The most promising techniques to date have been very unique processes requiring expensive tools and sometimes very hazardous materials. Under the Nancy Grace Roman Technology Fellowship, a novel technique has been formulated for in-house films at JPL/Caltech utilizing common PVD techniques. Over the past year, these films have achieved critical temperature > 35 K with smooth, large area capability. The NGRTF program has enabled the development of these thin films, however, there are a number of applications that require some prototype demonstrations for infusion of the novel material into promising applications. More specifically, some proof of concept was necessary to show that these great films can be made into great devices.

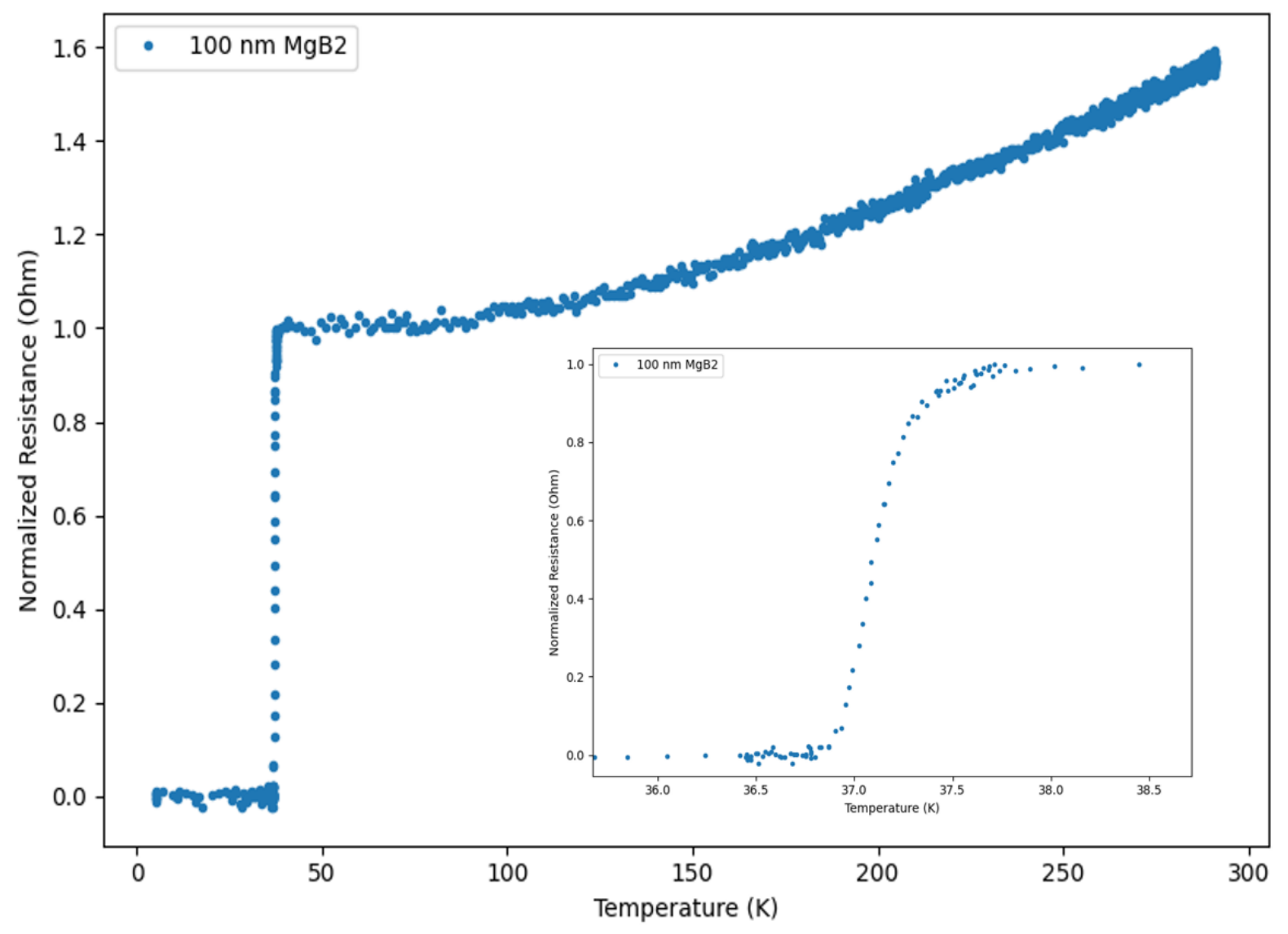

Figure 1. Resistance verses temperature for a 100 nm-thick MgB2 thin film grown at JPL/Caltech. Inset zooms in to the transition above 36 K.

Approach and Results

In this work, we fabricated devices made with the existing MgB2 thin film process and characterized these devices. This project enabled the first fabrication of MgB2 thin films on a 4" wafer (see fig. 1a). Films grown on this scale showed uniformity better than 3% across the wafer, as shown in Fig. 1b. The array of devices on this wafer included CPW resonators and bridges designed for 4-point DC measurements. The fast turnaround of our process enabled about 5 fabrication runs, and a new maskless lithography tool at the MDL enabled changes in the design from run to run. From the first fab run to the last, the yield and performance improved in almost every figure of merit.

The main figure of merit for these films beyond the critical temperature is the critical current density (JC), or the maximum supercurrent through a specified cross-sectional area. To measure this, a test chip was designed with different linewidths. Devices ranged in width from 1 um wide to 20 um wide (see fig 1c). The early results achieved anywhere from 2-8 MA/cm2 but after modifying the recipe to minimize defects in the films, JC ~ 10 MA/cm2 was achieved in these films. Fig. 1d shows the temperature dependence of the critical current density of the last fab run during this effort.

Microwave resonators were also made and characterized from these films. The initial low yield and quality factor in the first devices demanded that effort be put into improving performance and yield of these microwave devices. The first devices had internal Qi (a measure of losses in the superconducting and dielectric material system) around 1000. This value is poor compared to more mature materials, where values around 10^6 can be achieved. By improving the recipe used to synthesize the films, the Qi was improved by nearly an order of magnitude to 10^4. This is actually the limit you might expect for the substrate we are using (LPCVD SiNx on Si). We are working to reduce the thickness of the nitride to negligible values in terms of dielectric losses. Beyond the substrate, the highly reactive nature of Mg means that the surface of the devices is also typically covered by a dielectric to prevent oxidation of the MgB2. We hope to stabilize the films so that a self-limiting native oxide (few nm thick) will sufficiently passivate the devices.

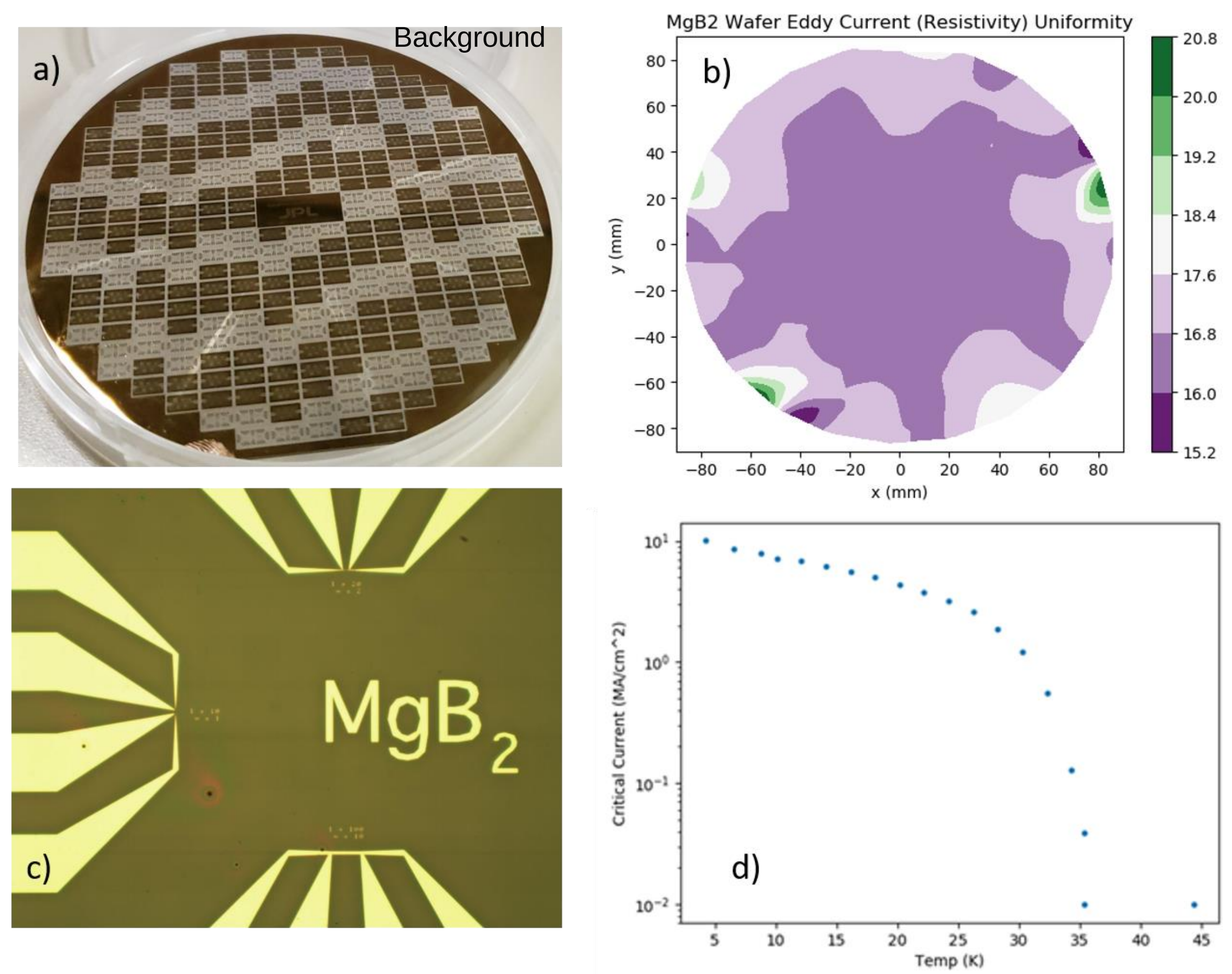

Figure 2. (a) Example of wafer scale fabrication of MgB2 thin films. The 4" wafer includes an array of chips for testing critical current density and RF losses. (b) Measurement of sheet resistance across a 4" wafer. Spread is just 2-3 % across the whole wafer. (c) Close up image of a test structure to measure the critical current density in the films. (d) Temperature dependence of the critical current density in the films. Values at low temperature exceed 107 A/cm2.

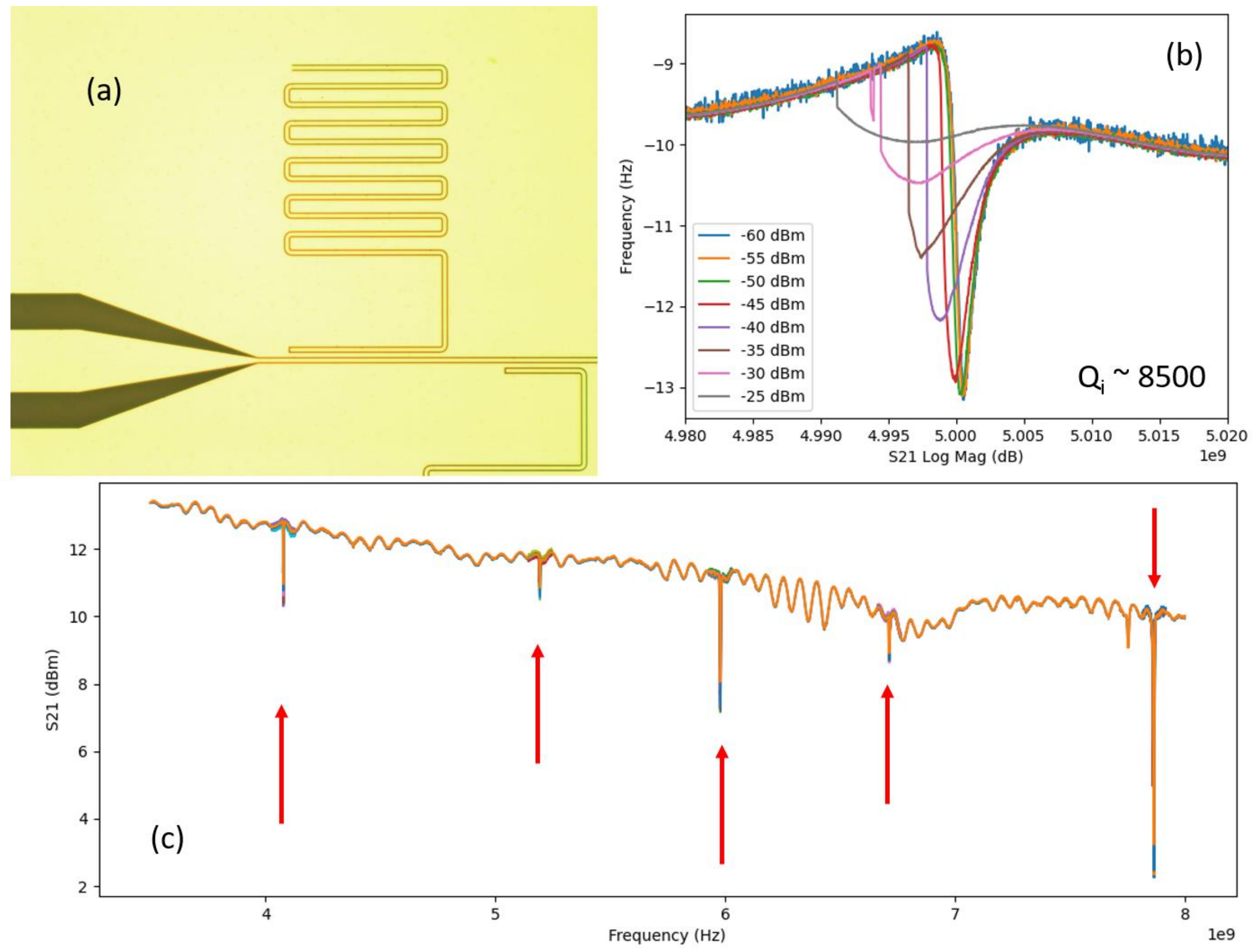

Figure 3. Example of CPW resonators fabricated for this effort. (a) Optical image of a typical device. (b) One of the best resonators achieved through this effort. (c) Sweep showing all five resonators achieved on a single chip (identified by the red arrows). Early devices only saw 1-2 resonators yielding, likely due to weak links in the resonator cpw shortening the effective length.

Significance/Benefits to JPL and NASA

JPL has a history of being at the forefront of mm/sub-mm technology for doing space science for decades. In recent years this has been due to the invention of many devices utilizing the non-linear kinetic inductance. This work is advancing the state of the art (and hence TRL) of a novel material that is potentially the only solution to moving these devices to frequencies beyond 1 THz or operating at higher temperatures. As these films become more available and widely known, the application base continues to grow. The prospects for this material to enable or enhance future science instruments is growing exponentially as this research is disseminated and applications advance in tandem.

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