Fabricating Superconducting Microwave Resonators for On-Chip Electron Spin Resonance Spectroscopy

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ABM Contact Aligner, PT770 Etcher, DISCO Dicing Saw

Abstract:

Electron spin resonance (ESR) spectroscopy has been a useful tool for measuring defect spins in semiconductors [1-6]. We are utilizing the robust capabilities of the Cornell NanoScale Facility (CNF) to develop an ESR spectrometer with the capability to measure defect spins in MBE-grown films as thin as 100 nm. Here, we demonstrate a planar microwave resonator, the principal device to be used in the spectrometer, fabricated using the superconducting metal niobium (Nb). The superconducting metal allows us to shrink the dimensions of our device by a hundred times, compared to a copper resonator, while avoiding any kind of resistive loss. This allows us to simultaneously benefit from a high quality-factor (*Q*-factor) and a small spatial extent of the microwave-spin interaction.

Summary of Research:

Electron spin resonance (ESR) spectroscopy is based on exploiting the Zeeman interaction between a magnetic field and a spin. Ever since it was proposed to study nuclear spins nearly a century ago [8], it has been a useful tool to study spins in materials (1-7).

A (non-oscillating) magnetic field splits degenerate spin states by an energy, $E = \gamma_S B$ (assuming spin-1/2 particles), where γ_S is the gyromagnetic ratio (the ratio between the magnetic moment of a particle to its angular momentum) and B is the applied magnetic field. The energy E for magnetic fields on the order of 1 T can easily be supplied by microwaves of frequencies, $f \sim$ 1-10 GHz.

Thus, the essential idea of ESR spectroscopy is that by supplying microwave radiation to semiconductor samples subject to a magnetic field, we can induce transitions between spin states of defects when the condition, $hf = \gamma_S B$ is met, where h is Planck's constant.

By observing these transitions, we can extract the gyromagnetic ratio, γ_S, associated with a defect-spin state, giving us insight into its electrical/magnetic properties. Figure 1 shows a schematic of such an ESR experiment.

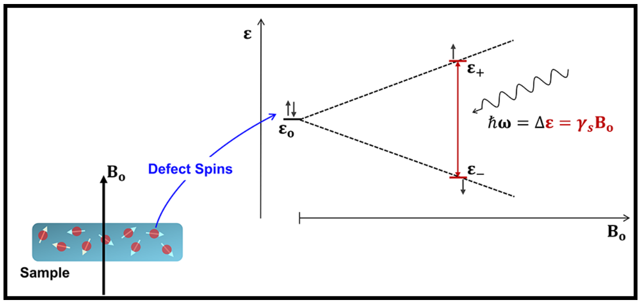

Figure 1: Schematic showing the basic principle of electron spin resonance (ESR) spectroscopy.

ESR spectrometers, by and large, use a 3-D microwave resonator to deliver microwaves to samples subject to a DC magnetic field. 3-D microwave resonators, owing to their large magnetic field mode volumes, are not sensitive to MBE grown thin films. Using a 2-D, planar microwave resonator we can minimize the magnetic field mode volume, and thus minimize the magnetic field fill factor (represents the fraction of magnetic field seen by the film being probed). A small magnetic fill factor (close to unity) will allow us to probe defect spins in semiconductor films as thin as ~ 10 nm. The key to a high magnetic fill factor is shrinking the dimensions of the resonator. However, small dimensions also mean higher resistive losses in metals. We use the superconducting metal Nb, to overcome this trade-off, thus maintaining a high magnetic fill-factor and near-zero resistive loss [9]. The small mode volume of a 2-D planar resonator also means that much of the magnetic field is within the substrate on which the resonator is patterned. To minimize the dielectric loss resulting from this, we use a sapphire substrate, owing to sapphire's small loss-tangent and high dielectric constant.

Methods and Results:

We used the Cornell NanoScale Facility (CNF) to fabricate this superconducting 2D resonator. Figure 3a shows the fabrication procedure for our devices. We sputter deposit 100 nm of Nb. We measured the temperature dependent resistance of this film and found the superconducting transition temperature T_c, to be ~ 6 K. Since we will be conducting our experiments in a 4.2 K liquid He cryostat, this T_c will work well for our experiments. Figure 4 shows the critical dimensions of the fabricated device.

Conclusion and Future Steps:

The next step is to measure the transmission through the fabricated resonators and measure the *Q*-factor. This will be followed by an ESR measurement of MBE grown thin films of ultrawide-bandgap semiconductor β-Ga_2O_3.

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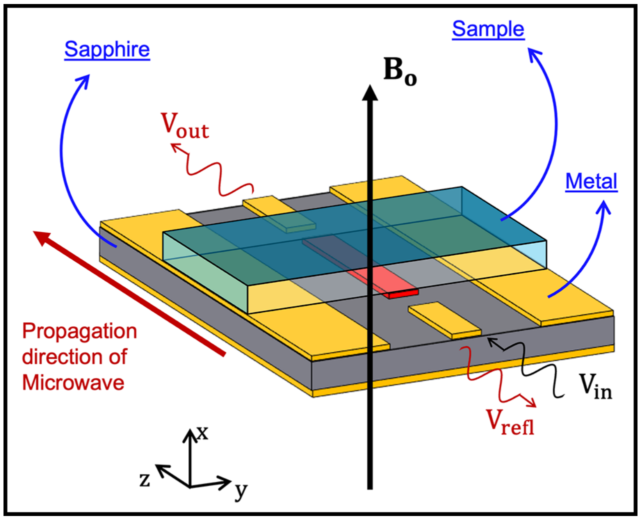

Figure 2: Basic layout of our ESR measurement. The planar microwave resonator lies at the heart of the setup and is fabricated at the Cornell NanoScale Facility (CNF).

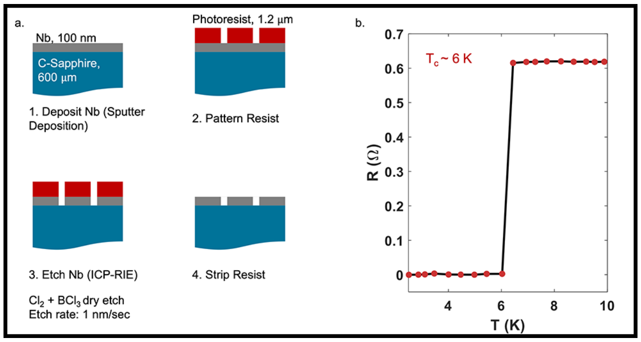

Figure 3: (a) Shows the schematic of the fabrication process used to fabricate our microwave resonator. (b) Shows Resistance vs. Temperature of our deposited Nb film.

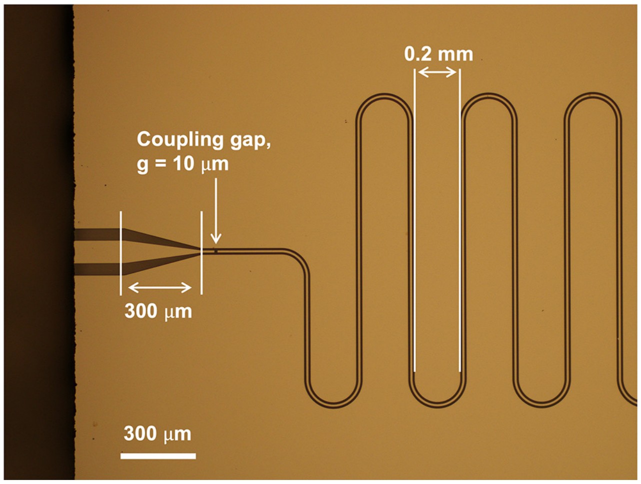

Figure 4: Key dimensions of the fabricated superconductor microwave resonator.