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

CNF Project Number: 2705-18

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Primary Source(s) of Research Funding: Air Force Research Lab (AFRL) Grant No. FA9550-18-1-0529

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Primary CNF Tools Used: AJA sputter deposition tool, CVC SC4500 odd/even evaporator, copper electroplating hood, Logitech Orbis chemical-mechanical-polisher (CMP)

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, with an internal *Q*-factor over 150 at ~ 10 GHz, fabricated completely at CNF. We use a unique "photoresist-mold-defined" fabrication process to pattern copper thicker than 5 μm.

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.

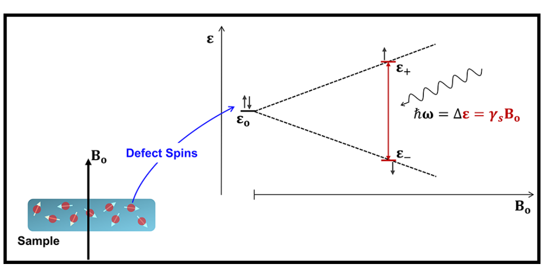

Figure 1: Schematic showing the basic principle of electron spin resonance (ESR) spectroscopy.

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.

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 ~ 100 nm. However, 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. To minimize the conductor loss, we use thick copper (~ 5 μm) to define our resonating circuit. Figure 2 shows the experimental setup we use for ESR spectroscopy.

Methods and Results:

We used the Cornell NanoScale Facility (CNF) to fabricate this 2D resonator. Since we had to pattern copper 5 μm thick, we adopted a unique fabrication process [9], which is schematically described in Figure 3a.

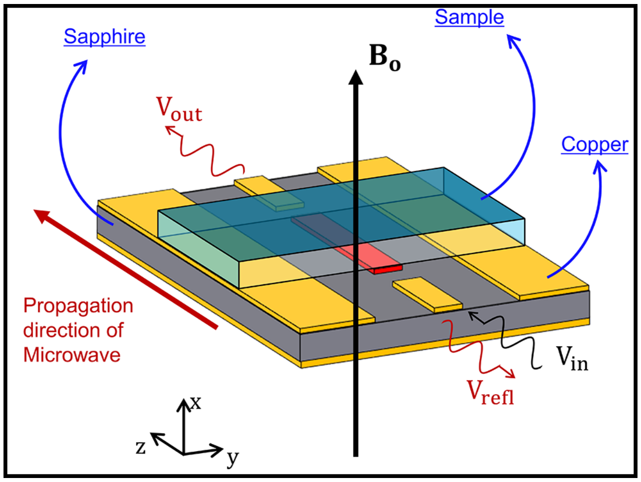

Figure 2: Basic layout of our ESR measurement. The planar microwave resonator lies at the heart of the setup and is fabricated at the Cornell NanoScale Facility (CNF).

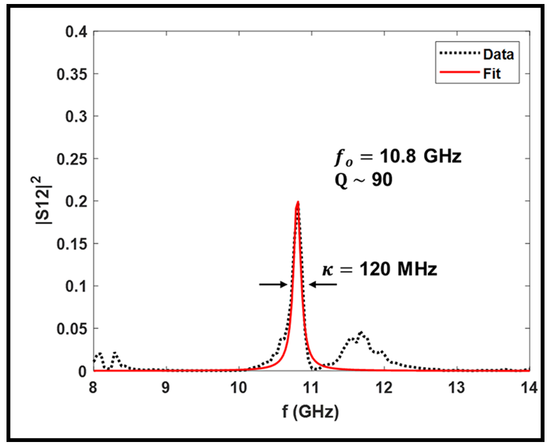

Figure 4: The S21 parameter (transmission coefficient) of our resonator, along with a Lorentzian fit to the data.

The basic principle is as follows. (1) We first define a mold by patterning thick (~ 6 μm) photoresist on a 600 μm sapphire substrate, using *contact photolithography*. (2) We then deposit a thin (~ 80 nm) film of platinum using the *sputter deposition tool*. (3) This platinum film serves as the seed to then *electroplate* ~ 8 μm of copper. (4) We then use the *chemical-mechanical-polisher* (CMP) in the cleanroom to lap and polish the copper film down to ~ 5 μm and make it smooth (roughness on the order of 10 nm). (5) Finally, we strip the photoresist, which leaves us with our patterned devices. A picture of the finished devices can be seen in Figure 3b.

Figure 4 shows the S21 (transmission coefficient) parameter of our device. We clearly see a sharp resonance at 10.8 GHz, which we fit using a Lorentzian lineshape. This resonance corresponds to a linewidth of 120 MHz, a loaded Q-factor of 90, and an internal Q-factor of ~ 162.

Conclusion and Future Steps:

This microwave characterization shows that our devices are functioning well with high quality factors. We hope to now use these devices to do ESR measurements on semiconductor thin films.

Future work at CNF will also involve fabricating devices that use a superconducting metal (niobium or aluminum), instead of copper, to define out resonators. This will allow us to reduce our conductor loss to a point that we can approach the quantum limit of spin detection [10].

Acknowledgements:

I would like to thank the CNF staff, without whom this work would not have been possible and will not be able to continue. I especially thank Chris Alpha, Aaron Windsor, Tom Pennell, Garry Bordonaro, and Jeremy Clark for their invaluable input and support.

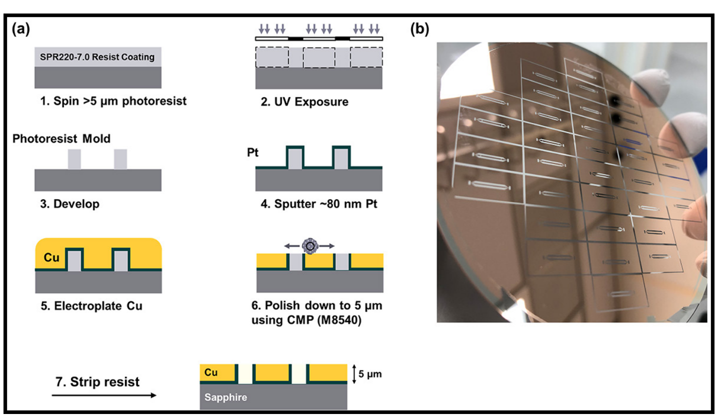

Figure 3: (a) Shows the schematic of the fabrication process used to fabricate our microwave resonator. (b) Shows the finished devices made using said process.

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