Low Loss Superconducting LC Resonator for Strong Coupling with Magnons

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Primary CNF Tools Used: AJA Sputter Deposition, Heidelberg Mask Writer - DWL2000, GCA 6300 DSW 5X g-line Wafer Stepper, YES Asher, PT770 Etcher - Left Side, P7 Profilometer, Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), JEOL 6300, Dicing Saw – DISCO, Westbond 7400A Ultrasonic Wire Bonder

Abstract:

We present a hybrid system based on strongly coupled microwave photons hosted by a microstructured resonator and magnon modes of the molecular ferrimagnet vanadium tetracyanoethylene (V[TCNE]x). Using Cornell NanoScale Facility (CNF), we develop a process to integrate the fabrication of high quality-factor (Q-factor) superconducting LC resonators and the deposition of lithographically patterned V[TCNE]x films. We improve the encapsulation of the V[TCNE]x film using atomic layer deposition (ALD) of alumina (Al2O3). We also discuss the design and fabrication of new broadband structures capable of exploring high-power parametric processes in V[TCNE]x films.

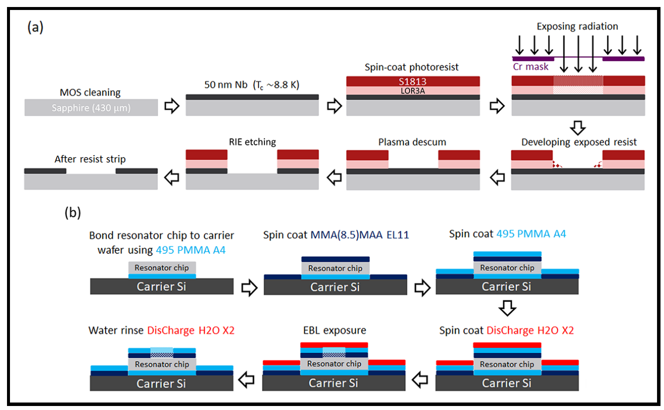

Figure 1: Process flow for (a) patterning the LC resonator using photolithography, and (b) e-beam patterning for V[TCNE]x deposition.

Summary of Research:

This research is focused on studying two systems.

(i) A strongly coupled hybrid photon-magnon system where the coupling strength between the two sub-systems exceeds the mean energy loss in either of them. The key figure-of-merit of this hybrid system is its cooperativity $C=4g^2/k_m k_r$, where g is the coupling strength between magnons and photons, and k_m and k_r are the damping rates for magnons and photons, respectively. The system operates in strong-coupling regime if $C > 1$. (ii) The non-linear excitation of magnons in V[TCNE]x waveguides using high microwave powers.

As a cavity for microwave photons for the coupled photon-magnon system, we use lumped-element planar LC resonators fabricated on superconducting niobium thin-film offering high Q-factor and thus low ..... The basic steps for patterning our LC resonators using photolithography are shown in Figure 1(a).

First, we sputter a 50 nm thick niobium film (thickness measured using P7 profilometer) on a MOS cleaned sapphire substrate using the AJA sputter deposition tool. The superconducting transition temperature (T_c) of our niobium film is ~8.8 K, which is high enough to offer low damping in our operating temperature range of 0.4 - 4 K. The resonator design, patterned on a photomask using Heidelberg Mask Writer-DWL2000, is then cast onto the resist coated wafer (we spin-coat a resist bilayer of LOR3A and S1813) using 5X g-line Wafer Stepper. The developed resist (in AZ726MIF) is descummed in YES Asher followed by dry etching of niobium in PT770.

Finally, we strip the resist in 1165 and dice the wafer using Dicing Saw–DISCO to separate the chips patterned on the wafer. For the magnon sub-system, we use the low-loss organic ferrimagnet V[TCNE]x with a low

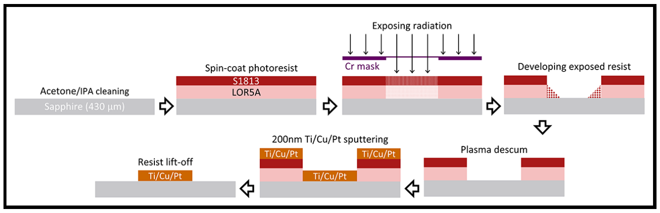

Figure 2: Process flow for fabricating broadband chips with Ti/Cu/Pt tri-layer.

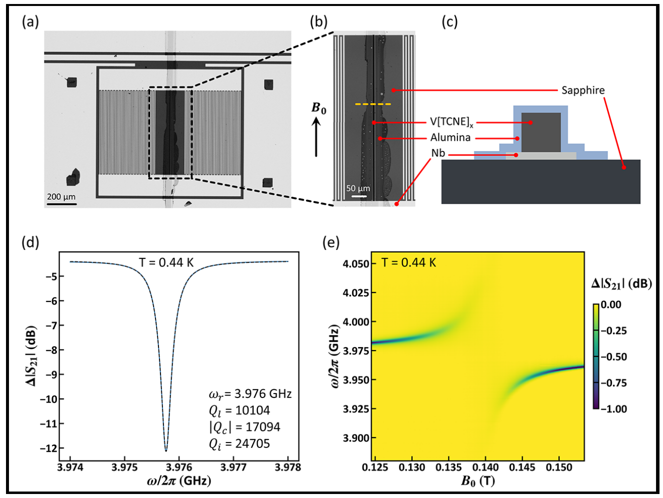

Figure 3: (a) Microscope image of LC resonator device with patterned V[TCNE]x and ALD encapsulation. (b) Magnified microscope image around the region marked with black dashed rectangle in (a). (c) Illustration of the cross section of the device along the yellow dashed line in (b). (d) Fitted (black dashed line) resonator response (blue curve) with extracted Q-factors at 0 T at 0.44 K. (e) 2D colormap of .|S21| as a function of static magnetic field and microwave frequency at 0.44 K.

Gilbert damping $\alpha \sim 10^{-4}$ offering long magnon lifetime and thus low k_m Using e-beam lithography in JEOL 6300 or Nabity Nanometer Pattern Generator System (NPGS) connected to Zeiss Supra SEM, we pattern a 6 μm wide and 600 μm long bar on the 10 μm wide and 600 μm long inductor wire using the steps shown in Figure 1(b). We then ship the exposed resonator chips to our collaborators in Ohio State University for V[TCNE]x growth and liftoff.

To avoid saturation of the superconducting niobium film due to formation of vortices at high microwave powers, we chose to fabricate the broadband chips with low resistivity Ti/Cu/Pt tri-layer. The steps for this fabrication are illustrated in Figure 2. First, we coat clean (with acetone followed by IPA) sapphire wafers with bilayer of LOR5A and S1813. The resist coated wafer is then exposed in 5X g-line Wafer Stepper to be patterned with the design written on a photomask using Heidelberg Mask Writer-DWL2000. The developed resist (in AZ726MIF) is descummed in YES Asher followed by deposition of 200 nm thick Ti/Cu/Pt tri-layer in the AJA sputter deposition tool. Finally, we lift-off the resist using 1165 and then dice the wafer using Dicing Saw–DISCO.

The degradation of the organic ferrimagnet V[TCNE]x when exposed to air has necessitated its encapsulation, primarily with epoxy and cover glass as also adopted in our earlier studies [1,2]. Despite offering protection against air exposure, this encapsulation suffers from the demerit of exerting large inhomogeneous strain on V[TCNE]x as the sample is cooled down due to the disparate thermal expansion coefficients of sapphire and epoxy. A solution to this problem is to encapsulate with a material that has a similar thermal expansion coefficient to sapphire, like alumina (Al_2O_3). To test the performance of the hybrid resonator-magnon system with alumina as the encapsulation material, we collaborated with Ohio State University for V[TCNE]x growth and Northwestern University for the atomic layer deposition (ALD) of alumina. Figure 3(a)-(c) showcases the microscope images and the schematic cross-section of the alumina encapsulation on the V[TCNE]x bar grown on the inductor wire of our LC resonator. The fitted resonator response at 0.44 K as shown in Figure 3(d) reveals the internal Q-factor as high as 24705. The anti-crossing obtained for the coupled resonator-magnon system is shown in Figure 3(e). The uniaxial anisotropy field H_k, a quantitative measure of the inhomogeneous strain on the V[TCNE]x, extracted from the anti-crossing turns out to be 6.8 mT which is an order of magnitude lower than that obtained for our previous epoxy encapsulated sample [2].

Conclusions and Future Steps:

We have demonstrated our successful upgradation of the V[TCNE]x encapsulation to reduce the strain and hence the magnetocrystaline anisotropy at the cryogenic temperature. We will integrate the broadband chips with V[TCNE]x encapsulated with alumina to explore high-power non-linear instability processes in V[TCNE]x.

References:

[1] H. F. H. Cheung, et al, "Raman Spectroscopy and Aging of the Low-Loss Ferrimagnet Vanadium Tetracyanoethylene", The Journal of Physical Chemistry C 125, 20380 (2021).

[2] Q. Xu, et al, "Strong Photon-Magnon Coupling Using a Lithographically Defined Organic Ferrimagnet", Advanced Science 11, 2310032 (2024).