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, AJA Ion Mill, 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 quantum system based on strong coupling between microwave photons host by micro-structured resonators 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 thin-film superconducting LC resonators and the deposition of lithographically patterned V[TCNE]$_x$ films. We explore ways to enhance the quality factors of our LC resonators with the aim to elevate its performance in the strong coupling regime. We also focus on designing and fabricating new resonator structures capable of decoupled excitation and read-out of the hybrid magnonic system.

Summary of Research:

This research is focused on studying 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 $C = 4g^2/\kappa_m\kappa_r$, where g is the coupling strength between magnons and photons, and κ_m and κ_r are the damping rates for magnons and photons, respectively. The system operates in strong-coupling regime if $C > 1$.

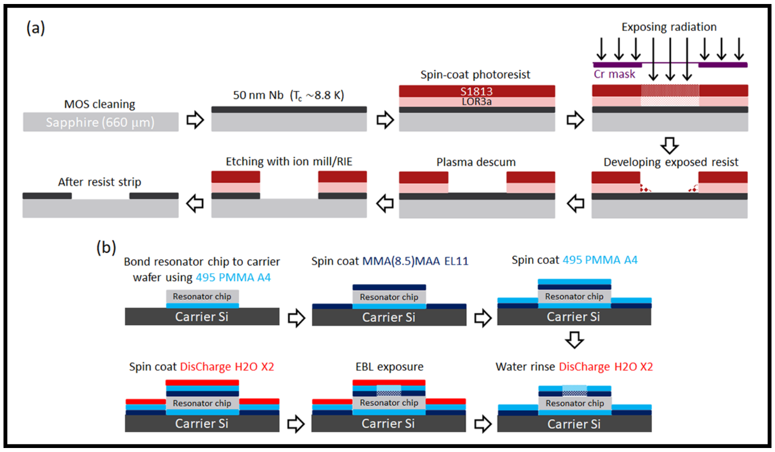

Figure 1: Process flow for (a) patterning the LC resonator using photolithography, and (b) e-beam patterning for V[TCNE]$_x$ deposition.

In this work, we use lumped-element planar LC resonators fabricated on superconducting niobium thin-film offering high quality factor (Q-factor) and thus low κ_r. 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 MOS cleaned sapphire substrate using AJA sputter. The superconducting transition temperature (T_c) of our niobium film comes out to be ~ 8.8K, which is high enough to offer low damping. 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 bi-layer of LOR3A and S1813) using 5X g-line Stepper. The developed resist (in AZ726MIF) is descummed in the YES Asher followed by dry etching of niobium in AJA Ion Mill (and recently 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 Gilbert damping $\alpha \sim 10^{-4}$ offering long magnon lifetime and thus low κ_m. Using e-beam lithography in the 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.

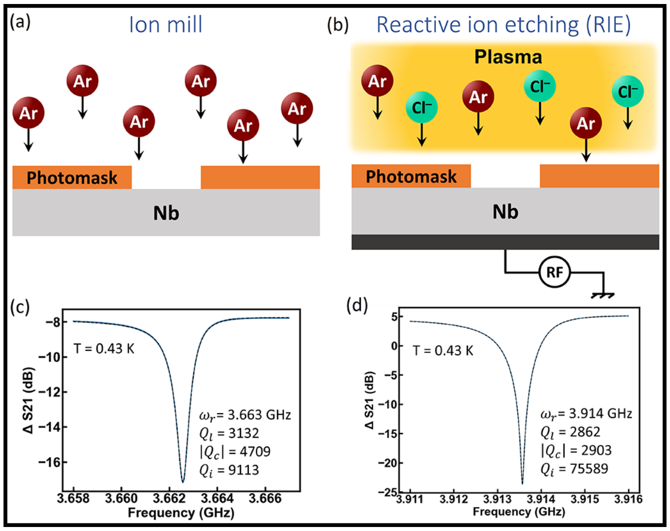

Figure 2: (a)-(b) The schematics of the ion mill and reactive ion etching processes, respectively. (c)-(d) Fitted resonator response with extracted Q-factors for the ion milled and reactive ion etched chips, respectively.

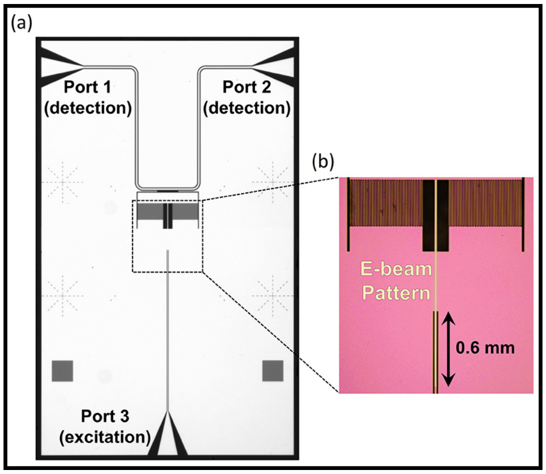

Figure 3: (a) Microscope image of the 3-port LC resonator with separated excitation and detection ports. (b) E-beam pattern with resist on (exposed and developed) for V[TCNE]$_x$ deposition.

The results on our first-generation coupled resonator-V[TCNE]$_x$ system are summarized in our recent arXiv article [1]. Our first-generation 2-port LC resonators were etched by ion milling (AJA Ion Mill) by neutral argon beam [Figure 2(a)]. The process of ion milling for our resonator design suffers from the drawbacks of — (i) slow overall etch-rate, (ii) non-uniform etch-rates at different parts of the design (especially drastically lower etch-rates for interdigitated capacitor fringes than that at other parts), (iii) substrate heating during the physical bombardment process of the high-energy Ar-beam, and (iv) possibly the etching residues of ejected niobium. These factors contributed to limit the internal *Q*-factor of our LC resonators to ~ 10^3 as shown in the transmission spectrum of Figure 2(c). The details of the fitting parameters are elucidated in reference [1]. To overcome the limitations of ion milling, we have recently adopted a chlorine-based reactive ion etching (RIE) process (PT770) shown in Figure 2(b). The key advantages of this etching method are — (i) extremely high etch-rates, (ii) uniform etching at all parts of the resonator, (iii) minimal heating of the substrate, and (iv) niobium is etched in the form of volatile niobium chlorides minimizing the contamination by residues. Upgradation to this RIE process resulted in an increase in the internal *Q*-factor of our LC resonators by a factor of ~ 8 [Figure 2(d)].

The performance of our old 2-port resonator design is limited due to the inseparable excitation and detection mechanism of the hybrid system. To get around this limitation, we have modified our resonator design where the V[TCNE]$_x$ bar is extended over a third port employed to excite the magnons without driving the resonator. The magnons are then expected to travel to the resonator which, in this case, can be used solely for sensing. Figure 3(a) shows our very first design for the 3-port resonators. We are currently in the process of optimizing this design with a primary goal of achieving high internal-*Q*, moderate co-operativity for the coupled magnon-resonator system, and a minimal crosstalk between the excitation port and the LC resonator system. The e-beam pattern for a future V[TCNE]$_x$ deposition on the 3-port resonator chip is shown in Figure 3(b).

Conclusions and Future Steps:

We have demonstrated the fabrication and integration of a low-loss hybrid photon-magnon system based on strong coupling between superconducting LC resonators and the organic ferrimagnet V[TCNE]$_x$. We have been able to enhance the intrinsic quality factor of our LC resonator by improved fabrication. We have further modified our resonator design for future experiments envisioned to disentangle the excitation and read-out mechanisms. After a successful optimization of our primordial 3-port resonator design, we plan to impose further modification to the design for developing experiments for magnon lasing and sensing magnon Bose-Einstein condensate (mBEC) states.

References:

[1] Q. Xu, H. F. H. Cheung, D. S. Cormode, T. O. Puel, H. Yusuf, M. Chilcote, M. E. Flatté, E. Johnston-Halperin, and G. D. Fuchs, "Strong photon-magnon coupling using a lithographically defined organic ferrimagnet", arXiv:2212.0442.