Low Loss Superconducting LC Resonator for Strong Coupling with Magnons

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Primary Source(s) of Research Funding: Center for Molecular Quantum Transduction (CMQT)
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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, P7 Profilometer, Zeiss Ultra SEM, DISCO Dicing Saw, Nabity Nanometer Pattern Generator System (NPGS), Westbond 7400A Ultrasonic Wire Bonder

Abstract:

We design, fabricate and study an on-chip superconducting LC resonator that is strongly coupled to a magnon mode of the molecular ferrimagnet vanadium tetracyanoethylene ($V[TCNE]_x$). We demonstrate a fully integrated, lithographically defined photon-magnon hybrid quantum system in the strong coupling limit where all elements have low damping.

MATERIALS

Summary of Research:

The goal of this research is to study a strongly coupled hybrid quantum device composed of a superconducting microwave resonator and a magnon mode. A key figure-of-merit is the cooperativity $C = 4g^2/K_m K_r$ between magnons and resonator photons, where g is the coupling strength between magnons and photons, and K_m, K_r are damping rate for magnons and resonator respectively. The two systems are strongly coupled if $C > 1$.

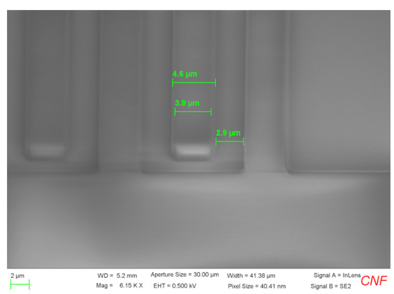

Figure 1: SEM image of the profile of resist after being exposed and developed.

We use $V[TCNE]_x$ as the magnetic material in this work because of its low Gilbert damping rate $\alpha \sim 10^{-4}$ and thus low K_m, and because it can be grown on most materials and patterned via electron beam lithography. To increase the coupling g, we design an LC resonator with a small inductance and a narrow inductor wire. We pattern the $V[TCNE]_x$ directly on the inductor wire of LC resonator.

We first designed the LC resonator based on a single layer of photolithography. We used KLayout to design the structure and ADS to simulate its microwave response. The simulation predicts a resonance frequency around 4.2 GHz. We then patterned the photomask with the Heidelberg Mask Writer - DWL2000.

The superconducting material for our device is niobium that we deposited on sapphire using the AJA Sputter Deposition (second tool) at 600°C. The resulting Nb thickness is around 60 nm measured with the P7 profilometer. It has a critical temperature (T_c) of 7.3 K. The high T_c of Nb and the low loss tangent of sapphire help limit the damping rate of the superconducting device.

We patterned the Nb using photolithography followed by dry etching. We spun LOR3a and then S1813 on the Nb with hotplate baking, exposed the resists in GCA 6300 DSW 5X g-line stepper, and then developed the resist in MIF 726. The profile of the patterned resists was checked in Zeiss Ultra SEM. Figure 1 shows the SEM image of the patterned resists which looks perfect.

Then we descummed the developed resists in YES Asher, etched the Nb not covered by resist in AJA ion mill, and then put the wafer into the solution 1165 to strip off all the resists on the wafer. We patterned around 50 resonators on a 2-inch wafer. Because of the dust on the wafer during photolithography, around 20 of the devices have defects on their patterns, but the remaining 30 looked perfect under the microscope.

Before $V[TCNE]_x$ deposition, we tested the resonator itself. For measurement setup, we cut the wafer and

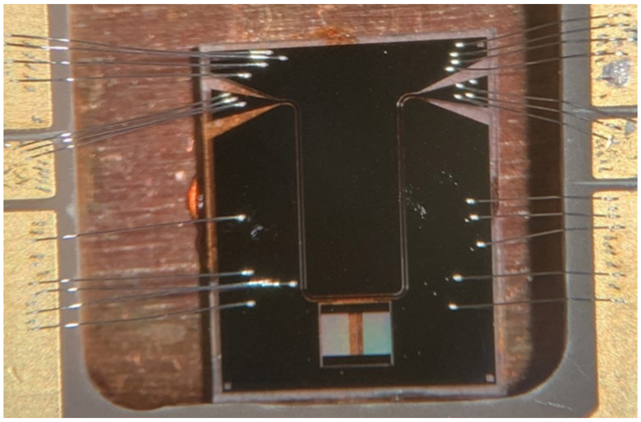

Figure 2: The LC resonator device bonded to a chip carrier.

separated those 50 devices using the DISCO dicing saw, glued one of the resonators on a PC board with varnish and then used the Westbond 7400A Wire Bonder to wire-bond the device for microwave measurement.

Figure 2 shows a microscope image of the device wire bonded on the PC board.

With a vector network analyzer (VNA), we tested the resonator device in a He-3 cryostat at base temperature 0.43 K. The transmission spectrum of the frequency scan shows the resonator has a quality factor of 5031.

We use an electron-beam lithography liftoff process to template the growth of V[TCNE]$_x$. We spun the e-beam resist on the resonator chip and then exposed the resist in Nabity Nanometer Pattern Generator System (NPGS). Figure 3 shows the device after being exposed in the NPGS, where vertical line of the T-shaped part is the inductor wire.

We then shipped the templated device to Ohio State University for collaborator Donley Cormode in Professor Ezekiel Johnston-Halperin's group for V[TCNE]$_x$ growth and liftoff. The dimension of the V[TCNE]$_x$ is 600 µm times 6 µm times 300 nm.

We studied the integrated hybrid device at 0.43 K. We measured the microwave transmission coefficient using a vector network analyzer.

Figure 4 shows the trans-mission spectrum as a function of magnetic field and frequency. The avoided level crossing characteristic of a strongly coupled hybrid device is observed. We find the coupling coefficient is g = 90.4 MHz, the resonator damping rate is K_r = 0.90 MHz and the magnon damping rate is K_m = 33.3 MHz. Using these values, we find the cooperativity $C = 4g^2/K_mK_r$ = 1091, which greatly exceeds 1.

Conclusions and Future Steps:

We have demonstrated the design and fabrication of a low loss superconducting on-chip LC resonator in the CNF cleanroom. Our device achieved strong coupling between V[TCNE]$_x$ magnons and resonator photons with a cooperativity greater than 1000. In this experiment the V[TCNE]$_x$ appeared inhomogeneously broadened (not limited by intrinsic damping). We may increase the cooperativity further by better understanding and controlling the mechanisms of V[TCNE]$_x$ linewidth at cryogenic temperatures.

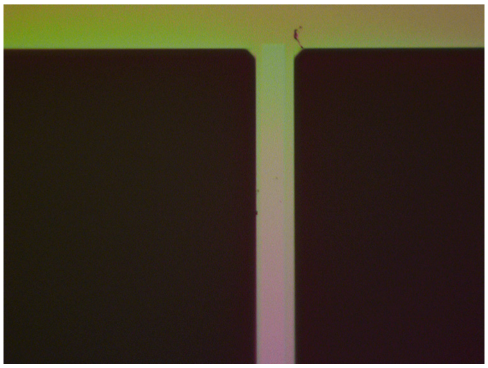

Figure 3: Microscope image of LC resonator device after being coated with e-beam resist and then being exposed in Nabity. The T-shaped part represents the superconducting film, and the lighted vertical rectangle on the vertical line of the T-shaped part represents the Nabity exposed area.

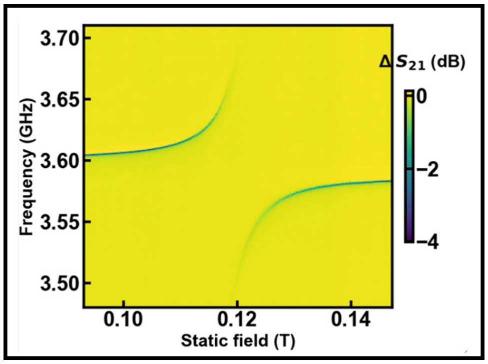

Figure 4: The transmission spectrum of field-frequency scan of the resonator-magnon system. The anti-crossing of the dip is the signature of coupling between resonator photons and V[TCNE]$_x$ magnons.

MATERIALS