Optimization of infrared and magnetic shielding of superconducting TiN and Al coplanar microwave resonators

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Abstract

We present a systematic study of the effects of shielding on the internal quality factors \(Q_i\) of Al and TiN microwave resonators designed for use in quantum coherent circuits. Measurements were performed in an adiabatic demagnetization refrigerator, where typical magnetic fields of 200 μT are present at the unshielded sample stage. Radiation shielding consisted of 100 and 500 mK Cu cans coated with infrared absorbing epoxy. Magnetic shields consisted of Cryoperm 10 and Sn plating of the Cu cans. A 2.7 K radiation can and coaxial thermalization filters were present in all measurements. TiN samples with \(Q_i = 1.3 \times 10^6\) at 100 mK exhibited no significant variation in quality factor when tested with limited shielding. In contrast, Al resonators showed improved \(Q_i\) with successive shielding, with the largest gains obtained from the addition of the first radiation and magnetic shields and saturating before the addition of Sn plating infrared absorbing epoxy.

Keywords: shielding, coplanar waveguide resonator, aluminum, titanium nitride

(Some figures may appear in colour only in the online journal)
The stainless steel microwave input line was thermally anchored and attenuated at all temperature stages terminating with a 50 Ω lossy filter with 3.5 dB of attenuation at 5 GHz to ensure thermalization of the coaxial lines and to absorb infrared photons [13]. At the coldest stage, Sn plated Cu coax cable was used and the total attenuation of the input line was 70 dB at room temperature. After the sample, two circulators were used to provide approximately 36 dB of isolation from microwaves propagating towards the sample from the output line. The signal then passed through another lossy filter before entering a Nb coax leading to a LNF-LNC4_8A HEMT at 2.7 K. A vector network analyzer recorded transmission spectra (S21) after passing through an additional room temperature amplifier. The resulting trace was fit using a least squares optimization described in [14].

Experimental data from the shielding study for Al CPW resonators are shown in figure 2. The sample was first mounted in a minimally shielded configuration consisting of a wirebonded chip in a Cu cryopackage with no lid such that the sample had no magnetic shielding and was directly exposed to 2.7 K infrared radiation. With this configuration, we measured a mean internal quality factor $Q_i = 1.71 \times 10^5$ at single photon powers ($\bar{n} \approx 1$). The addition of an initial layer of infrared shielding in the form of a cryopackage lid approximately doubled $Q_i$. Removing the lid and adding cryoperm at 2.7 K as an initial layer of magnetic shielding also resulted in $Q_i$ doubling. The cryoperm is nominally expected to reduce the magnetic field by a factor of $\sim 1500$. Since these two shields are protecting the Al CPW resonator from different loss mechanisms, we expect that their effects would combine linearly, and indeed the data show an improvement in $Q_i$ by a factor of 3.5 over the unshielded configuration. These systematic improvements confirm the trends reported in the literature [6], and we find that Al CPW resonators benefit from both infrared shielding and reduction in ambient magnetic fields.

With a closed cryopackage and cryoperm, we obtain $Q_i = 5.9 \times 10^5$. By adding subsequent layers of infrared radiation shielding in the form of two Cu cans, at 100 and 500 mK, which were designed to be nearly-light tight, we see a small increase to $Q_i = 6.45 \times 10^5$. Repeated measurement in this configuration three months later exhibited no degradation, but rather a slight increase in $Q_i$ representative of run-to-run scatter. Adding shielding beyond this configuration gives a null result where the variation of the sample with time is larger than any improvement due to the shielding. This small drift in $Q_i$ is not yet understood, and can also be seen by repeating many measurements within a single cooldown.

The shields that were shown to have little effect on $Q_i$ for Al CPW resonators were a 2 μm layer of Sn, a superconducting magnetic shield, and an $\sim 2$ mm thick coating of infrared absorbing epoxy on the inside of the 100 mK Cu can and on the surface of the cryopackage lid facing the sample. The Sn was electroplated onto the Cu radiation cans before Au plating. Devices tested with the Sn plating but without the cryoperm performed the same as having no magnetic shielding, suggesting that this specific type of shield is not effective. The infrared absorbing epoxy consisted of, by mass,
68% Stycast 2850 LT, 5% Catalyst 24LV, 7% Carbon lampblack, and 20% 350 μm SiC grit [15]. The lack of improvement in $Q_i$ after adding this epoxy suggests there is no infrared light within the 100 mK radiation can. To test our hypothesis, we removed the cryopackage lid but kept all other shields, resulting in a slightly decreased $Q_i$, but broader range of $Q_i$, and the highest $Q_i$ measured for Al CPW resonators in the shielding study at single photon powers, supporting the claim that resonators are not infrared light limited. The dominant source of drift in $Q_i$ appears to be cooldown to cooldown variations and infrared absorbing epoxy and Sn plating do not result in improvement greater than this drift.

Figure 2. (a) Single photon power $Q_i$ of Al CPW resonators at 100 mK in various shielding configurations for the five resonators on the die. The error bars represent the uncertainty of the least squares fit and the black + is the average of the five resonators. A: directly exposed to 2.7 K radiation in a 200 μT ambient field. B: with cryopackage lid. C: no lid, but with cryoperm at 2.7 K. D: lid and cryoperm. E and E’: lid, cryoperm, and 500 and 100 mK Cu cans repeated three months apart. F: with Sn on Cu cans. G: with infrared absorbing epoxy on lid and Cu cans. H: kept all shields, except cryopackage lid. I: kept all shields, except cryoperm. (b) $Q_i$ of all 5 resonators as a function of power in configurations A and E.

Figure 3. (a) Single photon power $Q_i$ of TiN CPW resonators at 100 mK in various shielding configurations for the five resonators on the die. The error bars represent the uncertainty of the least squares fit and the black + is the average of the five resonators. A: directly exposed to 2.7 K radiation in a 200 μT ambient field. B: with lid. C: with 100 and 500 mK Cu cans D: with cryoperm. E: Sn plate Cu cans. F: with infrared absorbing epoxy on Cu cans and surface of lid opposite the sample. A lack of systematic gain suggests that the film is strongly decoupled from loss due to flux vortices and quasiparticle generation in the films. (b) $Q_i$ of all five resonators as a function of power in configurations A and E.
For TiN, a strikingly different result emerges from the same systematic study, seen in figure 3. Again, starting with the sample directly exposed to 2.7 K radiation, and then adding successive shields, we see that $Q_i$ does not improve in a systematic way, but rather variations appear to be attributable to measurements being performed at different times, between which the sample is heated and cooled. Stray infrared light from higher temperature stages can cause excess quasiparticle generation in superconducting films, and Al is particularly susceptible to this effect since the superconducting gap is small and quasiparticle recombination times are slow [6, 16]. TiN has a 4.6 times larger superconducting gap, resulting in a predicted 46% reduction in quasiparticles generated from the same background radiation. In addition, TiN’s lack of response to reductions in ambient magnetic fields by factors of $\sim 1500$ suggests that these 10 $\mu$m wide TiN resonators have a threshold higher than 200 $\mu$T to expel all trapped magnetic flux [7, 17].

In conclusion, we have presented a systematic study of the effect on $Q_i$ with various levels of infrared and magnetic shielding around Al and TiN CPW resonators in an adiabatic demagnetization refrigerator. We have found that magnetic and infrared radiation shielding is key to optimal performance for Al CPW devices. A superconducting shield should further reduce ambient magnetic fields around the sample compared to cryoperm alone, but 2 $\mu$m of electroplated Sn is insufficient. The effect of adding infrared absorbing epoxy is smaller than the variation in $Q_i$ cooldown to cooldown and our inner radiation can is just as effective as a cryopackage lid for blocking infrared radiation. TiN, a material with a significantly larger superconducting gap, shows no dependence of $Q_i$ on added shielding. Devices exhibit nearly identical behavior when exposed directly to 2.7 K radiation and 200 $\mu$T magnetic fields as when they are maximally shielded. Further experiments will be performed to see if this same behavior occurs with transmon qubits made of Al coupled to TiN resonators.

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