Reduced frequency noise in superconducting resonators

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We report a reduction of the frequency noise in coplanar waveguide superconducting resonators. The reduction of 7 dB is achieved by removing the exposed dielectric substrate surface from the region with high electric fields and by using NbTiN. In a model-analysis the surface of NbTiN is found to be a negligible source of noise, experimentally supported by a comparison with NbTiN on SiOx resonators. The reduction is additive to decreasing the noise by widening the resonators.

The development of large and sensitive imaging arrays for far infrared astronomical instrumentation is rapidly progressing with microwave kinetic inductance detectors [1]. Arrays have already been taken to ground-based telescopes [2,3], and readout using frequency domain multiplexing has been demonstrated [4]. The frequency noise in these superconducting resonators is two to three orders of magnitude above the fundamental limit of generation-recombination noise. The noise has been conjectured to arise from dipole two-level systems (TLS) in surface di-electrics [5], which is supported by recent experiments: The surface has been shown to be a dominant source of noise, by measurements on the width scaling by Gao et al. [6]. Moreover, we have shown that introducing dielectrics by covering the resonators with SiOx leads to an increase in the noise [7]. Noroozian et al. showed that the noise arises predominantly from the capacitive portion of the resonator by using a lumped element capacitor [8]. Noise reduction can be achieved by widening the resonator, in essence decreasing the surface to volume ratio [9, 8, 3]. However, the practically limiting source of noise remains to be identified and reduced.

Here, we show that the noise can be decreased by minimizing the dielectrics in the resonator itself. The lowest noise is achieved by using NbTiN deposited on top of a hydrogen passivated substrate as well as by removing the substrate from the region with the largest electric fields. The combination of removing the substrate and widening the resonator leads to a reduction of 9 dB for our first-generation resonators.

Dipole TLS are known to influence the temperature dependent permittivity $\epsilon$ [10], and consequently the resonance frequency. The superposition of permittivity and complex conductivity ($\sigma_1 - i\sigma_2$) controls the resonance frequency [7, 11]

$$\frac{\delta f}{f_0} = \frac{\alpha \beta \delta \sigma_2}{4 \sigma_2} \frac{F \delta \epsilon}{\epsilon}$$

(1)

with $\alpha$ the kinetic inductance fraction and $\beta = 1$ for the thick film and $\beta = 2$ for the thin film limit. The filling factor $F$ [11] takes into account the location of the dielectric and weighs its contribution to the frequency by the electric field energy inside our resonator geometry. It is defined by $F = \frac{1}{4} \int \frac{dV}{V} \left[ \frac{d \delta \epsilon}{\delta \epsilon} \right]$, with $C$ the capacitance per unit length, $V_r$ the standing wave voltage, $l$ the length of the resonator, and $\epsilon_h$ the relative permittivity and $V_h$ the volume of the dielectric hosting the TLS.

Similarly, dipole TLS cause frequency noise through the time-varying permittivity $\epsilon(\vec{r}, t)$ [2]. Consequently, the power spectral density of the permittivity $S_{\epsilon} = 2 \frac{4}{3} \int \left\langle \frac{d \delta \epsilon}{\delta \epsilon} \right\rangle$ translates to frequency noise $S_{f_0}$,

$$\frac{S_{f_0}}{f_0^2} = \frac{2}{3} \int \frac{V_h}{l} S_{\epsilon} |\vec{E}(\vec{r})|^4 d\vec{r}$$

(2)

with $S_{f_0}/f_0^2$ the normalized frequency noise.

In order to identify the contribution of the various surfaces to noise we calculate the effect of a hypothetical surface layer with thickness $t \rightarrow 0$ containing dipole TLS. The electric fields in the coplanar waveguide geometry are calculated using the potential matrix to find the charge density. The approach is detailed in Ref. [12].

![Figure 1](image-url)

**FIG. 1:** (Color online) (a) The coplanar waveguide with the top metal surface, the exposed substrate, the substrate-metal interface and the etched metal edges outlined. (b) A scanning electron microscope image from the standard resonator design. (c) The etched grooves near the open end of the resonator, its cross section is outlined in (a) (dashed). The central line width is $S = 3 \mu m$ in both images.
We adopt the assumption by Gao et al. [6] that the noise spectral density follows: $S_{\text{noise}} = \frac{\nu^2}{\sqrt{E}^2 + E_s^2}$, with $E_s$ the saturation electric field strength, following the saturation of microwave loss due to TLS at high intensities [10].

The hypothetical layer is placed along each of the outlined surfaces in Fig. 1b, the exposed substrate surface, the top metal surface, the etched metal edges and the substrate-metal interface. The results are shown in Fig. 2a-b. Importantly, the contribution to the frequency noise is about two orders of magnitude larger when the layer is placed on surfaces adjacent to the metal than when placed on the exposed substrate. This is due to the high electric fields close to the metal. Moreover, we find that the noise follows $S_{\text{noise}} / f_0^2 \propto 1 / P_{\text{int}}^{0.5}$ in the relevant power range, with $P_{\text{int}}$ the internal resonator power [13]. In addition, when widening the resonator geometry the noise decreases. We have also calculated the influence of a metal surface dielectric with finite thickness $t$ on the noise as well as the frequency shift, i.e. Eq. 1 and Eq. 2. We find that for the noise, only the first few nanometers matter, whereas the full volume influences the frequency shift. This is consistent with our previous experiments, where we showed that frequency deviations arise from the bulk of the dielectric while noise arises predominantly at surfaces and interfaces [6]. The difference arises from the surface layer being weighed by $|\vec{E}(\vec{r})|^4$ for the noise and $|\vec{E}(\vec{r})|^2$ for the frequency shift. Interestingly, the power and width dependence is very similar for each of the surfaces, and identification of the dominant noise source can be done only by removing or altering a specific surface.

In order to identify and reduce the dominant noise source, we have fabricated a series of devices aimed at addressing a specific surface, see Fig. 1. We use NbTiN quarterwave coplanar waveguide resonators [1, 7] with varying geometry or composition. Resonance frequencies lie between 3-5 GHz. As a reference a 300 nm NbTiN film is DC sputtered on an HF-cleaned high resistivity (> 1 k$\Omega$cm) (100)-oriented Si wafer. Patterning is done using SF$_6$/O$_2$ reactive ion etching. The critical temperature is $T_c = 14.8$ K, the low temperature resistivity is $\rho=170 \mu\Omega$cm and the residual resistance ratio is 0.94. To identify the importance of using hydrogen passivated Si, a 300 nm NbTiN film has been deposited on the native oxide of Si ($T_c = 15.5$ K, $\rho = 84 \mu\Omega$cm and $RRR = 1.0$). We have also removed the exposed substrate surface from the region with large electric fields: fully straight, 50 nm thick, NbTiN resonators are made on Si, aligned along the (110) axis of the Si substrate ($T_c = 13.6$ K, $\rho = 142 \mu\Omega$cm and $RRR = 0.96$). Using KOH wet etching, 0.9 $\mu$m deep grooves (dashed lines in Fig. 1b) are etched in the gaps along the full length of the resonators. As a reference for the latter sample as well as to clarify the influence of the metal edges, a straight, 50 nm thick NbTiN resonator is made where the Si substrate is not removed.

The frequency noise is measured using a homodyne detection scheme based on quadrature mixing [1, 7, 13]. The samples are cooled to a temperature of 310 mK using a He-3 sorption cooler placed in a 4.2 K liquid He cryo-
FIG. 4: (Color online) The normalized frequency noise spectra of NbTiN, NbTiN on SiO$_x$, and NbTiN with grooves etched in the gaps. The widths are $S = 3 \mu m$, $W = 2 \mu m$ except for the wide resonator with grooves: $S = 6 \mu m$, $W = 2$. The bath temperature is 310 mK and the internal resonator power is $P_{int} \approx -30$ dBm. The inset shows the power dependence, see Fig. 3 for the legend. Dashed lines are fits to the spectral shape and power dependence.

The data and analysis show that NbTiN is a clean material and point towards SiO$_x$ as the dominant source of noise. First, the exposed Si surface dominates the noise as its removal decreases the noise considerably. Second, when placing SiO$_x$ below or on top of NbTiN the noise increases (Fig. 4 and Ref. [7]). Third, the analysis in Fig. 2 indicates that the NbTiN surface is clean compared to that of Si, as the metal surfaces influence the noise much stronger than the exposed substrate. In addition, the monotonic temperature dependence of the resonance frequency down to 350 mK indicates that NbTiN has a minimal dielectric layer, in contrast to Nb, Ta and Al [7] as well as NbTiN on SiO$_x$. Moreover, the metal edges are not dominant, as the noise level is independent of the thickness of the metal. Finally, the removal of dielectrics from the gaps leads to a decrease in the capacitance $C$ in Eq. 2. Hence, if the metal surfaces would dominate, the noise would increase. Quantitatively, we estimate $\nu/(1 \text{kHz}) \approx 5 \cdot 10^{-27} \text{1/Hz for SiO}_x$, assuming $t = 3 \text{nm}$. Importantly, the noise reduction is significant: it is 7 dB below our standard NbTiN on Si resonators and 11 dB below the lowest values reported for coplanar waveguide resonators by Gao et al. [4]. In addition, the noise is 2 dB lower when widening to $S = 6 \mu m$, which is consistent with our calculation (1.9 dB, see Fig. 2.) and shows that further improvements can be obtained by widening the resonator.

The data in Fig. 4 provide a clear guide to low noise superconducting resonators, by using NbTiN and removing the exposed substrate surface from the region with the largest electric fields. A particular approach to remove the dielectric was followed in Ref. [19]. Importantly, we show that both the removal of dielectrics as well as the widening of the resonator leads to a significant decrease of the noise. Hence, both approaches can be considered to be additive to decreasing the noise. Our approach can be implemented for lumped element resonators [8, 19] as well: by using a ⟨100⟩-oriented Si wafer and aligning the fingers and edges of the interdigitated capacitor along the two perpendicular ⟨110⟩ axes, grooves can be etched with a minimal amount of undercut. Interestingly, our resonators with grooves etched in the gaps also have higher quality factors at high internal power levels as well as at the single microwave photon levels needed for circuit quantum electrodynamics [13].

To conclude, we have reduced the frequency noise by using NbTiN and removing the substrate from the region.
with the highest electric fields. This indicates that the exposed Si substrate surface is the main source of the noise, hence the contribution to noise from the NbTiN surface is not dominant. The followed approach is a straightforward route to low frequency noise in superconducting resonators.

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