Noise in NbTiN, Al, and Ta Superconducting Resonators on Silicon and Sapphire Substrates

R. Barends, H. L. Hortensius, T. Zijlstra, J. J. A. Baselmans, S. J. C. Yates, J. R. Gao, and T. M. Klapwijk

***Abstract*—We present measurements of the frequency noise and resonance frequency temperature dependence in planar superconducting resonators on both silicon and sapphire substrates. We show, by covering the resonators with sputtered SiO_x layers of different thicknesses, that the temperature dependence of the resonance frequency scales linearly with thickness, whereas the observed increase in noise is independent of thickness. The frequency noise decreases when increasing the width of the coplanar waveguide in NbTiN on hydrogen passivated silicon devices, most effectively by widening the gap. We find up to an order of magnitude more noise when using sapphire instead of silicon as substrate. The complete set of data points towards the noise being strongly affected by superconductor-dielectric interfaces.**

***Index Terms*—Dielectrics, interface, kinetic inductance, noise, superconducting resonators.**

I. Introduction

SUPERCONDUCTING resonators are becoming increasingly attractive for photon detection [1] as well as for quantum computation [2]. Devices work well, showing quality factors in the order of 10^6 [3], and exhibiting quasiparticle relaxation times among the longest observed [4], [5], allowing for background limited photometry. Presently we reach an electrical noise equivalent power (NEP) as low as $6 \cdot 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ with Al resonators [6]. However, these resonators have ubiquitously been found to generate significant frequency noise, irrespective of superconducting materials or substrates [7], [8]. The frequency noise is observed to exhibit very comparable properties in all samples used: showing a $1/f^{\sim 0.4}$ spectrum (Fig. 1), decreasing with applied microwave power, following $1/P^{0.5}$, and decreasing with bath temperature, with $1/T^{1.1}$ [8] or $1/T^{1.7}$ [9]. The noise is a major issue for low temperature applications and determines further gains in the sensitivity of kinetic inductance photon detectors.

In independent work low temperature non-monotonic deviations in the resonance frequency temperature dependence [10] and frequency noise [11] have been observed in Nb on sapphire resonators. These results have been interpreted to arise from dipole two-level systems in dielectrics in the active region of the resonator, which couple to the electric fields; the experimental data point towards two-level systems distributed either on the surfaces of the superconducting film and/or on the surface of the exposed substrate in the gaps. In the proposed interpretation the low temperature resonance frequency deviations with temperature are coupled to the noise, supported by the width scaling of the noise and resonance frequency deviations with temperature [10], [11]. However, the various processes arising in the volume of the thin surface layer or in the interface between the superconductor and surface layer may contribute differently to the noise and/or the resonance frequency variations with temperature.

II. Contribution of Dielectric Coverage

Recently, we have measured the noise and temperature dependent resonance frequency in NbTiN superconducting resonators covered with a 10, 40 or 160 nm thick amorphous dielectric SiO_x layers [8]; the sample chips contain both fully covered, i.e. both the superconducting film and the gaps, and fully uncovered resonators. The nearby part of the feedline was covered or kept uncovered as well. We find that the noise jumps to a higher level as soon as the samples are covered with SiO_x, independent of the layer thickness, see Fig. 1. Additionally, the deviations in the resonance frequency grow linearly with increasing layer thickness, exhibiting the expected characteristic logarithmic temperature dependence for dipole two-level systems affecting the permittivity [12], see inset Fig. 1. These observations show that the resonance frequency temperature deviations are due to the *volume* of the SiO_x, whereas the observed increase in the noise is due to the *interface*. Moreover, separately, the noise level of Ta and uncovered NbTiN is very similar, whereas the resonance frequency temperature dependence is significantly different, showing a clear non-monotonicity for Ta while for uncovered NbTiN Mattis-Bardeen theory [16] is followed closely.

The data in Fig. 1 support the conjecture that the low temperature resonance frequency deviations are due to dipole two-level systems in the bulk of the dielectric. However, our observations indicate that the noise is differently related to the dielectric coverage. The data point towards the noise being strongly affected by the superconductor-dielectric interfaces. This is supported by measurements by Gao *et al.* [11] on the geometric scaling of the noise in Nb on sapphire resonators, placing the location of the noise source at the interfaces. This however leaves the

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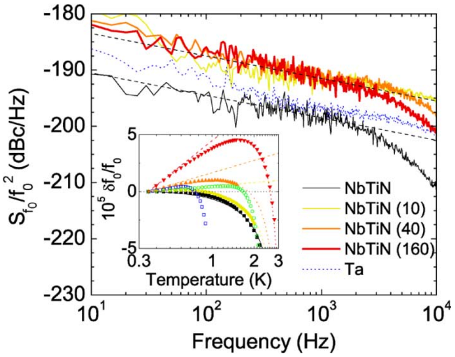

Fig. 1. Noise spectra of the normalized frequency for NbTiN samples without and with a 10, 40 or 160 nm thick SiO_x layer as well as for Ta at a bath temperature of 350 mK. The dashed lines are fits to the spectral shape, $S_{f_0}/f_0^2 \propto f^{-0.4}$. The inset shows the temperature dependence of the resonance frequency of the same NbTiN samples, uncovered (■) and covered with a 10 (●), 40 (▲) or 160 nm (▼) layer, and Ta (□) and Nb (○). The resonance frequency of the uncovered resonator closely follows the Mattis-Bardeen theory (solid line) [16]. For increasing SiO_x thickness a logarithmic temperature dependence develops (dashed lines). The superposition of these two temperature dependencies (dotted lines) closely describes the data. Figure reproduced from [8].

source of the frequency noise unresolved. In order to elucidate this issue we have performed noise measurements on NbTiN resonators with varying central line widths *or* gap widths. Despite a virtually absent dielectric surface layer, we find a very similar pattern: by increasing the width the noise is reduced; most effectively by widening the gap. Additionally, we find that the noise is increased when using sapphire as substrate instead of Si, indicating that the choice of crystalline substrate affects the frequency noise.

III. EXPERIMENT

The NbTiN quarter wavelength superconducting resonators consist of a meandering coplanar waveguide (CPW), coupled capacitively by placing the open end alongside the feedline. The resonance frequency is given by: $f_0 = 1/4l\sqrt{(L_g + L_k)C}$, with L_g and C the geometric inductance and capacitance per unit length and l the resonator length. The kinetic inductance L_k arises from the complex conductivity $\sigma_1 - i\sigma_2$ of the superconducting film, for films with arbitrary thickness $d : L_k = \mu_0 \lambda \coth(d/\lambda)$ [13], [14], with $\lambda \propto \sqrt{1/\sigma_2}$ in the dirty limit [15]. The imaginary part σ_2 arises from the accelerative response of the superconducting condensate, while the real part σ_1 reflects conduction by the quasiparticles [16]. The resonance frequency is a probe for the change in the complex conductivity, in the dirty limit

$$\frac{\delta f_0}{f_0} = \frac{\alpha\beta}{4}\frac{\delta\sigma_2}{\sigma_2}, \tag{1}$$

with $\alpha = L_k/(L_g + L_k)$ the kinetic inductance fraction and $\beta = 1 + 2d/\lambda/\sinh(2d/\lambda)$; for the bulk limit: $\beta = 1$, and for the thin film limit: $\beta = 2$. Near f_0 the feedline transmission shows a dip in the magnitude and a circle in the polar plane [1]. Resonance frequencies used lie between 3–9 GHz.

The NbTiN film, 300 nm thick, is sputter deposited on a high resistivity ($> 1\ \mathrm{k\Omega cm}$) hydrogen passivated (HF-cleaned) (100)-oriented Si substrate. The film critical temperature T_c is 14.7 K, the low temperature resistivity ρ is 160 $\mu\Omega\mathrm{cm}$ and the residual resistance ratio RRR is 0.94. Alternatively, a 300 nm thick NbTiN film is deposited on A-plane sapphire ($T_c = 14.8\ \mathrm{K}, \rho = 150\ \mu\Omega\mathrm{cm}, RRR = 0.98$). Patterning is done using optical lithography and reactive ion etching in a $\mathrm{SF_6/O_2}$ plasma. We use central line widths S of 1.5, 3, 6, 15 and 30 $\mu\mathrm{m}$ while keeping the gap width W at 2 $\mu\mathrm{m}$. Additionally, gap widths W of 1, 2, 4, 10 and 20 $\mu\mathrm{m}$ are used while keeping $S = 3\ \mu\mathrm{m}$. Scanning electron microscope inspection, see inset Fig. 4, indicates the etched edges of the NbTiN film to be vertical as desired. In addition, we find that the values for S are approximately 0.5 $\mu\mathrm{m}$ smaller than intended for both films, adding to the values of W. An undercut of roughly 150 nm is present in the NbTiN on Si samples. The samples are placed inside a gold plated Cu sample box, mounted on a He-3 sorption cooler inside a cryostat. The sample space is surrounded by a superconducting shield. The feedline transmission is sensed using a signal generator, low noise amplifier and quadrature mixer. The frequency noise is obtained by measuring the feedline transmission at the resonance frequency in the time domain and calculating the power spectral density (for more details see [1], [4], [8]).

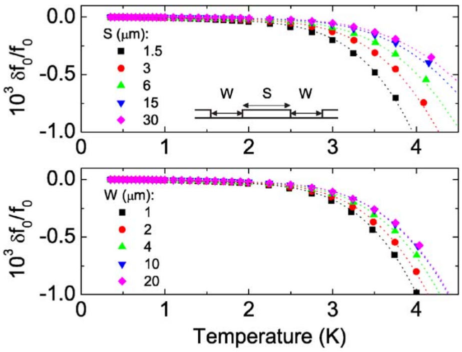

Fig. 2. The temperature dependence of the resonance frequency of NbTiN on Si resonators for varying central strip width S while keeping $W = 2\ \mu\mathrm{m}$ (upper figure) and for varying gap width W while keeping $S = 3\ \mu\mathrm{m}$ (lower figure). The resonance frequency closely follows Mattis-Bardeen theory (dotted lines), Eq. (1). The cross-section of the CPW geometry is shown in the inset.

IV. NOISE WIDTH DEPENDENCE

The temperature dependence of the resonance frequency for resonators of NbTiN on Si is shown in Fig. 2 down to bath temperatures of 350 mK. For increasing temperature the resonance frequency decreases monotonically, following the Mattis-Bardeen expression for the complex conductivity (dotted lines). We include a broadening parameter of $\Gamma = 17\ \mu\mathrm{eV}$ in the density of states, analogous to [8]. When the central line (above) or the gap (below) are widened, the temperature dependence is less pronounced, indicating a decrease in the kinetic inductance fraction α, see Eq. (1). Using the extracted values for α, by fitting the data in Fig. 2 to a numerical calculation of the complex conductivity (Eq. (1)), we find for this film a magnetic penetration depth of $\lambda(0) = 350\ \mathrm{nm}$ [17].

The normalized frequency noise at 1 kHz for varying central strip and gap width is shown in Fig. 3 as a function of internal resonator power for samples of NbTiN on Si. At resonance a standing wave develops inside the resonator, being composed of a forward and backward traveling wave. The internal resonator power associated with this wave is:

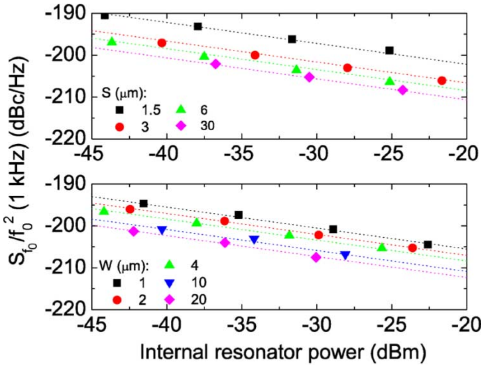

Fig. 3. The normalized frequency noise at 1 kHz of NbTiN on Si resonators for varying central strip width (upper figure) and varying gap width (lower figure) versus internal resonator power, taking into account the changing impedance of the resonator waveguide (see text). The dotted lines are fits to the power dependence, $S_{f_0}/f_0^2 \propto P_{int}^{-0.5}$. The bath temperature is 350 mK.

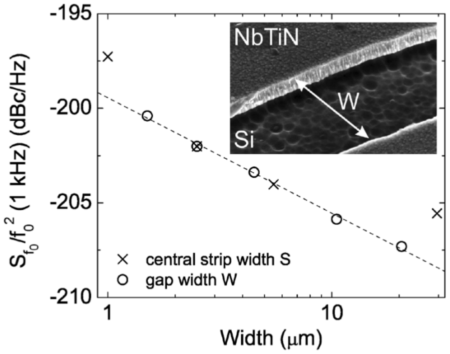

Fig. 4. The normalized frequency noise at 1 kHz of NbTiN on Si resonators, for varying central strip width S and gap width W. The internal resonator power is $P_{int} = -30$ dBm and the bath temperature is 350 mK. Actual values for the width are determined by scanning electron microscopy. The dashed line is a fit to varying gap data: $S_{f_0}/f_0^2 \propto W^{-0.6}$. The inset is a scanning electron micrograph showing of one of the two gaps of a NbTiN on Si resonator in detail; the gap width of this resonator is close to 1.4 μm.

$P_{int} = 2/\pi[Q_l^2/Q_c][Z_{feed}/Z_{res}]P_{read}$, with P_{read} the microwave power applied along the feedline for readout, Q_l and Q_c the loaded and coupler quality factor, and Z the impedance of the feedline, fixed at 50 Ω, or the resonator waveguide. The noise is measured by converting the complex transmission into a phase θ with respect to the resonance circle. This phase reflects the variation in resonance frequency by: $\theta = -4Q_l\delta f_0/f_0$. The normalized frequency noise power spectral density is calculated by: $S_{f_0}/f_0^2 = S_\theta/(4Q_l)^2$, see [8] for further details. The values at 1 kHz are shown in the main figure as a function of internal resonator power. All samples follow $S_{f_0}/f_0^2 \propto P_{int}^{-0.5}$ (dotted lines), consistent with previous measurements [7]. A clear trend of decreasing noise level for increasing width is visible. When increasing the central line width S from 1 to 30 μm the noise is decreased by 8.4 dBc/Hz, whereas widening the gaps from a value of 1.5 to 20 μm decreases the noise by 6.9 dBc/Hz.

The data are summarized in Fig. 4, where the noise value at a power level of $P_{int} = -30$ dBm is plotted versus both central strip and gap width. We find that with increasing central strip width the noise first decreases strongly while further increases do not lead to a large reduction of the noise. With widening gap the noise decreases gradually, following the powerlaw: $S_{f_0}/f_0^2 \propto W^{-0.6}$ (dashed line).

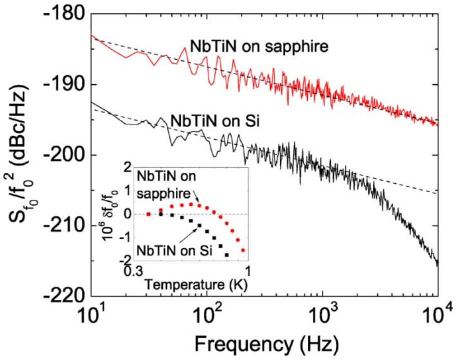

Fig. 5. The normalized frequency noise spectra of NbTiN on Si and NbTiN on sapphire resonators having the same geometry, $S = 3\ \mu\mathrm{m}$, $W = 2\ \mu\mathrm{m}$, and resonance frequency, 3.70 GHz and 3.76 GHz respectively, for $P_{int} = -30$ dBm, at a bath temperature of 350 mK. The dashed lines are fits to the spectral shape $S_{f_0}/f_0^2 \propto f^{-0.4}$. The roll-off is due to the resonator-specific response time. The inset shows a monotonic temperature dependence of the resonance frequency for NbTiN on Si (squares) and a non-monotonic one for NbTiN on sapphire (dots).

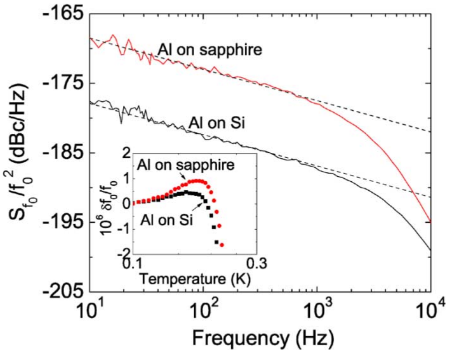

Fig. 6. The normalized frequency noise spectra of Al on Si and Al on sapphire resonators with equal geometry ($S = 3\ \mu\mathrm{m}, W = 2\ \mu\mathrm{m}$) and similar resonance frequency, 4.22 GHz and 4.57 GHz respectively, for $P_{int} = -40$ dBm, at a bath temperature of 100 mK. The dashed lines are fits to the spectral shape $S_{f_0}/f_0^2 \propto f^{-0.45}$. The roll-off is due to the resonator-specific response time. The inset shows a more pronounced non-monotonicity in the temperature dependence of the resonance frequency for Al on sapphire (dots) compared to Al on Si (squares).

V. CONTRIBUTION OF SUBSTRATE

Apart from the influence of the dielectrics at the top surface the interface with the substrate also plays a role. In Fig. 5 the frequency noise power spectral density is shown for comparable NbTiN on hydrogen passivated Si and on sapphire resonators, deposited and measured under identical conditions.[1] We find a similar spectral shape for both resonators, following $1/f^{0.4}$ (dashed lines), and a clearly *increased* noise level, by 10 dBc/Hz, when using sapphire instead of Si. A similar pattern is found for Al resonators, see Fig. 6. The noise in Al on sapphire resonators is 9 dBc/Hz larger than for Al on HF-cleaned Si, its spectrum following $1/f^{0.45}$ (dashed lines) in both cases. Both Al films have a thickness of 100 nm and a critical temperature of 1.2 K. Interestingly, in NbTiN on sapphire a non-monotonic temperature dependence of the resonance frequency is re-established (inset Fig. 5), analogously to covering the NbTiN on Si

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[1] Additional measurements on the noise show it to be independent of the resonance frequency: a variation of $\sim$ 1 dBc/Hz is observed for NbTiN on sapphire resonators with frequencies from 3–9 GHz and identical geometry.

samples with SiO_x (Fig. 1). Moreover, for Al on sapphire resonators the non-monotonic temperature dependence of the resonance frequency is stronger than for Al on Si (inset Fig. 6).

These results show that the lowest noise is obtained in NbTiN on hydrogen passivated Si. The non-monotonicity of the resonance frequency indicates the presence of dipole two-level systems, in the bulk or in the interface. Additionally, using sapphire shows an interesting resemblance to covering the NbTiN on Si samples with SiO_x (Fig. 1); suggesting by analogy that the superconductor-substrate interface contributes to the noise as well (in contrast to the assumption by Bialczak *et al.* [18]). Most importantly, both the effect on the noise of a dielectric layer on top in Fig. 1, and the change in substrate as shown in Figs. 5 and 6 strongly suggest that *superconductor-dielectric interfaces* contribute to the frequency noise.

VI. DISCUSSION AND CONCLUSION

The identification of the source of the frequency noise is reminiscent of experiments on the coherence for quantum information processing with superconductors. Josephson circuits exhibit a poorly understood $1/f$ flux noise. The source of this flux noise is suggested to be related to spins at the surface. The physical mechanism has been conjectured to be due to spins of electrons in interface defect states [19] or due to paramagnetic dangling bonds at interfaces [20]. In this respect the hydrogen passivation of the Si is an important step in reducing these contributions. Recently, the source of the flux noise has been suggested to arise from RKKY (Ruderman-Kittel-Kasuya-Yosida) interactions between electron spins at interfaces of metals [21], supported by measurements on the magnetic properties of SQUIDs indicating the presence of surface spins on superconducting films [22]. In our resonators such interface spins would possibly couple to the magnetic fields inside the resonator active region, appearing in the inductance. Our data appear to be compatible with such a conceptual framework. On the other hand, in recent work [23], connecting an interdigitated capacitor to a transmission line resonator results in a reduction of the noise by 10 dB, indicative of a strong contribution of a noise process located in dielectrics near the superconductor.

To conclude, we find that the frequency noise in coplanar waveguide superconducting resonators and the deviations in the temperature dependence of the resonance frequency are differently dependent on dielectrics, by measurements on NbTiN on Si resonators with various coverages of SiO_x. Additionally, the noise can be decreased by increasing the width of the waveguide. The choice of substrate is crucial for the level of noise, as we observe up to an order of magnitude more noise in resonators comprised of NbTiN and Al on sapphire compared to Si. The data indicate that the noise is strongly affected by superconductor-dielectric interfaces. The source of the frequency noise in resonators, possibly being correlated to the flux noise in Josephson circuits which is associated with recently observed surface spins, is a subject of future experimentation.

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