

Contribution of dielectrics to frequency and noise of NbTiN superconducting resonators

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We study NbTiN resonators by measurements of the temperature dependent resonance frequency and frequency noise. Additionally, resonators are studied covered with SiO_x dielectric layers of various thicknesses. The resonance frequency develops a nonmonotonic temperature dependence with increasing SiO_x layer thickness. The increase in the noise is independent of the SiO_x thickness, demonstrating that the noise is not dominantly related to the low temperature resonance frequency deviations. © 2008 American Institute of Physics. [DOI: 10.1063/1.2937837]

The interest in the low temperature properties of superconducting resonators for photon detection,^{1,2} quantum computation,^{3,4} and quasiparticle relaxation experiments⁵ increases. In principle, these properties are determined by the superconductor, but in practice excess noise and low temperature deviations in the resonance frequency have been observed, which are attributed to dielectrics. It is understood that two-level systems in dielectrics in the active region of resonators contribute to limiting the quality factor and phase coherence, cause noise, and affect the permittivity ϵ .⁶⁻⁹ In order to identify the physical mechanisms through which two-level systems in dielectrics affect the microwave properties of superconducting films, we have chosen to study NbTiN resonators with various coverages of SiO_x. We find that NbTiN follows the Mattis–Bardeen theory for the complex conductivity more closely than any of the other previously used superconductors (Nb, Ta, and Al).¹⁰ We demonstrate that deviations from the ideal superconducting properties can be generated by covering the resonators with a thin amorphous dielectric layer. In addition, we find that this dielectric layer affects the noise and the permittivity differently.

We have made thin film NbTiN coplanar waveguide quarter wavelength resonators. The resonator (see lower inset Fig. 1) is formed by a central line, 3 μm wide, and slits of 2 μm wide, with a NbTiN film thickness of 300 nm. The resonator is capacitively coupled to the feedline by placing the open end alongside it. The complex conductivity $\sigma_1 - i\sigma_2$, with σ_1 reflecting the conductivity by quasiparticles and σ_2 arising from the accelerative response of the Cooper pair condensate, leads to a kinetic inductance $L_k \propto 1/d2\pi f\sigma_2$ for thin films with thickness d .^{10,11} The resonance frequency is controlled by the kinetic inductance and permittivity $f_0 = 1/4l\sqrt{(L_g + L_k)C(\epsilon)}$, with l the length of the central line and L_g the geometric inductance and $C \propto \epsilon$ the capacitance per unit length. The resonance frequency is therefore a direct probe for both the complex conductivity and the permittivity,

$$\frac{\delta f_0}{f_0} = \frac{\alpha}{2} \frac{\delta \sigma_2}{\sigma_2} - \frac{F}{2} \frac{\delta \epsilon}{\epsilon}, \quad (1)$$

with $\alpha = L_k / (L_g + L_k)$ the kinetic inductance fraction and F a factor which takes into account the active part of the resonator filled with the dielectric, as argued by Gao *et al.*⁹ Resonance frequencies lie between 3–6 GHz. Near the resonance frequency the forward transmission of the feedline S_{21} shows a dip in the magnitude when measured as a function of the microwave frequency f (Fig. 1) and traces a circle in the complex plane (upper inset Fig. 1). In our experiment we measure both the temperature dependence of f_0 as well as the noise in f_0 in both bare resonators and resonators covered with SiO_x. The combination of these measurements allows us to study the possible correlation between the noise and resonance frequency deviations.

The NbTiN film, 300 nm thick, is deposited by dc magnetron sputtering on a HF-cleaned high resistivity (>1 k Ω cm) (100)-oriented silicon substrate. Patterning is done using optical lithography and reactive ion etching in a SF₆/O₂ plasma. The critical temperature is $T_c = 14.8$ K, the

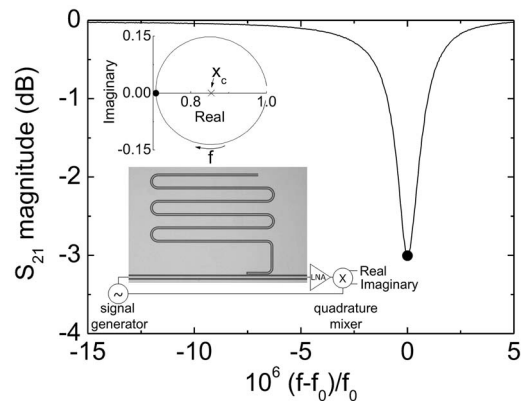


FIG. 1. The resonance feature appears as a dip in the magnitude and circle in the complex plane (upper inset) of the feedline transmission S_{21} . The quarter wavelength resonator is capacitively coupled to a feedline, formed by the superconducting film (gray) interrupted by slits (black) (lower inset). The loaded quality factor for this NbTiN resonator is $Q_l = 630 \times 10^3$, its resonance frequency is $f_0 = 4.47$ GHz. The feedline transmission is measured with a signal generator, low noise amplifier (LNA), and quadrature mixer.

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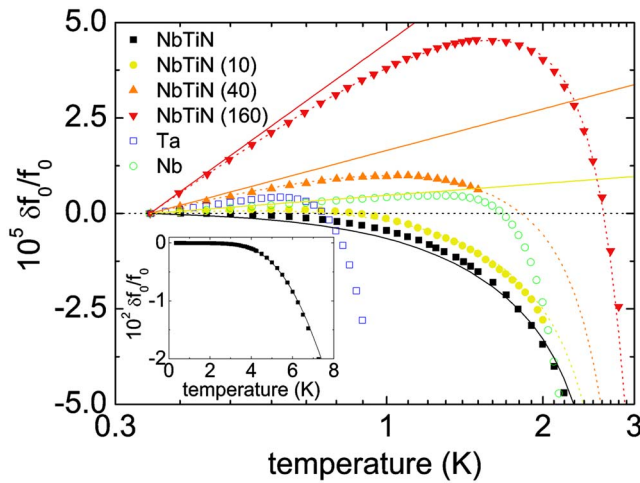


FIG. 2. (Color online) The temperature dependence of the resonance frequency of NbTiN samples with no coverage, NbTiN samples with a 10, 40, or 160 nm thick SiO_x coverage, and samples of Ta and Nb. The solid yellow, orange, and red lines are fits of the low temperature data to Eq. (2). The inset shows the temperature dependence of the resonance frequency of a NbTiN sample over a broader temperature range which closely follows Mattis–Bardeen theory (solid black line) (Ref. 10). The superposition of the Mattis–Bardeen theory (solid black line) and fits to the logarithmic temperature dependence found in data of covered samples (solid yellow, orange, and red lines) yields the dotted yellow, orange, and red lines [Eq. (1)].

low temperature resistivity is $\rho = 170 \mu\Omega \text{ cm}$ and the residual resistance ratio is 0.94. After patterning, we have covered several samples with a 10, 40, and 160 nm thick SiO_x layer, rf sputtered from a SiO_2 target, hence x is expected to be close to 2. Three chips are partly covered with SiO_x , i.e., each chip contains both fully covered and uncovered resonators, the latter serving as reference. A fourth chip is kept uncovered. Measurements are done using a He-3 sorption cooler in a cryostat, with the sample space surrounded by a superconducting magnetic shield. The complex transmission S_{21} is measured by applying a signal along the feedline and amplifying and mixing it with a copy of the original signal in a quadrature mixer, whose outputs are proportional to the real and imaginary parts of S_{21} (lower inset Fig. 1). We find quality factors in the order of 10^6 .

The temperature dependence of the resonance frequency is shown in Fig. 2 down to a temperature of 350 mK. The data shown is representative for all samples. NbTiN (black squares) closely follows the theoretical expression for the complex conductivity¹⁰ (black line) (inset of Fig. 2 and main figure), provided a broadening parameter of $\Gamma = 17 \mu\text{eV}$ is included in the density of states, following the approach in Ref. 12. We find a kinetic inductance fraction of $\alpha = 0.35$, from which we infer a magnetic penetration depth of $\lambda = 340 \text{ nm}$.¹³ The resonance frequency decreases monotonically with increasing bath temperature. For both 150 nm Ta on Si (blue open squares) ($T_c = 4.43 \text{ K}$) and 100 nm thick Nb on Si (green open circles) ($T_c = 9.23 \text{ K}$), the resonance frequency increases with increasing temperature at low temperatures, displaying a nonmonotonic temperature dependence over the full range. Bare NbTiN is in this respect different from Ta and Nb. However, the NbTiN samples covered with a 10 nm (yellow circles), 40 nm (orange triangles pointing upward), and 160 nm (red triangles pointing downward) SiO_x layer exhibit a nonmonotonicity in the resonance frequency temperature dependence, an effect stronger in samples with thicker layers.

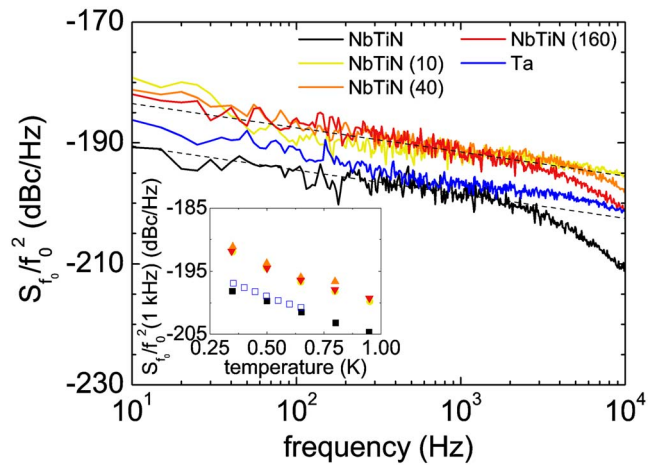


FIG. 3. (Color online) Noise spectra of the normalized frequency for NbTiN samples without and with a 10, 40 or 160 nm thick SiO_x layer as well as for Ta. The bath temperature is 350 mK and the internal resonator power is $P_{\text{int}} \approx -30 \text{ dBm}$ (standing wave amplitude $V_{\text{rms}} \approx 14 \text{ mV}$). 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 noise spectra at 1 kHz (see legend in Fig. 2).

The data in Fig. 2 clearly demonstrate that a nonmonotonic resonance frequency temperature dependence, similar to what we find for Ta and Nb samples and for samples of Al on Si,¹⁴ and what has been reported for Nb on sapphire samples,⁹ can be created in NbTiN by covering the samples with SiO_x . SiO_x is an amorphous dielectric that contains a large amount of defects,¹⁵ giving rise to two-level systems having a dipole moment, which affect the high frequency properties.^{16,17} At low temperatures, the resonant interaction of the dipole two-level systems with the electric fields dominates and leads to a temperature dependent permittivity (in the limit $kT > hf$) (Ref. 7),

$$\frac{\delta\epsilon}{\epsilon} = -\frac{2p^2P}{\epsilon} \ln\left(\frac{T}{T_0}\right), \quad (2)$$

with p the dipole moment, P the density of states, and T_0 an arbitrary reference temperature (here, we choose T_0 equal to the base temperature of 350 mK). At low temperatures, the resonance frequency increases logarithmically with increasing temperature, indicated by the solid yellow, orange, and red lines in Fig. 2. The slope of the logarithmic increase scales linearly with the SiO_x thickness. The superposition of the complex conductivity (solid black line) and the fits to the logarithmic temperature dependence [Eq. (2)] closely describes the observed resonance frequency [Eq. (1), dotted lines]. The logarithmic temperature dependence and the thickness scaling indicate that dipole two-level systems distributed in the volume of the SiO_x affect the permittivity. At higher temperatures, the complex conductivity dominates, leading to a decrease in the resonance frequency.

In the second experiment, we have measured the normalized frequency noise spectra S_{f_0}/f_0^2 of bare NbTiN and Ta samples and NbTiN samples with various SiO_x coverages (Fig. 3). The noise is measured by converting the complex transmission at the resonance frequency into a phase $\theta = \arctan\{\text{Im}(S_{21})/[\chi_c - \text{Re}(S_{21})]\}$ with χ_c the midpoint of the resonance circle (see upper inset of Fig. 1). The frequency is related to the phase by $\theta = -4Q_l \delta f_0/f_0$, with Q_l the resonator loaded quality factor. The power spectral density is calculated by $S_{f_0}/f_0^2 = S_\theta/(4Q_l)^2$. The noise spectra of samples of

NbTiN (black) and NbTiN with a 10 nm (yellow), 40 nm (orange), and 160 nm (red) thick SiO_x layer follow $S_{f_0}/f_0^2 \propto f^{-0.4}$ (dashed black) until a roll off at a frequency in the order of 10 kHz. The roll off is due to the resonator-specific response time and is a function of the loaded quality factor and resonance frequency. We find that the noise is significantly increased by approximately 7 dBc/Hz as soon as the samples are covered by SiO_x and that this increase is independent of the further increase in SiO_x layer thickness. This behavior persists with increasing temperature, where the noise decreases (inset of Fig. 3), consistent with recent observations for Nb.¹⁸

These measurements clearly show that the increase in the noise is independent of the SiO_x layer thickness, whereas the change in resonance frequency is thickness dependent. It has recently been argued, in independent work,^{9,19} that the dielectric influences *both* the resonance frequency and the noise through the capacitance. In this work, we have demonstrated that indeed the resonance frequency is controlled by the bulk of the dielectric. However, the observed noise enhancement appears due to the interface. The latter suggests that it is related to quasiparticle trapping and release at the interface, influencing the inductance rather than the capacitance. We find that the noise of NbTiN samples covered with SiO_x has a spectral shape and temperature dependence which is very comparable to the noise of NbTiN samples without coverage and also of Ta samples. In addition, the noise of NbTiN and Ta samples is very similar, while the temperature dependence of the resonance frequency is significantly different. This points toward an interpretation of the noise in terms of inductance fluctuations.

In summary, we conclude that the frequency noise and the low temperature deviations in the resonance frequency of planar superconducting resonators are differently dependent on two-level systems in dielectrics. Using NbTiN samples and introducing dipole two-level systems by covering the samples with various SiO_x layer thicknesses we find that the logarithmic temperature dependent increase in the resonance frequency scales with the layer thickness. The frequency noise increases strongly as soon as a SiO_x layer is present

and is, in contrast to the resonance frequency results, thickness independent.

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