NONLINEARITY IN SUPERCONDUCTING TITANIUM NITRIDE COPLANAR WAVEQUIDE RESONATORS

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1. Introduction

Superconducting coplanar waveguide resonators are a subject of intensive research recently. They are distributed element electrical resonators which can be easily designed and fabricated by standard photolithographic methods on metalized substrates [1].

They find wide range of applications. As an example, in quantum information experiments, superconducting CPW resonator is coherently coupled to superconducting qubit. In these experiments, known as cavity quantum electrodynamics experiments [2, 3], the high internal quality factor of the resonator is substantial to obtain long coherence time of the qubit-resonator system. One promising material is titanium nitride (TiN_x). An advantage of TiN thin films, beside of their low loss rate [4], is their large normal state resistivity providing a large kinetic inductance. The response of a resonator with large kinetic inductance strongly depends on power applied to the resonator and can by strongly nonlinear [5]. This nonlinearity recently finds application in microwave kinetic inductance detectors [6] and in the future, providing the essential nonlinearity, they can be a possible replacement of the Josephson tunnel junction in quantum flux qubits, as suggested in [7].

In this paper we present fabrication and characterization of superconducting CPW TiN resonator at *20* and *300nm* film thickness. Further we demonstrate strong nonlinearity in thin TiN resonators.

2. Coplanar waveguide resonator design

Coplanar waveguide resonators are on-chip transmission line resonators consisting of a center conductor of width w separated from the lateral ground planes by a gap of width s. The center conductor is coupled via gap capacitors to the input and output transmission lines. The impedance, the coupling strength and the fundamental frequency of the resonator is controlled by the lateral dimensions, by the gap capacitors and the center conductor length.

The center conductor width of our half-wave resonator design is $w=50\mu m$, the separation from the ground plane is $s=30\mu m$, corresponding to 50Ω impedance. The length of the resonator is $l=24\,000\mu m$, corresponding to fundamental frequency of *2.68GHz* at *0K* temperature for *300nm* thick conductor layer on sapphire dielectric layer with *450μm* thickness and relative dielectric constant $\varepsilon_r=9.5$. The loaded quality factor of this design is *35 000*. To design and simulate the properties of our resonator a commercial high frequency electromagnetic software Sonnet [8] were used.

3. TiN layers and resonator fabrication

The *20nm* and *300nm* thick TiN coatings were deposited on mirror-polished r-plane sapphires, using an unbalanced d.c. magnetron sputtering from a Ti target (*99.99%*, *50mm* in diameter) in $Ar+N_2$ (both *99.999%* purity) glow discharge. All substrates were ultrasonically cleaned in acetone and isopropyl alcohol. The vacuum chamber was evacuated initially to a residual gas pressure of $4 \times 10^{-5} Pa$. Then the substrates were heated on *450°C* for *10min* to remove water vapor from the surface. The $Ar+N_2$ reactive atmosphere was kept on *Ar/N2* ratio *1:10* by means of mass flow controllers during deposition. The power density on Ti target and total pressure were fixed at $13\ W.cm^{-2}$ and *0,64Pa*, respectively. Substrates were biased negatively $U_s = -100V$. The highest achieved critical temperature of these thin films is *4.1K* at *300nm* thickness and drops to *2.2K* at *20nm* thickness.

The resonators were patterned in optical lithography using a *2,5µm* thick layer of positive tone resist *AZ 6624* and reactively ion etched in *Ar* and SF_6 plasma.

4. Experimental set up

The Rf properties of the superconducting CPW resonators were measured in two different frequency ranges at temperatures from *5* to *0.3K* cryogen-free He^3 refrigerator.

For frequency range from *0.03-12.0GHz* an experimental set up consisting of a set of thermally anchored attenuators and coaxial cables were used. For frequency range from *2.2-3GHz*, at the lowest temperature stage, a cryogenic circulator and, at *3K* and *40K* stage, two low noise cryogenics amplifiers [9] were added (Fig.1). For both set-ups at input and output lines DC blocks and an additional amplifier (*B&Z BZP 112UC1 0.1-12Ghz*) was used. The transmission of the resonator was measured using an Agilent network analyzer (*N5242A*). The critical temperature of the TiN films was measured by standard 4 probe resistance measurement method.

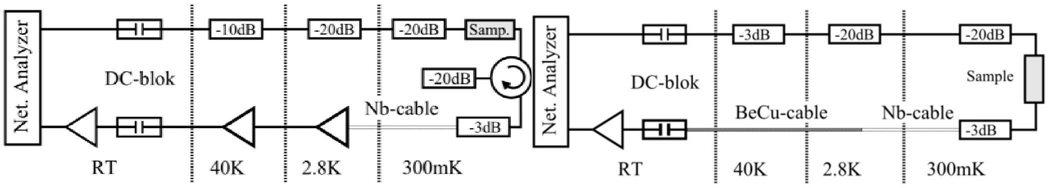

Fig. 1: *Scheme of the experimental set-up for* 2.2-3GHz (*on the left) and from 0.03-12.0 GHz frequency range (on the right).*

5. Results

Two superconducting CPW TiN resonators at *300* and *20nm* film thickness were measured. The resonance frequency and quality of the first resonator is *2.67GHz* and *27 000* at temperature *330mK*. These results are in good agreement with simulation, as shown in Fig 2. The estimated internal quality factor of this resonator is $>10^5$ and the critical temperature of the *300nm* thick TiN film is *4.1K.*

The second resonator was fabricated on *20nm* thin film. In this case the kinetic inductance of the resonator, which scales with the square root of the current density [6], is significant and result in large swift of the resonance frequency. The measured 2nd, 3th and 4th harmonics of the resonator are *1.45, 3.19* and *4.58GHz,* with corresponding qualities *320*, *250* and *120* at low driving power and *330mK* temperature. The critical temperature of this film is *2.2K.* The transmission curve of the resonator reveals a strong dependency on the driving power (see fig 2.). At low driving power *(-53dBm*) the resonator response is lorentian, as expected. As the driving power increases, the resonant peak becomes asymmetric due to the nonlinear inductance of the resonator. Starting from a critical driving power *(-37dBm* and frequency shift *6MHz,* which is of the order of the peak width) the transmission shows a jump on the left side of the curve. This abrupt change, bifurcation, is a feature of strongly nonlinear systems and can by described by the Duffing model[5].

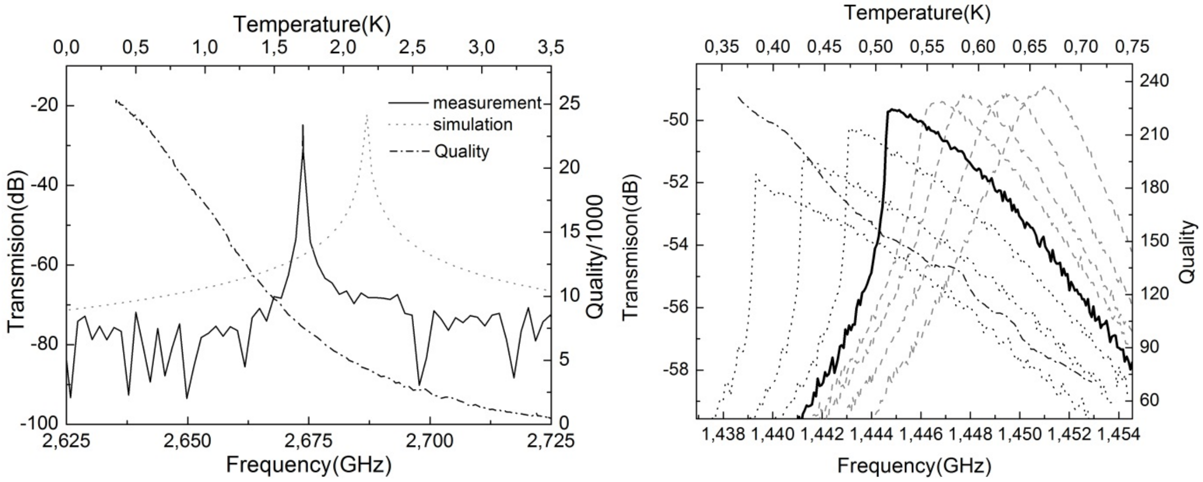

Fig. 2*:The simulated and measured transmission curve (on the left). On the right, the transmission of the 20nm resonator at different driving powers (from the right:-51,-45,-41,-39,-**37**,-35,-33,-31). The dash dotted line depicts the measured quality.*

6. Conclusion

We presented a design, fabrication and characterization of two superconducting CPW TiN resonators at *20* and *300nm* film thickness. The obtained nonlinearity of the *20nm* resonator is comparable (in terms of quality, frequency shift and critical power) with Niobium resonators with focused ion beam fabricated nanobridges [7].

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