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Investigation of dielectric losses in hydrogenated amorphous silicon (a-Si:H) thin films using superconducting microwave resonators

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Abstract

The improvement of the coherence times of superconducting qubits depends on the reduction of the dielectric losses in the insulating materials implemented for the device fabrication. These losses depend on the density of spurious dipoles of different nature (two-level systems, TLSs) which couple to phase qubits and, hence, limit their coherence times. Hydrogenated amorphous silicon (a-Si:H), because of its lower loss tangent ($\tan\delta$) among conventional dielectrics (a-SiO, a-SiO_2, a-SiN_x:H), is considered as the best amorphous dielectric for superconducting qubit application. We have developed a reliable method for the direct measurement of dielectric losses in amorphous dielectric thin films using a novel design based on four lumped superconducting LC resonators connected in series without coupling capacitors. The losses are obtained as $\tan\delta = 1/Q_0$, where Q_0 is the intrinsic quality factor of the resonator, measured at 3 dB above the resonance frequency without any fitting procedure. The series type LC resonators with a-Si:H as dielectric were fabricated by the Nb technology. The measurements were done at the conditions of a qubit application (0.5 - 10 GHz frequency range and low temperatures). The low values of the loss tangent of a-Si:H (up to 2.5 x 10^{-5} at 4.2 K) have required the development of superconducting housing for the resonators in order to eliminate a spurious dependence of $\tan\delta$ on the microwave power, by reducing losses which were not originated in the dielectric itself. The results of the simulations agree well with the experiments.

Keywords: Microwave resonator, Superconducting qubit, Decoherence, Dielectrics losses, Hydrogenated amorphus silicon

1. Introduction

It is well known that the a major source of decoherence in superconducting qubits based on the Josephson effect, and of reduced quality factors in superconducting microwave resonators, is the presence of microscopic defects in the materials utilized for their fabrication [1].

So far, the microscopic origin of these defects has not been fully identified and they are generally considered as two-level state (TLS) systems. As described by the tunneling model [2], TLSs can couple to the

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qubit's and to resonator's electric field, extracting their energy, and thus limiting their coherence time T_2 and quality factor Q_0, respectively. These defect are commonly found in all the amorphous dielectrics involved in the qubit fabrication [3], including the tunnel barrier, the layers for wiring insulation, and the capacitor dielectrics [4], but also the metal oxides on the surfaces of the superconducting films [5] and the interfaces between different materials (*e.g.* between crystalline substrates and superconducting metal layers).

Thus, wiring insulator, superconductor/insulator interfaces, and tunnel barrier are the favorite candidates to be studied and optimized, in order to reduce decoherence in the next generation superconducting qubits.

The transverse relaxation time T_2 of a qubit (*i.e.* the net decay time of quantum information) is related with the energy relaxation time T_1 as

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\Phi} \tag{1}$$

where $1/T_\Phi$ is the pure dephasing rate, which is determined by the low-frequency fluctuations in the circuit controlling the energy separation between the qubit states, and T_1 is inversely proportional to the loss tangent $\tan\delta$ of the dielectrics used to build the superconducting circuit [4]. Therefore, it is clear that the less the dielectric losses ($\tan\delta$), the longer the decay time of quantum information of the qubit.

So far, the hydrogenated amorphous silicon (a-Si:H) is considered as the best amorphous dielectric for qubit application due to its extremely low $\tan\delta$ among the conventional dielectrics (such as SiO, SiO_2, SiN_x) [6]. Both the coplanar waveguide (CPW) and lumped LC superconducting resonators represent two present-day technique for experimental measurement of the loss tangent of dielectrics. The latter is a direct and reliable tool for the characterization of the loss tangent of any dielectric at the conditions at which a qubit device is typically operated, namely at the lowest cryogenic temperatures, in the 1 - 10 GHz microwave range, and at extremely low excitation power (10^{-6} - 10^{-3} V). In the present work, we optimize the technique of multiplexed lumped LC superconducting resonator in such a manner to obtain the experimental conditions for reproducible measurements of the low losses of a-Si:H thin films.

2. Experiments

After our effort to develop a reliable method for the integration of low-defective a-Si:H in the standard fabrication of superconducting circuits based on Nb Josephson junction technology [7], we realized superconducting LC lumped resonators consisting of a superconducting inductive coil and superconducting parallel-plate capacitor containing the dielectric under investigation, as in Fig. 1.

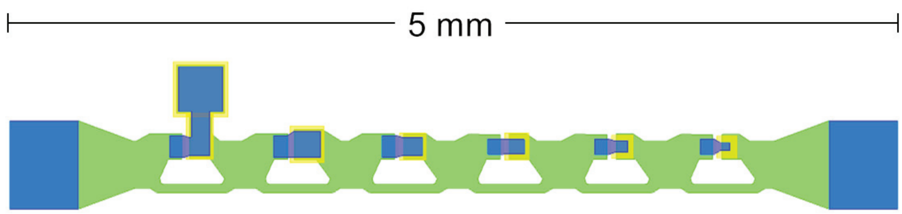


Fig. 1. The newest layout with 6 multiplexed resonators and high temperature a-Si:H lift-off process. Green: base superconducting layer; yellow: dielectric layer; blue: superconducting wiring layer.

The a-Si:H films studied in this work were deposited by high-frequency plasma enhanced chemical vapour deposition (PECVD) [8] on silicon substrates, on which 200 nm thick niobium films were already been deposited and patterned with several geometries of inductors and capacitors. During the PECVD no photoresist was present on the samples, in order to avoid the contamination of both the deposited a-Si:H and the reactor chamber, but also because the high temperatures required to obtain the highest quality a-Si:H (~ 250° C) would have permanently burnt any conventional photoresist.

The PECVD parameters were optimized during preliminary tests: the silane pressure was set to P_{SiH_4} = 200 mTorr at an incident power of 5 W; the plasma was driven at 100 MHz and the substrate temperature was set at 250° C in order to obtain the lowest defective films.

After the deposition, the a-Si:H films covered uniformly all the sample's surfaces: it was necessary to open a contact via through the insulating film by means of CF_4/O_2 reactive ion etching before completing the capacitor fabrication with the niobium counterelectrode lift-off deposition.

In addition to the conventional RIE process for definition of the a-Si:H layer, a high temperature lift-off process based on the PMGI photoresist was also developed and successfully applied for patterning the a-Si:H film. In fact, in order to realize high quality superconducting resonators or qubits, it is preferable to reduce the dielectric coverage of the underlying superconductor [1, 7, 9], limiting the contamination of the superconducting surfaces by hydrogen and dielectric inclusions.

In the actual experimental setup [10], the resonators under investigation are directly coupled to the microwave cables through microwave SMA connectors and indium contact bonding, *i.e.* no coupling capacitor are inserted in series on the line. This configuration realizes a stop-band notch filter, in contrast to the majority of CPW or lumped element superconducting resonators so far realized, which are band-pass filters [11, 12].

Careful electromagnetic simulations lead to a design of 4 and 6 multiplexed resonator in series, with orthogonal resonances and negligible cross talk interference, as shown in the left panel of Fig. 2 in the case of a 4 series circuit.

The lumped LC resonator technique allows to directly measure the loss tangent of the dielectric via the intrinsic quality factor $Q_0 = 1/\tan\delta$, using no fitting parameters. The measurement of Q_0 is performed by means of a microwave network analyzer, by taking the width of the resonance peak at 3 dB above the minimum of the transmissivity $|S_{12}|$ data (right panel of Fig. 2).

3. Results and Discussion

The present analysis of a-Si:H resonators came right after an extensive survey of commonly used dielectrics: a first set of measurements involved Nb_2O_5 resonators, where the anodic niobium oxide was grown under different conditions and chemistries in order to determine the dependence of the quality factor on the oxide preparation; then SiO, and SiN_x resonators were characterized, showing the expected increase in the quality factor due to their less defective dielectrics [10]. All these measurements were done in brass sample housings at IMS. With such configuration, the frequency dependencies of the dielectric loss of such insulating materials were measured with great reproducibility at T = 4.2 K.

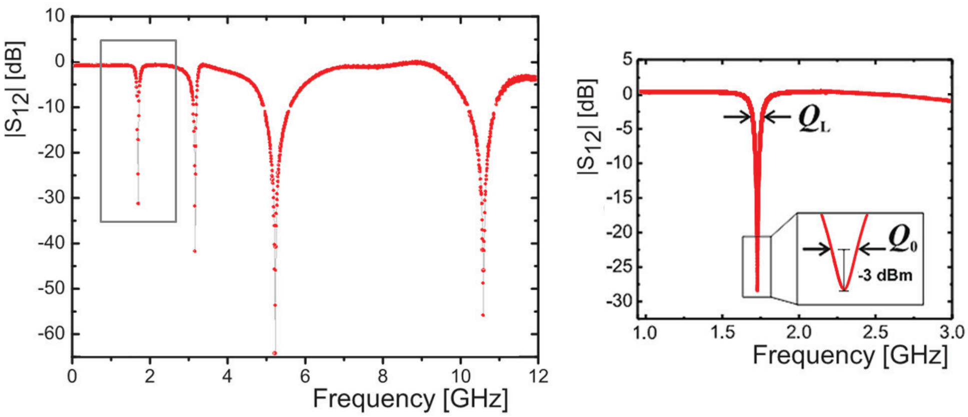


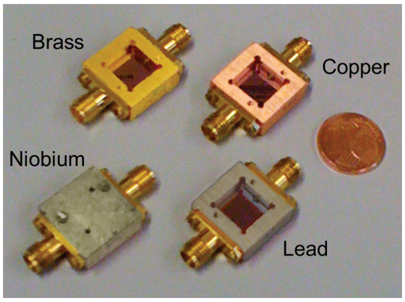
Fig. 2. Experimental data from a 4-multiplexed a-Si:H resonators. Left graph: all 4 resonances measured in a single frequency sweep (0 -12 GHz). Right graph: detail of the gray-box area from previous graph, showing the loaded quality factor Q_L and, in its inset, the -3 dBm method to determine the intrinsic quality factor Q_0 for the selected resonance.

Dielectric losses could be written as $\tan\delta \sim \chi''$ where χ'' is the imaginary part of the electric susceptibility [13]. The $\tan\delta$ data recorded for the different materials at 4.2 K and at different resonant frequencies were fitted by the "Universal Law" $\chi'' \approx \omega^{n-1}$ with $0 < n < 1$ and ω being the resonant frequency. The exponent n is indicative of the mutual interactions between TLS dipoles: for $n = 0$ there is no interaction, for $n \sim 0.5$ nearest-neighbor interaction is prevalent, and for $n > 0.6$ many body interaction is the main defect-defect one.

In the case of the above mentioned materials it was measured $0.63 < n < 0.68$, indicating that the TLS interaction could be described by strong dipole many-body interaction model.

As soon as we started to measure the resonators with a-Si:H as capacitor dielectric, it appeared evident that the measured quality factors were somehow "limited" to Q_0 values lower than 9000, by unknown reasons, instead of the expected unloaded quality factor $Q_0 \sim 30000$ for such resonators at 4.2 K. Moreover, for these resonators, the Q_0 were also strongly and anomalously dependent on the applied microwave power, unlike the case of all the perviously measured resonators.

Further analysis, and accurate simulations using Sonnet [14] Electromagnetic Field Solver pointed out that the limiting factor had to be found in the sample housing and, in particular, in the choice of its constituting material. Simulations of the housing influence on quality factors showed that superconducting housing reduces the housing influence to an absolute minimum. In fact, it came out that the on-chip microstrip lunchers, used to connect the SMA connectors to the lumped element resonator, although being well matched (50 Ω) to groundplane by means of its width and tapered design, induces currents in the groundplane. The latter, in the brass-housing experimental setup, is the lossy and rough brass-housing surface underneath the chip substrate. Moreover, under the superconducting lumped inductor, there is no need of a groundplane, and ideally there should not be at all. So having a lossy ground plane is the most undesirable condition in our experimental setup.



Housing material	Sonnet Q_0	Experimental Q_0
Brass	9255	8391
Copper	13724	12740
Lead	29000	19598
Niobium	29000	26400

Fig. 3. Left: photo of the samples boxes with installed SMA connectors and bonded samples (for the niobium housing, the Nb cover is also installed). Right: simulated and measured quality factors for a ~ 4.5 GHz a-Si:H resonator varying the sample housing material.

For the above reasons, we realized new versions of the sample housing, as shown in Fig. 3. We have been able to measure very low losses in the a-Si:H resonators (as low as $\tan\delta = 2.5 \text{ x } 10^{-5}$ at the highest frequencies, and as expected from amorphous silicon at 4.2 K) initially by means of housings made of copper, then of superconducting lead, and finally of superconducting niobium.

Thus, in order to measure the dielectric losses of an extremely low lossy material, like a-Si:H, with our microstrip-coupled lumped element resonators, one need to ensure that the dielectric losses have to be the dominant losses in the measurement setup. Furthermore, the difference between the measurements performed in lead and in niobium housings (right table in Fig. 3) could be indicative of the higher losses expected from lead oxides compared to niobium oxides.

Having minimized the spurious losses present in our experimental setup by using superconducting housings, we proceeded to correctly characterize the a-Si:H material, and we extracted a parameter $n = 0.57$, showing that the nature of the TLS interaction in such material seems to be closer to the nearest-neighbor one, which is indicative of a lower density of TLS defects.

Additionally, we have investigated resonators having the same resonance frequencies, but realized with different combination of the inductor length and capacitor area, demonstrating that the quality factor Q_0 is independent of the resonator geometry. Moreover, for all the investigated materials, no dependence of the losses on the dielectric film thickness was found.

4. Conclusions

The obtained loss tangent results at T=4.2 K and preliminary measurements at 300 mK (not reported in this work) confirm the suitability of fabricated a-Si:H films to be employed as dielectric layers for the realization of qubits with longer coherence times.

Furthermore, having minimized the spurious losses of our setup, we showed that the improved lumped LC lumped resonator method is a reliable direct measurement of low temperature dielectric loss and thus we opened the door for a new survey of a number of ultra-low loss amorphous (such as a-SiC:H, DLC, etc.) or single crystalline [15] dielectric candidates, in a quick and accurate way.

As a last remark, it could be very interesting to characterize losses of LC resonators and coherence times of qubits in the same measurement, to correlate the two phenomena at the same experimental conditions and in the same deposited material, by means of co-fabricated circuits. In this context, the developed lift-off process is capable to integrate the high temperature PECVD deposition of a-Si:H with existing Nb Josephson technology, fulfilling the above mentioned requirements of reduced coverage of the underlying superconducting films.

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