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A brief review on recent developments of superconducting microwave resonators for quantum device application

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Abstract

Quantum information processing using superconducting qubit based on Josephson junction has become one of the most promising candidates for possible realization of a quantum computer. In the heart of the qubit circuits, the superconducting microwave resonator plays a key role in quantum operations and measurements, which enables single-photon level microwave quantum optics. During last decade, the coherence time, or the lifetime of the quantum state, of the superconducting qubit has been dramatically improved. Among several technological innovations, the improvement of superconducting microwave resonator's quality has been the main driving force in getting the qubit performance almost ready for elementary quantum computing architecture. In this paper, I will briefly review very recent progresses of the superconducting microwave resonators especially aimed for quantum device applications during the last decade. The progresses have been driven by ingenious circuit design, material improvement, and new measurement techniques. Even a rather radical idea of three-dimensional large resonators have been successfully implemented in a qubit circuit. All those efforts contributed to our understanding of the qubit decoherence mechanism and as a result to the improvement of qubit performance.

Keywords: Superconducting microwave resonator, Qubit, Circuit QED, Quality factor, Coherence time

1. INTRODUCTION

High quality factor microwave resonators are of great importance in superconducting quantum electronics. In general, low-loss microwave circuit components are key elements for various superconducting quantum electronics including photon detectors [1] and nano-mechanical systems [2], as well as for the superconducting qubits [3].

In typical amorphous dielectric materials used in low-temperature microwave electronics, the quality factor, or the inverse of the loss tangent, is strongly dependent on the driving microwave power. In conventional superconducting materials of Al and Nb on typical substrate of high-resistive silicon or sapphire, the internal quality factor of ~10^5 or higher was achieved at high microwave power. But as the driving power is decreased, the low-power quality factors are reduced to ~10^4, which corresponds to the lifetime of ~ 1 μs in typical qubit operation frequency of 1~10 GHz. Since most of the quantum measurement and operation is performed at the single photon level, low-power quality factor is the quantity required for quantum operation. Therefore, the research has been focused on making high quality factor materials or structures at the single microwave photon level.

Since the superconducting qubit research has been truly successful in recent years, and the superconducting resonator is in the heart of those researches, I think it is proper time to briefly review recent developments, current status and issues of the superconducting resonator developments for quantum electronics.

2. BACKGROUND

The most widely accepted model of the power dependence of the quality factor is the two-level systems(TLS) model. The loss mechanism from TLS was first suggested to explain decoherence of the phase qubit, where the TLS's were assumed to be located in the tunnel barrier [4]. Charge fluctuation caused by TLS was thought to be the main source of decoherence [5, 6], therefore, with

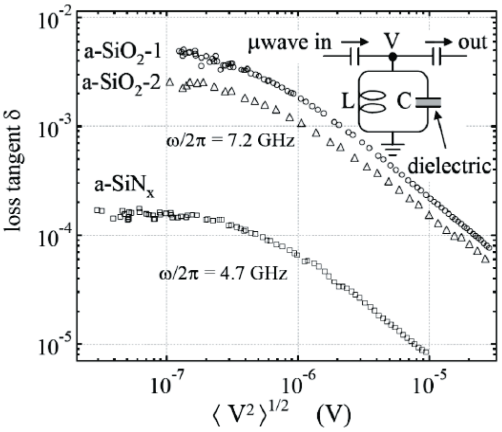

Fig. 1. Typical power dependence of the loss tangent (inverse of the loss tangent) measured in an LC resonator down to single-photon level power, from ref [6].

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a fixed TLS defect density, small-size junction qubits will have better coherence in general. In very small junction qubits(~100 nm), the loss from the amorphous dielectric materials around the qubit will become the dominant decoherence source [6].

The dielectric loss can be directly measured in various kinds of resonators with the dielectric materials. At low power, the bath of TLS will resonantly absorb microwave energy, causing dielectric loss, while larger quality factor at high power arises from saturation of individual TLS.

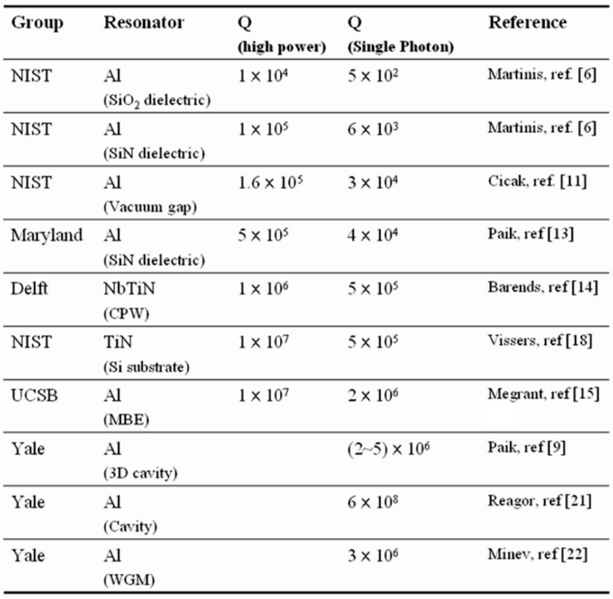
The coherence time of superconducting qubit has been dramatically improved for last decade [7]. Key breakthroughs were reducing the influence of the charge noise by qubit design, namely the transmon [8], and strong coupling of the qubit to the microwave resonator, the circuit quantum electrodynamics (QED) [3]. The long coherence time observed in 3D architecture [9] suggests that current limitation of the coherence time is not the Josephson junction itself, but the environment of the qubit, that is, the resonator. Identifying the location of TLS in resonators is important in improving the quantum coherence of superconducting qubit circuits. As an example, a simulation result in coplanar waveguide (CPW) resonators showed that the dominant candidates are the metal-substrate and substrate-air interface, rather than the substrate-air interface [10].

3. RECENT PROGRESS

Representative works on superconducting resonator development for last decade were summarized in Table I.

Resonators with amorphous silicon oxide dielectric typically show quality factor of 10^4 to 10^5 at high microwave power, but the quality factor is reduced by one or two order of magnitudes at lower power down to single-photon level [6]. Martinis *et al.* first pointed out that the power-dependent dielectric loss can be related to the TLS defects and can be overcome by proper material engineering, and they demonstrated silicon nitride has at least an order of magnitude larger quality factor compared to oxide [6]. Motivated by this idea, Cicak *et al.* tried to remove any dielectric in the circuit by making a vacuum gap capacitor, using aluminum MEMS technology [11]. This aluminum-based vacuum capacitor has not been widely used yet in actual qubit circuits (partly because there were better solutions), but this aluminum membrane technology later played an important role in realizing quantum measurement of nanomechanical oscillators in strong -coupling regime [12].

TABLE I
SUMMARY OF SEVERAL REPRESENTATIVVE SUPERCONDUCTING MICROWAVE RESONATOR WORKS FOR QUBIT APPLICATIONS.



Group	Resonator	Q (high power)	Q (Single Photon)	Reference
NIST	Al (SiO_2 dielectric)	1×10^4	5×10^2	Martinis, ref. [6]
NIST	Al (SiN dielectric)	1×10^5	6×10^3	Martinis, ref. [6]
NIST	Al (Vacuum gap)	1.6×10^5	3×10^4	Cicak, ref. [11]
Maryland	Al (SiN dielectric)	5×10^5	4×10^4	Paik, ref [13]
Delft	NbTiN (CPW)	1×10^6	5×10^5	Barends, ref [14]
NIST	TiN (Si substrate)	1×10^7	5×10^5	Vissers, ref [18]
UCSB	Al (MBE)	1×10^7	2×10^6	Megrant, ref [15]
Yale	Al (3D cavity)		$(2\sim5) \times 10^6$	Paik, ref [9]
Yale	Al (Cavity)		6×10^8	Reagor, ref [21]
Yale	Al (WGM)		3×10^6	Minev, ref [22]

Researches on material processing have focused on the direction to reduce the loss tangent at single-photon level microwave power at several GHz and at mK temperature. Paik *et al.* reported that fine tuning of the nitrogen content in amorphous hydrogenated silicon nitride (a-SiN_x:H) dielectric will result in an order of magnitude improvement of dielectric loss in Si-rich nitride films [13]. On the other hand, based on the assumption that the crucial sources of the power-dependent loss are dielectrics on the surface of the metal (superconductor) and substrate, proper material choice of the superconductor and substrate has also resulted in great improvements. Barends *et al.* performed a comparison study between Ta and NbTiN superconductors in CPW quarter-wavelength resonator geometry, patterned on a hydrogen-passivated high resistivity (>1kΩ cm) silicon substrate. Because NbTiN has a minimal dielectric surface layer compared to Al, Nb and Ta, they observed unloaded quality factor of NbTiN resonators as high as 4.7×10^5 at 4.2 GHz, which corresponds to the single photon lifetime of 18 μs [14].

Internal quality factor over one million at low microwave power (single photon level) was achieved in MBE (molecular beam epitaxy)-grown aluminum film resonators on a surface-treated sapphire substrate. Megrant *et al.* reported low power quality factor approaching 2×10^6 [15]. This MBE-aluminum was successfully applied to the Xmon qubit (UCSB version of transmon qubit, in the shape of “X”) circuit which has demonstrated the record-high gate fidelity in superconducting qubit operation [16]. Because this result was already above the fault-tolerance threshold of the surface-code architecture, it suggested a possibility of scaling up Josephson qubit circuits to real fault-tolerant processor level.

Nitride superconductors provide better chance of less surface defects. TiN film grown on hydrogen-terminated intrinsic silicon substrate showed exceptionally high quality factor at high power [17] and also at low power [18]. A resonator made with TiN film was successfully integrated with a transmon qubit in circuit QED architecture [19], and a huge improvement of the coherence time was obtained over those with lift-off aluminum. The improvement of the qubit coherence time using TiN film provides evidence that the TLS defects are residing at or near interfaces.

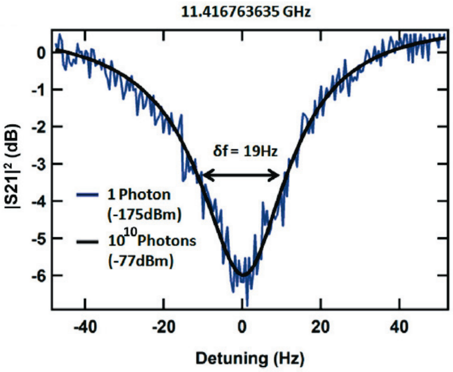


Fig. 2. Transmission measurement of a cylindrical resonator coupled to a transmission line, from ref. [21]. The internal quality factor is 6×10^8, which is same for microwave powers at single photon and 10^{10} photon level.

Careful surface preparation and design optimization in planar circuits have enabled a quality factor over one million in thin film resonators. Planar resonators with larger features generally show high quality factors, which again implies that the dominant sources of loss are defects on the surfaces and interfaces. One straightforward way of minimizing the influence of these surface defects is to reduce the participation ratio of the surface by increasing the mode volume of the resonator. Paik *et al.* successfully applied the three-dimensional superconducting resonator to the construction of circuit QED architecture with a transmon qubit, and they demonstrated radically increased coherence time [9]. This is clear evidence that currently the limiting factor of the qubit coherence is not the Josephson junction itself, but the environmental defects around it. Because this large 3D resonator is supposed to be insensitive to surface defects (or TLS's), its quality factor shows little dependence on the microwave power. The quality factor remains almost same from high power down to the single-photon level [20]. Proper design and surface treatment of a cylindrical resonator made of aluminum alloy enabled an intrinsic quality factor greater than 0.5 billion, or 10 ms of single photon lifetime in a superconducting cavity resonator [21].

Inspired by the 3D resonator results, several approaches were made to implement hybrid structure of 3D and planar resonators in order to take advantages of both. One of the examples was by Minev *et al.*, where a planar superconducting whispering gallery mode (WGM) resonator was fabricated by bonding two wafers with lithographically defined planar structures. This WGM resonator showed internal quality factor above 2×10^6 at the single photon level [22].

4. FURTHER CONSIDERATIONS

Although it is well accepted that defects on surfaces and interfaces are the main sources of the microwave loss, the exact locations of TLS defects are not unambiguously identified yet. There are sill on-going studies to identify the TLS locations. Oates *et al.* applied their dielectric resonator measurement technique with the front- and back-side of the superconducting thin film wafers [23]. This would separate contributions from the film surface and the film-substrate interface to the microwave loss at mK temperature. Detailed circuit designs also need to be devised how to couple a qubit effectively to the specific mode of the high quality factor resonator. Most importantly, in materials science, there are still many improvements to be done. Superconducting resonator technology at the single photon level is obviously still one of the main driving force in development of quantum circuits, especially highly coherent quantum bit circuits.

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