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To cite this article: Oliver Dial et al 2016 Supercond. Sci. Technol. 29 044001

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Bulk and surface loss in superconducting transmon qubits

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Received 30 November 2015, revised 14 January 2016
Accepted for publication 27 January 2016
Published 3 March 2016

Abstract

Decoherence of superconducting transmon qubits is purported to be consistent with surface loss from two-level systems on the substrate surface. Here, we present a study of surface loss in transmon devices, explicitly designed to have varying sensitivities to different surface loss contributors. Our experiments also encompass two particular different sapphire substrates, which reveal the onset of a yet unknown additional loss mechanism outside of surface loss for one of the substrates. Tests across different wafers and devices demonstrate substantial variation, and we emphasize the importance of testing large numbers of devices for disentangling different sources of decoherence.

Keywords: transmon, sapphire, loss tangent, surface loss

Superconducting transmon qubits [1], often studied in both planar (2D) and waveguide (3D) modalities, have become important elements for extensible quantum computing architectures [2–4] which employ circuit quantum electrodynamics (cQED). Typically, transmon coherence times are largely dominated by amplitude damping ($T_1$) and for low temperatures and devices which are not Purcell limited [5], are often observed to become shorter with smaller physical device sizes [6, 7]. This trend, complementary to that observed for quality factor dependence on physical trace and spacing widths in planar resonators [8, 9], is suggestive that devices are surface loss limited; as the transmon becomes smaller, a greater fraction of the electric field energy lies within a hypothetical layer of lossy material on different device surfaces [10–12].

The 3D waveguide approach to cQED [13] is particularly well-suited for investigation of loss mechanisms directly on fabricated transmon devices, because of the clean microwave environment it provides. A transmon qubit device is only subject to environmental coupling through the high-quality rectangular waveguide modes supported by the 3D cavity. As such, the Purcell limit to coherence times can be high, providing a window into the losses due to the qubit design, fabrication processes, and bulk materials. These particular losses, we refer to as intrinsic to the devices.

In this paper, we present an experimental investigation of intrinsic loss mechanisms of transmon devices exploiting 3D waveguide approach. Surface losses of different transmon device interfaces are examined via targeted designs with varying participation susceptibilities to these losses. Our results are consistent with the substrate-vacuum and substrate-metal interfaces being the most likely contributors to transmon decoherence. Fabrication processing variations in the device lift-off medium to target removal of lossy interfaces are also studied, though with no strong conclusion. Finally, we observe a strong overall dependence on the intrinsic bulk loss properties of the substrate which the qubits are fabricated on, indicating the superiority of heat exchanger method (HEM) sapphire, over the more commonly used edge-defined film-fed grown (EFG) sapphire.

First, we formalize the surface loss picture in the transmon devices by examining the participation of electric fields in various lossy interface layers. We consider a thin surface layer contained in a volume $V_s$, from which we can define the electric participation ratio $R = \iiint E \cdot \hat{D}dV / E_{\text{tot}}$, where $E_{\text{tot}}$...
is the total electrical energy $\iiint E \cdot \vec{D} \, dV$. If this layer, with a small microwave loss tangent $\delta$, is the most dominant source of loss, the qubit will then have a quality factor $Q \equiv \omega T_1 = 1/(R \tan \delta)$ where $\omega$ is the qubit frequency. Finite element solvers (Ansoft HFSS) can be used to estimate the surface participation of various films in complex geometries (such as for transmon qubits). However, there is a vast difference in scale between typically estimated thicknesses of the thin surface loss layers (~nm) and the width-scale typical of 3D qubit geometries (>100 $\mu$m) which renders this computation difficult. To counteract this, we make the assumption that the electric field variation is small across the thickness, $t$, of a lossy layer, such that we can approximate the volume integral with a surface integral, giving $R = \int E_\perp \cdot \vec{D} \, dS/E_{\text{ penal}}$. Here the surface of integration is the hypothetical lossy layer and the integral is over the volume of the device. In the absence of any outside knowledge of the nature of the lossy layer, we note that $Q \sim 1/\delta t$, so $T_1$ measurements alone cannot determine $t$ or $\delta$, but only their product. We thus introduce the surface loss sensitivity $r \equiv R/t$ which has units of inverse length and describes how sensitive a device is to a given surface.

To investigate surface loss in 3D superconducting transmon qubit devices [13] (figure 1(a)) we hypothesize that each of the qubit’s important interfaces, substrate-vacuum, substrate-metal, and metal-vacuum, may have a uniform lossy layer covering it (see figure 1(b)). We designed four benchmark transmon qubits designed to have different sensitivities to these interfaces which are shown in figure 1(c). The ‘Hero’ and ‘Extended Hero’ are motivated by the original 3D qubit work of [13], but reflect a scaling to minimize overall sensitivity to all surface losses in the larger design. The ‘Guard’ design maintains a small gap throughout the extent of the qubit, so as to be intentionally very sensitive to both the substrate-metal and substrate-vacuum layers. Finally, the ‘Skeleton’ design actually contains many thin floating islands of metal in the gap between the two main qubit capacitive pads. These additional ‘bones’ in the Skeleton design are meant to not contribute to the overall capacitance, but in effect to minimize the sensitivity of the qubit to the substrate-vacuum but more sensitive to the substrate-metal interface.

We fabricated and measured multiple instances of these different qubit designs both within the same wafers and between wafers on two types of substrates: c-Plane EFG sapphire from Kyocera, used in previous work [14], and ‘LED Grade’ HEM Sapphire from GT Advanced Technologies. We note that all of our results are dependent on accurate and reproducible measurements of qubit $T_1$, a quantity observed to fluctuate over time [15]. Each $T_1$ trace is averaged across several hours to average across this fluctuation, and the mean value is reported in this work. A typical trace and histogram across several hours is shown in figures 2(a) and (b) for a particular Extended Hero qubit on an HEM sapphire substrate.

To visualize the importance that loss at different interfaces may have, we plot the quality factor $Q$ of the measured qubits against $1/r$ for each particular surface layer; a linear relationship would be expected if the $T_1$ of the qubit were limited by that layer. The dielectric constant of the imputed layer also has some impact on the resulting loss sensitivity. We assume a value of 6.2, intermediate between that typical for oxides and for organic films, although the precise value does not materially impact our conclusions. As part of this study, note that we have prepared a number of qubits with identical capacitor designs but different Josephson junction areas, resulting in qubit frequencies that differed by a factor of two. Across these different devices, we find $Q$ to be similar, with $T_1$ being overall shorter for the higher frequency devices, consistent with the loss model indicated above. This confirms that the correct way to compare qubits of different frequency in our experiment is by comparing $Q$, not $T_1$. Our
measurements are split across two dilution refrigerators, with microwave switches and multiple input lines allowing measurements of up to 12 devices in a single cooldown. Using long $T_1$ pre-vetted ‘canary’ qubits shared between the refrigerators and for different input lines, we have confirmed that there is no significant variation for any of the test setups. By comparison, $T_2$ appears to be sensitive to the details of the filtering and attenuation in the experimental setup and is different between the two refrigerators, and as such cannot be compared between samples in an unbiased way.

The extracted $Q$ values of 35 qubit devices fabricated on six wafers are shown in figure 3. Each position along the x-axis corresponds to one of the four qubit types, each distinct symbol represents devices drawn from a different wafer, and each color indicates a different fabrication process variation. In figure 3(a), red points indicate qubits fabricated on EFG sapphire substrates and black points indicate HEM sapphire. For the EFG data, we note that although the dependence of $Q$ on the substrate-vacuum participation ratio is monotonic, it saturates at very large qubit designs (small surface sensitivities) to a fixed value. The solid purple curve is a hypothesized fit to this with two contributions: a surface loss proportional to $r$ and a fixed background loss (dashed purple lines). The best-fit parameters to $r$ are $1.6 \times 10^{-11}$ m$^{-1}$ for the slope (which can be interpreted as $1/(\tan \delta)$) and $3 \times 10^6$ for the fixed background. By comparison, if we
examine the substrate-metal interface as in figure 3(c), we also find a saturation at small participation. Within the scatter of our data we are not able to rule out either substrate-metal or substrate-vacuum as dominating the loss.

Taken together, the observed fixed background loss and wafer-to-wafer variability were suggestive of substrate loss, i.e. that the sapphire substrates had a fixed, non-negligible loss tangent of around $3 \times 10^{-7}$. Particular pieces of specially prepared HEM sapphire have been known to have very low cryogenic loss tangents [16]. To elucidate this issue, we prepared additional 3D qubits on HEM sapphire, and observed improved quality factors for the Hero and Extended Hero design (black data in figures 3(a) and (c)). Based on this result, we believe the original Hero and Extended Hero devices on EFG sapphire were largely limited by bulk substrate loss, which would be independent of qubit design.

As a final process variation, we used glacial acetic acid for liftoff rather than acetone. This is reported to give cleaner surfaces when processing graphene, another surface sensitive material [17, 18]. These additional data are shown in green and purple for EFG and HEM substrates respectively in figures 3(b) and (d); there appears to be no large change as compared to our original processing. We note that given our observed spreads, large numbers of devices need to be compared both within a wafer and between wafers to reliably resolve even large effects. Measuring single qubits is inadequate.

The results in this work are likely to be particular to the details of process steps and conditions currently in use at our fabrication facility; however, the approach of designing a series of qubits of carefully controlled loss sensitivities as a technique for disentangling multiple coexisting loss mechanisms as well as extrapolating practical limits on qubit coherence times in various material systems is broadly applicable in both 2D and 3D qubits.

Qubits were fabricated on 330 μm thick c-plane HEM sapphire wafers or c-plane EFG sapphire wafers using a Dolan bridge technique. The ‘paddles’ of the qubits are deposited along with the junction, and as such have an aluminum oxide layer inside of them. First the wafers are cleaned with a 5:1:1 DI water to 30% ammonium hydroxide to 30% ammonium oxide layer inside of them. First the wafers are cleaned with ultrasonic agitation and rinsed with IPA. Finally, the resist was then developed for 1 min in a 1:3 MIBK:IPA bath and rinsed with IPA and blown dry with nitrogen. The junction deposition was done in a K J Lesker e-beam deposition tool. After a 30 s argon ion mill, the junction was formed with a double angle aluminum deposition. The first aluminum layer was 35 nm, followed by a junction oxidation with 0.5 Torr of oxygen, followed by an 85 nm aluminum layer. After deposition, liftoff was performed in either acetone or acetic acid at room temperature with ultrasonic agitation and rinsed with IPA. Finally, the wafers were coated with resist and diced on a Disco DAD3240 dicing saw. The dicing resist was removed with acetone and IPA.

During preparation of this paper, a broadly similar result was published by Wang of the Schoelkopf group [19]. We note that although Wang et al make use of EFG Sapphire, they do not report a saturation of quality factor at small participation. With the limited data available in each work, the cause of this discrepancy is unclear but will hopefully be elucidated in the future. Additional $Q$ factor data for devices with small participation would be particularly helpful.

Acknowledgments

The authors would like to acknowledge discussions and contributions from John Cotte. We acknowledge support from IARPA under contract W911NF-10-1-0324.

References