Low-loss superconducting nanowire circuits using a neon focused ion beam

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We present low-temperature measurements of low-loss superconducting nanowire-embedded resonators in the low-power limit relevant for quantum circuits. The superconducting resonators are embedded with superconducting nanowires with widths down to 20 nm using a neon focused ion beam. In the low-power limit, we demonstrate an internal quality factor up to $3.9 \times 10^{12}$ at 300 mK (implying a TLS-limited quality factor up to $2 \times 10^{15}$ at 10 mK), not only significantly higher than in similar devices, but also matching the state of the art of conventional Josephson-junction-embedded resonators. We also show a high sensitivity of the nanowire to stray infrared photons, which is controllable by suitable precautions to minimise stray photons in the sample environment. Our results suggest that there are excellent prospects for superconducting-nanowire-based quantum circuits.

I. INTRODUCTION

Quantum circuits based on conventional Josephson-junctions have begun to tackle real-world problems.[1] This has been despite high decoherence produced by the loss[2] and noise[3] caused by parasitic two-level systems (TLS)[4]. In principle, superconducting nanowires can provide a route to low-decoherence quantum circuits due to their monolithic structure and lack of a TLS-hosting oxide layer. To date, superconducting nanowires with cross-sectional areas approaching the coherence length have demonstrated a variety of Josephson[5] and phase-slip[6,7] effects, but features such as their unconventional current-phase relationships[8] remain unexploited in quantum circuits. Previous demonstrations of superconducting nanowire-embedded resonators exhibit unusually high dissipation, with internal quality factors ($Q_i$) below $5 \times 10^9$[10,11,12], far lower than in similar conventional Josephson-junction-based circuits[10,11]. In general, the performance of nanowire-embedded resonators can be limited by material quality, interface imperfections, resist residues and the measurement environment.

We demonstrate superconducting nanowire-embedded circuits with single photon $Q_i$ up to $3.9 \times 10^{12}$, comparable to or even better than conventional Josephson-junction resonators. Superconducting nanowires with widths down to 20 nm were fabricated with a neon focused ion beam (FIB). We study the loss in our devices within the well-established framework of loss mechanisms in superconducting resonators[13,14,15,16] to determine which factors are significant in limiting their performance. The vastly improved $Q_i$ demonstrates that the detrimental effects can be sufficiently reduced and shows that competitive quantum circuits could be based on monolithic nanowire technology.

II. METHODS

Superconducting 20-nm-thick NbN films were deposited on sapphire by dc magnetron sputtering from a 99.99%-pure Nb target in a 1:1 Ar:N$_2$ atmosphere. The vacuum chamber was pumped to $6 \times 10^{-7}$ mbar before sputtering at a pressure of $3.5 \times 10^{-3}$ mbar and power of 200 W. The superconducting critical temperature, $T_c$, was 10 K with a sheet resistance of 450 Ω/sq. Electron-beam lithography (EBL) was used to pattern $\lambda/4$ and $\lambda/2$ coplanar microwave resonators capacitively coupled to a common microwave feed line (shown in Fig. 1). The width of the central conductor was 10 μm and the gap was 5 μm. This pattern was transferred from a 300-nm-thick-layer of polymethyl methacrylate (PMMA) into the film by a reactive ion etch (RIE) using a 2:1 ratio of SF$_6$:Ar, at 30 W and 30 mbar.

A neon FIB was used to directly pattern[20] nanowires in the central conductor of the microwave resonators at the current antinode - see Fig. 1a. With an acceleration voltage of 15 kV, the clearance dose for the NbN film is ≈ 0.3 nC/μm$^2$. 15 kV was chosen as a compromise between minimising the spot size and minimising lateral milling of the nanowire[21], leading to a few-minute mill time per μm$^2$ for a ~1 pA beam current. By prior patterning of a sub-200-nm-wide precursor wire in the same EBL step as the resonator (shown in Fig. 1c), we minimise the mill time and the total neon flux that the nanowire is subject to. Several devices were measured, and Table I shows important parameters including nanowire dimensions. The nanowire devices all feature two nanowires, configured either in parallel so that the nanowires complete a superconducting loop[12] or in series with a wider segment in between[22]. Here, there is no external flux- or gate-bias, so the nanowires are treated as simple constrictions within the superconductor.

Samples were enclosed within a brass box and cooled using a $^3$He refrigerator containing a heavily attenuated microwave in-line and an out-line with a cryogenic high-electron-mobility transistor (HEMT) amplifier.

III. RESULTS & DISCUSSION

Figure 1a shows the forward transmission ($S_{21}$) magnitude response of a nanowire-embedded resonator, at 307 mK and for an applied microwave drive of
−105 dBm, demonstrating $Q_i = 5.2 \times 10^5$. This $Q_i$ is significantly higher than in comparable nanowire-based devices. This highlights the promise of the neon FIB and demonstrates that superconducting nanowires are not intrinsically lossy. The complex $S_{21}$ notch response of the superconducting resonators is fitted by:

$$S_{21}(\nu) = a e^{i\phi} e^{-2\pi j \nu \nu_0} \left[ 1 - \frac{(Q_L/|Q_c|) e^{j\phi}}{1 + 2jQ_L(\nu/\nu_0 - 1)} \right]$$

where $\nu$ is the applied frequency, $\nu_0$ is the resonance frequency, $Q_L$ is the loaded quality factor and $|Q_c|$ is the absolute value of the coupling quality factor; $\phi$ accounts for impedance mismatches, $a$ describes a change in amplitude, $\theta$ describes a change in phase and $\tau$ is the change in the electronic delay. The internal quality factor, $Q_i$, is defined by $1/Q_i = 1/Q_L + \text{Re}(1/Q_c)$ and the energy within the resonator is $W_{\text{sto}} = 2P_{\text{app}} S_{\text{min}} Q_L/\nu_0$, where $P_{\text{app}}$ is the applied microwave power (in W) and $S_{\text{min}}$ is the normalized minimum of the resonator magnitude response. We describe the microwave power in terms of the average number of photons in the resonator, $\langle n \rangle$, given by $\langle n \rangle = W_{\text{sto}}/(h\nu_0)$, where $h$ is Planck’s constant.

To examine the effect of the neon FIB on the NbN film, we measured the resonator response as a function of temperature (shown in Fig. 2). As temperature decreases from 2 K to 1 K, the resonant frequency increases due to changes in the complex conductivity which are described by $\Delta \nu = \frac{\Delta \nu_0}{\nu_0} = \frac{\Delta \sigma}{\sigma_0} + \frac{\Delta \tau}{\tau_0}$, where $\Delta \nu_0$ is the normalised resonance frequency, $\Delta \sigma$ is the kinetic inductance fraction and $\Delta \tau$ is the imaginary part of the complex conductivity as given by Mattis-Bardeen (MB) theory. The inset of Fig. 2 shows the temperature dependence of the resonant frequency for all resonators on chip 1. The bunching of data points indicates a very similar $T_i$, whether the resonator contains nanowires or not, implying that the neon FIB has not significantly suppressed the superconductivity.

Further decreasing temperature from 1 K to 0.7 K the resonant frequency decreases due to the thermal desaturation of TLS, which can be described by

$$\frac{\Delta \nu}{\nu_0} = \frac{F \delta_{\text{TLS}}^i}{\pi} \left[ \text{Re} \Psi \left( \frac{1}{2} + \frac{1}{2\pi j} \frac{h\nu_0(T)}{k_B T} \right) - \ln \left( \frac{1}{2} \frac{h\nu_0(T)}{k_B T} \right) \right]$$

where $F$ is the filling factor which typically relates to device geometry and electric field density, $T_0$ is a reference temperature, $\Psi$ is the complex digamma function and $F \delta_{\text{TLS}}^i$ is the intrinsic loss tangent. Fig. 2 shows a fit to both the MB and TLS frequency shifts, and the extracted $F \delta_{\text{TLS}}^i$ is shown in Table I. Barends et al. have previously showed that, to determine $F \delta_{\text{TLS}}^i$ using both MB and TLS models, it is not necessary to obtain data in the temperature range covering the frequency upturn below 100 mK seen in the TLS fit curve in Fig. 2.

The thermal desaturation of TLS below 1 K results in absorption of microwave photons, leading to a power- and temperature-dependent resonator loss rate. At low microwave drive, the unsaturated TLS dominate the loss, but as the microwave drive increases these TLS become saturated and therefore their loss rate decreases. At high microwave drives, where the TLS are saturated, the loss becomes dominated by residual quasiparticles, with a loss rate $\delta_{\text{qp}}$, which is temperature-dependent but assumed to be independent of microwave power. The TLS and quasiparticle loss behaviour can be described by

$$\frac{1}{Q_i} = \delta_{\text{tot}}^i = F \delta_{\text{TLS}}^i \frac{\tan \left( \frac{h\nu_0}{2k_B T} \right)}{\left( 1 + \left( \frac{\nu}{\nu_0} \right) \frac{\nu}{\nu_0} \right)} + \delta_{\text{qp}},$$

where $\delta_{\text{tot}}^i$ is the total loss tangent, $\beta$ describes how quickly the TLS saturate with power and $F \delta_{\text{TLS}}^i$ is the TLS loss tangent. TLS models were originally based on the anomalous properties of glasses at low temperatures and assumed non-interacting TLS, which leads to a prediction of $\beta = 0.5$. However, as superconducting circuits have improved, this model has failed to accurately describe the power dependence of dielectric losses: a weaker power dependence with $\beta < 0.5$ is frequently found. This showed the need to consider TLS interactions, changing the loss model to:

$$\frac{1}{Q_i} = F \gamma \ln \left( \frac{C n_c}{\nu_0} + \delta_{\text{qp}}^i \right) \tan \left( \frac{h\nu_0}{2k_B T} \right),$$

where $\gamma$ is the dimensionless TLS parameter, $P_\gamma$ is the TLS switching rate ratio, $C$ is a large constant and $\delta_{\text{qp}}^i$ is the low-scaled quasiparticle loss rate.

This loss is examined in more detail by fitting the resonator $S_{21}$ response as a function of microwave drive and temperature (shown in Figs. 3a–c). Fig. 3a (Fig. 3c) show measurements of $\delta_{\text{tot}}^i$ (where $\delta_{\text{tot}}^i = 1/Q_i$) as a function of $\langle n \rangle$ on bare (nanowire-embedded) resonators. Each resonator has its own symbol, with solid (hole) symbols corresponding to measurements in a normal (Eccosorb-lined) sample box. Eccosorb CR-117 (see supplemental materials) is a microwave absorber which has been shown to reduce quasiparticle excitation from stray infrared (IR) photons; the Eccosorb lining is shown in Fig. 1. Different colours correspond to different temperatures. When analysing Figs. 3a, b & c with Eq. 4, we find $\beta \approx 0.1–0.2$ (see supplemental materials) implying interacting TLS. The solid lines represent fits to the interacting-TLS model, Eq. 4. Table I collects fit parameters from both models.

We first consider bare resonators measured in a standard sample box (solid symbols in Fig. 3). Resonators on the same chip show a fabrication-based variability, also found in the literature. High-$(n)$ $Q_i = 1.2–3.1 \times 10^6$ and low-$(n)$ $Q_i = 3.6–5.7 \times 10^5$ at 30 mK, increasing the temperature leads to an increase in low-$(n)$ $Q_i$ because, as thermal occupation of the TLS increases, their ability to absorb microwave photons decreases, as described by the tanh temperature term. Increasing temperature also leads to a decrease in high-$(n)$ $Q_i$. This is due to a higher quasiparticle density, meaning that more energy is lost to the quasiparticle system.
Figure 1. (a) The $S_{21}$ magnitude response of the nanowire-embedded resonator 3710_1qP. The red line is a fit to Eq. 1. (b) A false-colour He FIB micrograph of a neon FIB milled nanowire (3710_1qP) with dimensions of 27 nm by 1.2 µm. The NbN is shown in blue, while the milled region is shown in red. (c, d) Scanning electron micrographs of (c) the shorted end of a $\lambda/4$ resonator before milling by neon FIB. (d) the whole $\lambda/4$ resonator. (e) A photograph of the sample holder. In the centre is a chip, which is wirebonded to a microwave printed circuit board, the dark material is Eccosorb.

Table I. Table of resonator parameters. Resonators are named by $\nu_0$ (MHz), their chip number, $\lambda/4$ (q) or $\lambda/2$ (h) and whether they are bare resonators (B), have nanowires in series (S), have nanowires in parallel (P) or were measured in an Eccosorb-lined box (E). $\bar{w}$ refers to the nanowire widths. $\delta_{TLS}$ comes from fits to Eq. 2, while $\delta_{QL}$ & $\delta_{GP}$ come from fits to Eq. 3 and $FP\chi$ come from fits to Eq. 4.

| Resonator | $\bar{w}$ (nm) | $F\delta_{TLS}$ ($\times 10^{-6}$) | $FP\chi$ ($\times 10^{-6}$) | $F\delta_{QL}$ ($\times 10^{-6}$) | $\delta_{GP}$ ($\times 10^{-7}$) |
|-----------|----------------|-------------------------------|----------------------------|-------------------------------|-------------------------------|
| 4094_1qB  | -              | 6                            | 0.57                       | 6.6                           | 5.6                           |
| 3995_1hB  | -              | 6.3                          | 0.61                       | 6.2                           | 6.9                           |
| 3675_2qBE | -              | 9.8                          | 1.11                       | 9.5                           | 5.6                           |
| 2739_2hBE | -              | 12.6                         | 1.21                       | 10.2                          | 13.3                          |
| 3710_1qP  | 27, 30         | 4.8                          | 0.47                       | 5.9                           | 12.4                          |
| 3012_1hS  | 47, 48         | 6.9                          | 0.42                       | 7.8                           | 21.1                          |
| 3382_2qPE | 20, 23         | 12.9                         | 1.13                       | 14.3                          | 5.4                           |
| 3468_2hSE | 37, 34         | 13.0                         | 1.27                       | 14.2                          | 6.8                           |

We next consider nanowire-embedded resonators in the standard sample box (solid symbols in Fig. 3c). At 307 mK, at low $\langle n \rangle$, we find $Q_i = 2.7 - 3.9 \times 10^5$, in good agreement with the results from the bare resonators, so the FIB-based fabrication of the nanowire has produced very little additional TLS loss. At high $\langle n \rangle$, we find $Q_i = 4.1 - 7.2 \times 10^5$, 3–5 times lower than the bare resonators, indicating a higher residual quasiparticle density for the nanowire-embedded resonators.

Quasiparticles generated from pair-breaking events are an important consideration in conventional Josephson-junction devices, where Eccosorb is typically used to reduce quasiparticle-based losses caused by stray IR photons. We examined whether quasiparticles generated from IR photons are important for nanowire-embedded resonators by measuring them in an Eccosorb-lined sample box. As the hollow dotted symbols in Fig. 3c show, losses at high $\langle n \rangle$ are much lower than for the standard sample box and $Q_i \approx 6 - 9 \times 10^5$. This value matches that of the bare resonators for the same $\langle n \rangle$, suggesting that the density of residual quasiparticles has been reduced to that of the bare resonators (see Table I). A saturated high-$\langle n \rangle$ $Q_i$ is not observed, due to nonlinearities in the resonance lineshape of the nanowire-embedded resonators. With the smaller quasiparticle-based loss, the TLS-based low-$\langle n \rangle$ trend of loss increasing as $\langle n \rangle$ decreases is once again found. The high-$\langle n \rangle$ $Q_i$ is found to increase with increasing temperature, consistent with losses from thermally generated quasiparticles as found in the bare resonators, indicating that increased quasiparticle losses in nanowire-embedded resonators in the normal sample box arose from quasiparticles excited by IR photons.
Figure 3. (a) Loss tangent ($\delta_{\text{tot}} = 1/Q_i$) as a function of microwave drive for bare resonators. The colours correspond to different temperatures and the hollow symbols indicate the use of an Eccosorb CR-117 lined sample box. The solid lines in all plots represent fits to Eq. 4. (b) Loss tangent for the resonator 4094_1qB with and without the Eccosorb-lined box. (c) Loss tangent as a function of microwave drive for the nanowire-embedded resonators.

Table I shows, $\delta_{qp}$ of the nanowire-embedded resonators in the Eccosorb environment match those of the bare resonators (both with and without the Eccosorb environment) and are therefore limited by another mechanism which is not unique to the nanowire.

Figure 3b shows the loss for the same bare resonator with and without the Eccosorb enclosure. In contrast to nanowire-embedded resonators, the high-\langle n\rangle loss decreases only slightly when the Eccosorb-lined sample box is used. This is actually unsurprising since the energy gap of NbN is $\sim 10\times$ larger than in Al. On the other hand, the reason for the sensitivity to IR photons in the nanowire-embedded resonators is not immediately obvious. Our results demonstrate the importance of IR filtering even when nanowires have a large superconducting energy gap such as those in NbN. This is relevant to all nanowire-based devices. We note that a small suppression of $T_c$ in our nanowire (below the precision of our $T_c$ determination) could give some enhanced sensitivity to IR photons. Alternative explanations for the sensitivity include the nanowire exhibiting a different quasiparticle lifetime or non-equilibrium superconductivity, but these are beyond the scope of this study, although, since $Q_i$ remains high, the number of quasiparticles created from IR photons must still be quite small.

Finally, we compare the consistency of the TLS-loss rates (Table I and supplemental) obtained from the analysis of the data shown in Figs. 2 & 3. $F\delta_{\text{TLS}}^0$ and $F\delta_{\text{TLS}}^0$ differ by less than 20%, this difference is because $F\delta_{\text{TLS}}^0$ is only sensitive to near-resonant TLS, whereas $F\delta_{\text{TLS}}^0$ is also sensitive to a broad spectrum of off-resonant TLS. Next, we note that $\delta_{\text{TLS}} = \chi^2$ so that the ratio $FP_{\gamma}/F\delta_{\text{TLS}}^0$ gives $P_\gamma$. We find an average value of $P_\gamma = 0.093$. This agrees well (see supplemental) with the charge noise spectra of single-electron transistors that give $P_\gamma \approx 0.10$. Therefore, all TLS-loss rates are consistent with each other. The TLS loss rates imply a TLS-limited $Q_i$ up to $\approx 2\times 10^5$ in the quantum limit (at temperatures down to 10 mK and at single-photon energies). This is approximately $100\times$ larger than in equivalent nanowire-embedded resonators and compares favourably with Josephson-junction-embedded resonators.

IV. CONCLUSION

To conclude, we have used a neon FIB to create superconducting nanowires with widths down to 20 nm within superconducting resonators. In the low-power limit, these devices demonstrated $Q_i$ up to $3.9\times 10^5$ at 300 mK, with $\delta_{\text{TLS}}^0$ and $\delta_{\text{TLS}}^0$ corresponding to a TLS-limited $Q_i$ up to $2\times 10^5$ at 10 mK. These TLS losses arise from the NbN thin-film technology rather than the neon FIB, meaning a higher $Q_i$ should be possible with better resonator technology. By obtaining such a high $Q_i$ using nanowires, we have demonstrated a critical step towards realising nanowire-based, superinductance, phase-slip or Dayem-bridge circuits with coherence times comparable to conventional Josephson-junction-type devices.
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See Supplemental Material at [URL will be inserted by publisher] for details of the experimental setup & further discussion of TLS losses.

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