

Two-level system loss characterization of NbTi superconducting resonators on Si/SiO₂ substrates

Bongkeon Kim^{ID}, Yong-Joo Doh^{*} ^{ID}

Department of Physics and Photon Science, Gwangju Institute of Science and Technology, Gwangju, 61005, Republic of Korea

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ABSTRACT

Superconducting coplanar waveguide (SCPW) resonators, key components for quantum computing and sensing applications, require a high internal quality factor (Q_i) for effective qubit readout and quantum sensing applications. Minimizing two-level system (TLS) losses, particularly at material interfaces, is critical for gatemon and topological qubits operating at low temperatures and in high magnetic fields. NbTi, a superconducting alloy with a high upper critical field, enables SCPW resonators resilient to such conditions. We fabricated NbTi SCPW resonators on Si/SiO₂ substrates and systematically characterized their TLS-limited quality factors as functions of temperature and microwave photon number. Our results demonstrate that NbTi-based SCPWs on Si/SiO₂ substrates provide a promising platform for developing next-generation quantum circuits.

1. Introduction

Superconducting coplanar waveguide (SCPW) resonators consist of transmission lines with a central conductor and two ground planes [1]. These resonators, when coupled to superconducting qubits, enable quantum state readout [2,3] and quantum sensor applications [4,5]. Their performance is characterized by the internal quality factor (Q_i), defined as the inverse of microwave loss [6]. Since high Q_i means low microwave loss, the development of high- Q_i resonators is essential for advancing quantum computing and sensing technologies. In particular, defects in amorphous dielectrics or at the substrate–superconductor interface interact with microwave photons, resulting in two-level system (TLS) loss [7,8]. In the low-temperature and single-photon regime relevant to superconducting qubits, TLS loss dominates over other loss mechanisms [8].

Gatemon qubits, in which the qubit's properties are controlled using electrostatic gate voltages rather than magnetic flux, enable electrical tuning of both qubit frequency and coupling, offering notable advantages in tunability and scalability [9,10]. To prevent gate leakage current, gatemon qubits are typically fabricated on a silicon substrate covered with a silicon dioxide layer [9,11,12]. However, SiO₂, as an amorphous insulator, is known to exhibit significant TLS loss that can degrade qubit performance [8,9]. Moreover, a gate-tunable Majorana-transmon qubit [13,14], which is a gatemon qubit incorporating topologically protected Majorana zero modes [15] requires an external

magnetic field of approximately 1 T for its operation [16]. Thus a SCPW resonator with robust magnetic field resilience is essential for realizing gate-tunable topological qubits [17].

NbTi is a promising superconducting alloy for fabricating magnetic-field-resilient resonators [18], with an upper critical magnetic field exceeding 9 T [19]. In this study, we fabricated NbTi SCPW resonators on Si/SiO₂ substrates and measured Q_i and resonance frequency (f_c) as functions of temperature and input microwave power. The extracted TLS-limited quality factor ($Q_{\text{TLS},0}$) exceeded those of Nb- or Al-based superconducting resonators [20–23]. These results demonstrate that NbTi SCPW resonators provide a promising platform for realizing gatemon and topological qubits.

2. Experimental methods

The NbTi SCPW resonators were fabricated on undoped silicon (100) wafers with a room-temperature resistivity of $\rho_{\text{Si}} = 10 \text{ k}\Omega \text{ cm}$, coated with a 150-nm-thick thermally grown SiO₂ layer. NbTi film with a thickness of 154 nm was deposited using a pulsed DC sputtering system with a high-purity (99.9 %) NbTi alloy target (50/50 at.%, iTASCO). During deposition, the Ar pressure was maintained at 2.0 mTorr and the sputtering power at 200 W, yielding a deposition rate of 30 nm/min. The resonators were patterned using UV photolithography and etched by reactive ion etching in an SF₆/O₂ atmosphere with flow rates of 4 sccm/1 sccm under an operating pressure of 130 mTorr. Residual photoresist

* Corresponding author.

E-mail address: yjdoh@gist.ac.kr (Y.-J. Doh).

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was removed using mr-Rem 700 (Micro Resist Technology GmbH) to complete the resonator fabrication [24]. Optical microscopy images of the SCPW resonators are shown in Fig. 1a–d.

Each device contains either six (D1) or two (D2) quarter-wavelength ($\lambda/4$) SCPW resonators. These resonators, highlighted in purple in Fig. 1a, have different lengths (l) and are inductively coupled to a feedline (shown in green in Fig. 1b) through a hanger-type geometry. Each resonator has one end shorted to the ground plane at the coupling point (Fig. 1c) and the opposite end left open. The key design parameters are summarized in Table 1, including central conductor width (s), slot spacing (w), geometrical capacitance (C_g), geometrical inductance (L_g), kinetic inductance (L_k), and characteristic impedance (Z_0). The ground plane surrounding the resonators is patterned with hole arrays that trap Abrikosov vortices induced by external magnetic fields. Device D1 uses $5.8 \times 5.8 \mu\text{m}^2$ square holes with $5.8 \mu\text{m}$ spacing, while device D2 uses $4.0 \times 4.0 \mu\text{m}^2$ with $4.0 \mu\text{m}$ spacing. The resonant frequencies f_c range from 3.95 to 4.12 GHz for D1 and from 4.95 to 5.38 GHz for D2. Using these f_c values, the kinetic inductance $L_k = 1/(16l^2 f_c^2 C_g) - L_g$ and the kinetic inductance ratio $\alpha_k = L_k/(L_g + L_k)$ are calculated in Table 1.

After device fabrication, the resonator sample was bonded to a PCB sample holder using a wedge bonder, as shown in Fig. 2a. The assembled

holder was subsequently enclosed in an aluminum box to minimize losses from quasiparticles and magnetic fields. The aluminum box was then mounted onto the mixing-chamber plate of a dilution refrigerator (LD400, Bluefors Oy) and cooled to a base temperature of 8 mK (see Fig. 2b). The insertion loss ($|S_{21}|$) of the sample was measured using a vector network analyzer (VNA; PNA-L N5231A, Keysight Technologies Inc.) (see Fig. 2c). The input microwave signal was attenuated by a total of 60 dB within the refrigerator, while the output signal was routed through two cryogenic isolators (QCI-G0401201AU, Quinstar Technology Inc.) connected in series. The transmitted microwave signal was then amplified using a high electron mobility transistor (HEMT) amplifier (LNF-LNC0.3_14 B, Low Noise Factory AB) at 4 K and a low-noise amplifier (LNA; L3 AFS3-00101200-35-ULN-R, Narda-MITEQ) at room temperature.

3. Results and discussion

The $|S_{21}|$ characteristic curves measured from devices D1 and D2 are shown in Fig. 3a and b, respectively. The applied microwave power was $P_{\text{in}} = -115$ dBm after attenuation in the dilution refrigerator. Each resonance dip occurs at the resonant frequency f_c . The transmission

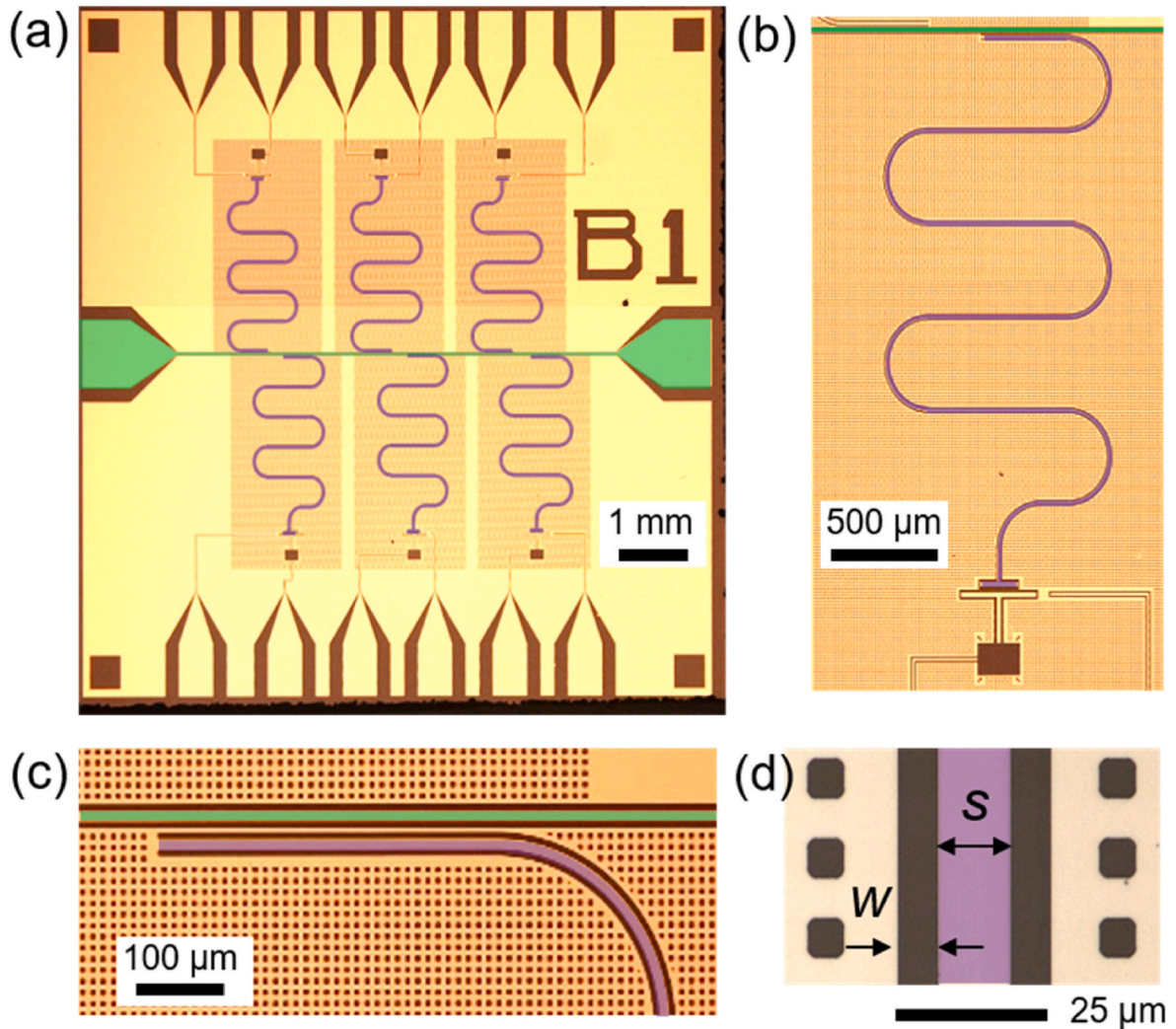


Fig. 1. Pseudo-colored optical microscope image of device D1. (a) Overview of the SCPW chip showing six $\lambda/4$ resonators (purple) inductively coupled to a central feedline (green). (b) Enlarged view of a single SCPW resonator. (c) Image of the coupling region between a resonator and the feedline. The light brown regions correspond to the NbTi superconducting film, while the dark brown areas indicate the SiO_2 layer on the Si substrate. (d) Magnified view of the central conductor (purple) and ground planes with square-hole arrays. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Physical parameters of NbTi SCPW resonators. The geometrical parameters (s and w) were obtained from optical microscopy images. The geometrical inductance (L_g) and capacitance (C_g) were calculated using the conformal mapping method [24]. The resonance frequency (f_c), coupled quality factor (Q_c), and internal quality factor (Q_i) were extracted from transmission spectra fitted to Eq. (1). The kinetic inductance (L_k), kinetic inductance fraction (α_k), and characteristic impedance (Z_0) were calculated from f_c . TLS model parameters including the TLS-limited quality factor ($Q_{\text{TLS},0}$), other loss contribution (Q_{other}), power dependence exponent (β), and saturation photon number (n_s) were obtained from fits to Eq. (2).

No.	s (μm)	w (μm)	L_g (nH/ m)	C_g (pF/ m)	f_c (GHz) at 8 mK	L_k (nH/ m)	α_k	Z_0 (Ω)	Q_c	Q_i	$Q_{\text{TLS},0}$	Q_{other}	β	n_s
D1R1	11.5	7.0	440	160	3.94835	102	0.188	58.2	4.37×10^3	1.89×10^3	–	–	–	–
D1R2	11.5	7.0	440	160	3.98716	101	0.187	58.1	5.90×10^3	5.63×10^3	–	–	–	–
D1R3	11.5	7.0	440	160	4.02774	109	0.199	58.6	4.37×10^3	4.95×10^4	7.61×10^4	6.65×10^4	0.82	67
D1R4	11.6	6.7	433	163	4.07825	96.6	0.182	57.0	4.83×10^3	5.92×10^3	5.14×10^4	6.24×10^3	0.82	26
D1R5	11.6	6.9	437	161	4.12380	93.5	0.176	57.4	4.74×10^3	1.22×10^3	–	–	–	–
D2R1	11.9	6.5	425	166	4.94704	114	0.212	57.0	9.52×10^3	1.07×10^5	9.21×10^4	2.08×10^5	0.80	79
D2R2	12.0	6.4	422	167	5.37955	92.4	0.180	55.5	3.64×10^3	5.82×10^4	6.99×10^4	6.02×10^3	0.87	95

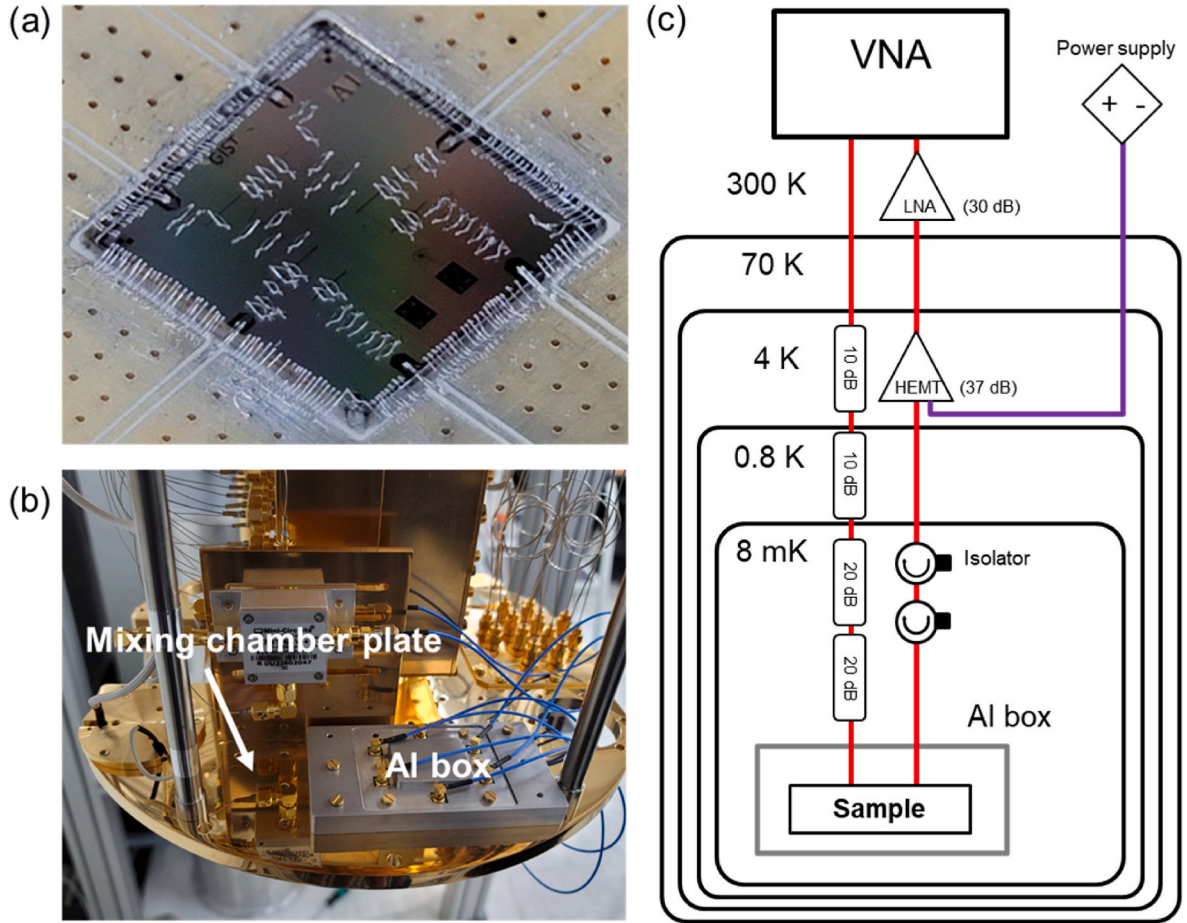


Fig. 2. (a) SCPW resonator chip wire-bonded to a PCB board. (b) Aluminum shielding box mounted on the mixing chamber plate. (c) Schematic of the measurement setup for $|S_{21}|$ measurements.

coefficient ($|S'_{21}|$) curves for resonators D1R3 and D2R1 are shown in Fig. 3c and d, respectively, which were obtained from $|S_{21}|$ using the relation of $|S'_{21}| = 10^{(|S_{21}| - LL)/20}$ with correction for the coaxial-line loss (LL). Here, $|S_{21}|$ and LL are expressed in decibels (dB), and we used LL = –55 dB for D1R3 in Fig. 3c and –57 dB for D2R1 in Fig. 3d, respectively. The complex transmission coefficient S'_{21} is expressed by the following equation [25]:

$$S'_{21} = A \left(1 + \alpha' \frac{f - f_c}{f_c} \right) \left(1 - \frac{Q_i e^{i\theta} / |Q_e|}{1 + 2iQ_i(f - f_c)/f_c} \right) \quad (1)$$

Here, A denotes the amplitude parameter, α' means the background slope, $Q_e = |Q_e|e^{i\theta}$ is the complex external quality factor, which is related

to the coupling quality factor Q_c through $1/Q_c = \text{Re}(1/Q_e)$. The loaded quality factor is given by $1/Q_l = 1/Q_c + 1/Q_i$. The solid curves in Fig. 3c and d represent the theoretical fits using Eq. (1), resulting $Q_i = 4.95 \times 10^4$ and $Q_c = 4.37 \times 10^3$ for resonator D1R3, and $Q_i = 1.07 \times 10^5$ and $Q_c = 9.52 \times 10^3$ for resonator D2R1. Additional fitting parameters are summarized in Table 1. We note that the average photon numbers (n_{ph}) within the resonators are $n_{ph} = 3.5 \times 10^2$ for D1R3 and 5.2×10^2 for D2R1, calculated using the equation of $n_{ph} = \frac{2}{\hbar f_c} \frac{Q_c^2}{Q_e} P_{in}$ [26], where h is Planck's constant.

The $|S_{21}|$ measurements as a function of photon number are displayed in Fig. 4a–b for resonators D1R3 and D2R1, respectively. Both resonators maintained a stable resonance frequency over six orders of

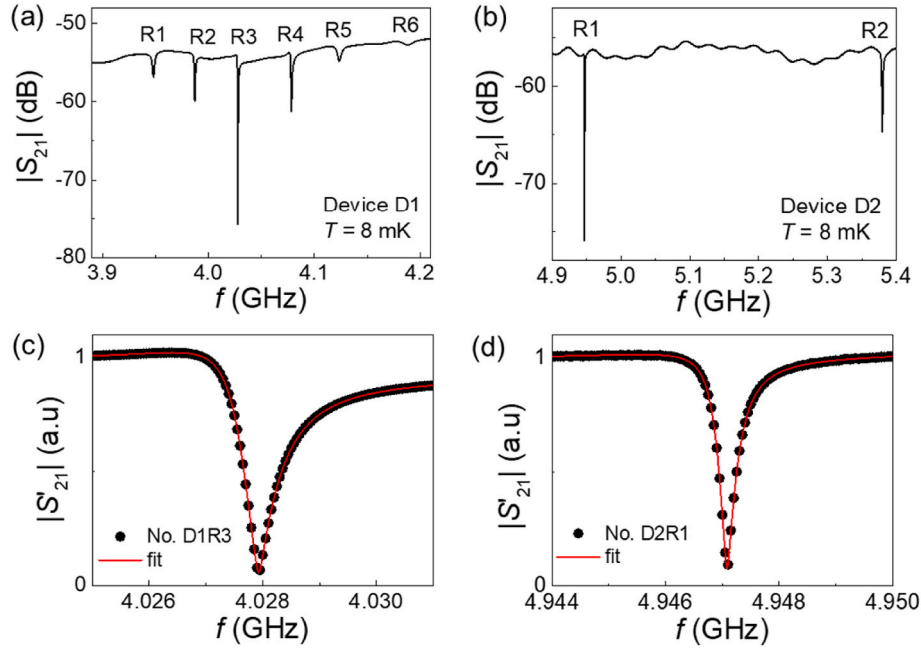


Fig. 3. $|S_{21}|$ resonance dips measured at $T = 8$ mK for (a) device D1 and (b) device D2. Normalized transmission data $|S'_{21}|$ (black dots) and corresponding fits (red solid line) for (c) resonator D1R3 and (d) resonator D2R1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

magnitude in n_{ph} , while the resonance dip exhibited increasing depth with higher n_{ph} . Similar behavior was observed in other devices. Quantitative fitting of the data using Eq. (1) indicates that the internal quality factor increases with n_{ph} and approaches saturation at large photon numbers, as shown in Fig. 4c–f. This behavior is attributed to the saturation of two-level systems (TLSs) [20,27]. At low photon numbers, TLSs residing in the substrate and interfacial regions of the resonator absorb photons, thereby reducing Q_i . With increasing n_{ph} , the stronger microwave field drives TLSs into saturation, suppressing their contribution to energy dissipation and enhancing Q_i [27]. At sufficiently large n_{ph} , however, other loss channels become dominant, leading to the saturation of Q_i . A detailed quantitative analysis is presented below.

In the TLS model, the total loss in SCPW resonators can be decomposed into TLS-induced loss ($1/Q_{TLS}$) and other residual loss channels ($1/Q_{other}$) [27]:

$$\frac{1}{Q_i(n_{ph}, T)} = \frac{1}{Q_{TLS,0}} \frac{\tanh(hf_c/2k_B T)}{\sqrt{1 + (n_{ph}/n_s)^\beta}} + \frac{1}{Q_{other}} \quad (2)$$

where $Q_{TLS,0}$ denotes the intrinsic TLS-limited quality factor at zero photon number, k_B is the Boltzmann's constant, n_s is the characteristic photon number associated with TLS saturation, and β is a fit parameter. Fig. 4c–f shows that the fitted curves (red lines) based on Eq. (2) agrees well with the experimental data (solid circles). The extracted fit parameters are summarized in Table 1. From the fits, we obtain $Q_{TLS,0} = 7.61 \times 10^4$ for the D1R3 resonator and 9.21×10^4 for the D2R1 resonator, corresponding to TLS-related loss tangents of $\delta = 1/Q_{TLS,0} = 1.31 \times 10^{-5}$ and 1.09×10^{-5} , respectively.

The temperature dependence of Q_i measured at various photon numbers is shown in Fig. 5a–d for both D1R3 and D2R1 resonators. For both devices, Q_i remains nearly constant below 0.1 K, but increases notably as temperature rises from 0.1 K to 1 K. This behavior occurs because thermal fluctuations depolarize the electric dipoles of TLS, thereby reducing photon loss caused by TLS defects [26,27]. Moreover, Q_i exhibits pronounced temperature dependence at low n_{ph} , in contrast to the minimal temperature dependence observed at high n_{ph} . At low n_{ph} , TLS defects remain unsaturated and thermal fluctuations become the dominant source of resonator loss [27]. However, once the

microwave field sufficiently saturates TLS defects at high n_{ph} , thermal effects no longer significantly affect the loss mechanism. Fitting the data in Fig. 5a–b using Eq. (2) yields $Q_{TLS,0} = (6.61 \pm 2.04) \times 10^4$ for D1R3 and $(5.98 \pm 1.14) \times 10^4$ for D2R1, averaged over different photon numbers. These values are comparable to those obtained from Q_i measured at 8 mK as a function of n_{ph} .

As temperature increases above 1 K, the saturated Q_i values decrease monotonically (Fig. 5c–d). This reduction in Q_i is attributed to the increase in thermal quasiparticle density at higher temperatures, as predicted by the Mattis-Bardeen (MB) theory [28–30]. According to MB theory, temperature-dependence of Q_i is described by:

$$\frac{1}{Q_{i,qp}(T)} = \alpha_{k,Q}(T) \frac{\sigma_1(T) - \sigma_1(0)}{\sigma_2(T)} \quad (3)$$

Here, $\alpha_{k,Q}$ is the kinetic inductance fraction, and $\sigma_1(T)$ and $\sigma_2(T)$ are the real and imaginary parts of the complex conductivity $\sigma = \sigma_1 - i\sigma_2$ of the superconducting film, respectively, which are given by:

$$\frac{\sigma_1}{\sigma_n} = \frac{4\Delta(T)}{hf_c} e^{-\frac{\Delta(T)}{k_B T}} \sinh\left(\frac{hf_c}{2k_B T}\right) K_0\left(\frac{hf_c}{2k_B T}\right) \quad (4)$$

$$\frac{\sigma_2}{\sigma_n} = \frac{\pi\Delta(T)}{hf_c} \left[1 - 2e^{-\frac{\Delta(T)}{k_B T}} e^{-\frac{hf_c}{2k_B T}} I_0\left(\frac{hf_c}{2k_B T}\right) \right] \quad (5)$$

where σ_n is the normal-state conductivity, $\Delta(T)$ is the temperature-dependent superconducting energy gap, and $I_0(x)$ and $K_0(x)$ are the modified Bessel functions of the first and second kind, respectively. The MB theory fits show good agreement with the experimental data (see Fig. 5c–d). From the theoretical calculations, the kinetic inductance fractions were obtained as $\alpha_{k,Q} = 0.182$ for D1R3 and 0.201 for D2R1, respectively. These values are consistent with α_k determined from f_c at 8 mK, as listed in Table 1.

The TLS-limited quality factor can also be inferred from the resonance frequency. Fig. 6a–b presents the temperature dependence of f_c , where the fractional resonance frequency, $\delta f_c(T)/f_c = [f_c(T) - f_c(8 \text{ mK})]/f_c(8 \text{ mK})$, is plotted. Unlike Q_i , f_c is almost insensitive to n_{ph} ; temperature is the primary factor to influence its behavior. Below 1 K,

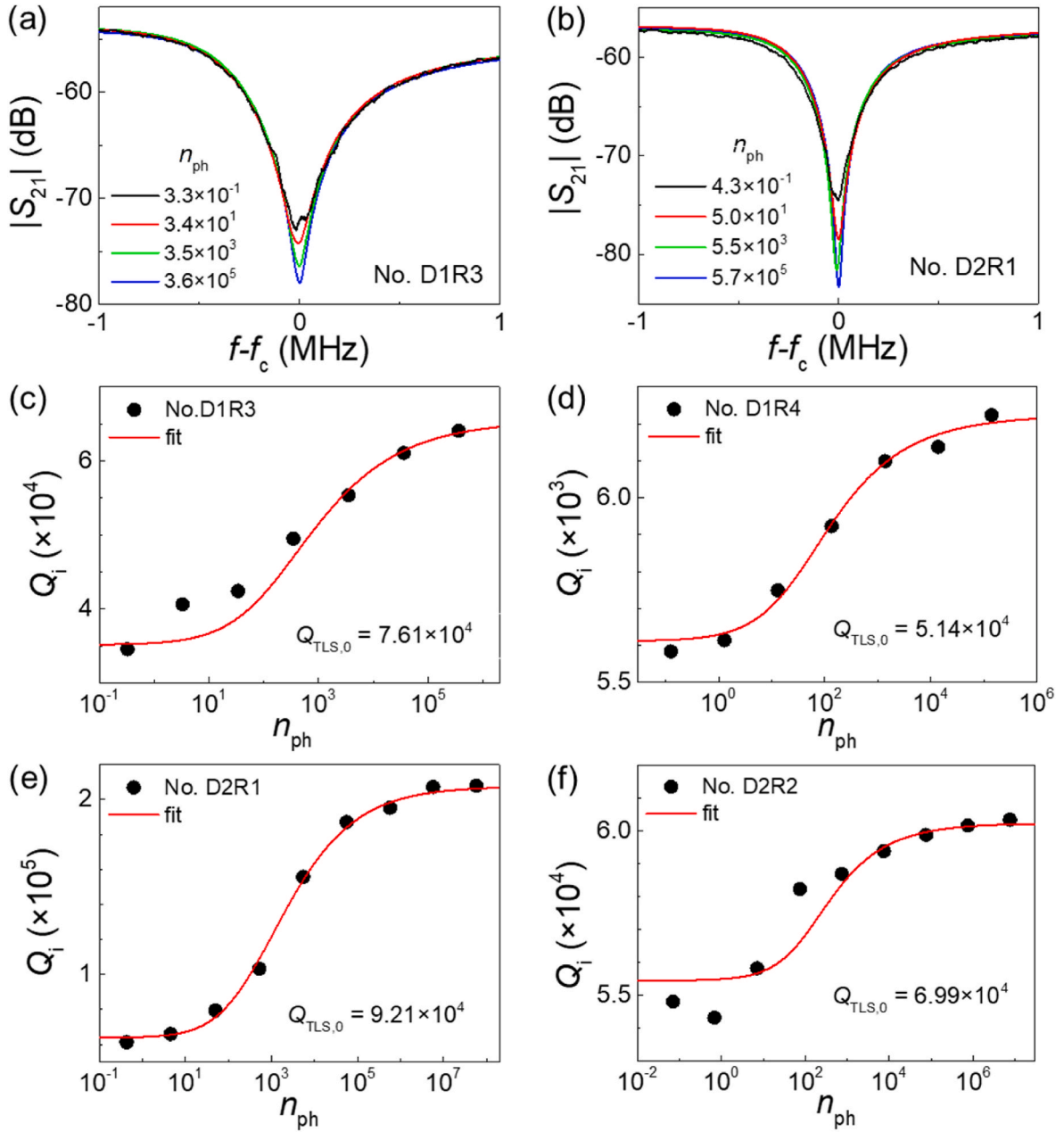


Fig. 4. Insertion loss of (a) D1R3 and (b) D2R1 resonators at $T = 8$ mK for different photon numbers. The photon numbers n_{ph} correspond to input powers $P_{in} = -145$ dBm (black), -125 dBm (red), -105 dBm (green), and -85 dBm (blue). Photon-number dependence of Q_i (symbols) obtained from (c) D1R3, (d) D1R4, (e) D2R1 and (f) D2R2 resonators at $T = 8$ mK. Solid lines represent fitting results (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$f_c(T)$ decreases as temperature decreases, which is attributed to changes in the effective permittivity induced by TLS defects [31]. As temperature decreases, TLS defects relax into their ground state and become increasingly polarized, thereby raising the effective permittivity. This increase in permittivity leads to higher capacitance, resulting in a negative shift of f_c .

The temperature dependence of f_c arising from TLS defects can be described by Ref. [31]:

$$\frac{\delta f_c(T)}{f_c} = \frac{1}{\pi Q_{TLS,0}} \text{Re} \left[\Psi \left(\frac{1}{2} + i \frac{hf_c(8 \text{ mK})}{2\pi k_B T} \right) \right] - \ln \left(\frac{hf_c(8 \text{ mK})}{2\pi k_B T} \right) \quad (6)$$

where $\Psi(x)$ is the complex digamma function. The fit results using Eq. (6), shown as solid lines in Fig. 6a–b, exhibit excellent agreement with the experimental data. The TLS-limited quality factors derived from f_c

are $Q_{TLS,0} = 6.40 \times 10^4$ for D1R3 and 8.02×10^4 for D2R1, which are consistent with those determined from the n_{ph} and temperature dependence of Q_i . Averaging the TLS quality factors obtained from three different methods yields $Q_{TLS,0,avg} = (6.87 \pm 0.65) \times 10^4$ for D1R3 and $(7.74 \pm 1.63) \times 10^4$ for D2R1, corresponding to loss tangents of $\delta_{avg} = 1.46 \times 10^{-5}$ and 1.29×10^{-5} , respectively. It is noteworthy that our averaged $Q_{TLS,0}$ values exceed those previously reported for Si/SiO₂ substrates by more than an order of magnitude [20], and represent the highest values achieved for Si/SiO₂ substrates to date [21–23]. In addition, these results predict a TLS-limited relaxation time of $T_1 = Q_{TLS,0}/2\pi f = 2.9 \mu\text{s}$ for qubits operating at 5 GHz, which is much longer than the $1.3 \mu\text{s}$ reported for single gatemon qubits on Si/SiO₂ [12]. Since NbTi resonators maintain a high Q_i under the influence of magnetic field [18], our observation of superior $Q_{TLS,0}$ values suggests that NbTi resonators

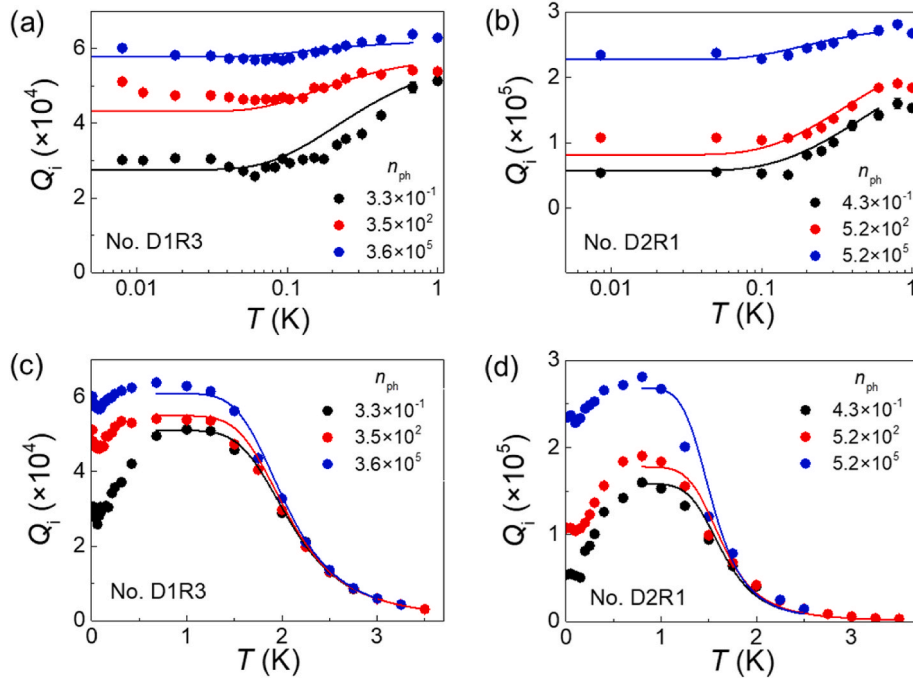


Fig. 5. Temperature dependence of Q_i for (a, c) D1R3 and (b, d) D2R1 resonators. Different colors represent different photon numbers n_{ph} . Solid lines denote calculation results (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

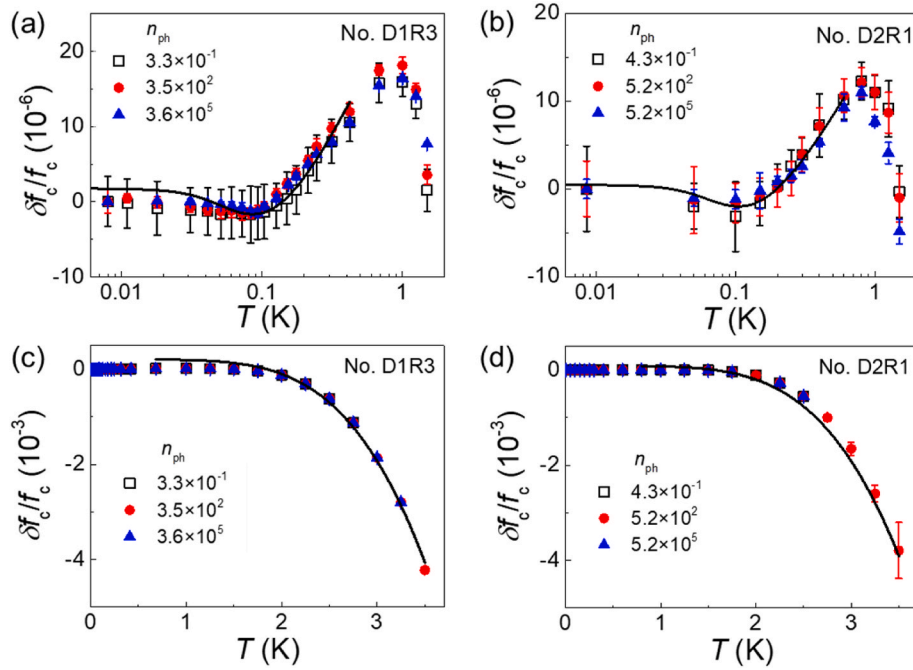


Fig. 6. Temperature dependence of the resonance frequency for (a, c) D1R3 and (b, d) D2R1 resonators. Different symbols represent different photon numbers n_{ph} . Solid lines represent fitted calculation results (see text).

on Si/SiO₂ substrates are promising platforms for gatemon and Majorana-transmon qubit applications.

Above 1 K, f_c decreases markedly as temperature increases (see Fig. 6c–d). This behavior is attributed to the generation of thermal quasiparticles [28,30]. As temperature increases, Cooper pairs in the superconducting film break, causing the London penetration depth (λ_L) to increase. Since the kinetic inductance in thin films is proportional to λ_L^2 [32], a larger λ_L results in a higher L_k and thus a reduction in f_c . This red shift is described by MB theory as [28–30]:

$$\frac{\delta f_c(T)}{f_c} = \frac{\alpha_{kf}(T)}{2} \frac{\sigma_2(T) - \sigma_2(0)}{\sigma_2(T)} \quad (7)$$

The fits to Eq. (7), shown as solid lines in Fig. 6c–d, agree well with the experimental results. The kinetic inductance fractions used in the theoretical calculations are $\alpha_{kf} = 0.174$ for D1R3 and 0.168 for D2R1, respectively. These values are consistent with those obtained from the temperature dependence of Q_i and with α_k determined from f_c . Therefore, the averaged fractions are $\alpha_{k,avg} = 0.185 \pm 0.013$ for D1R3 and

0.194 ± 0.023 for D2R1.

4. Conclusion

In this study, we fabricated NbTi SCPW resonators on Si/SiO₂ substrates and investigated their loss characteristics at low temperatures. By analyzing the temperature dependence of Q_i and f_c across various photon number regimes, we extracted TLS-limited quality factors ranging from $Q_{\text{TLS},0} = 5.14 \times 10^4$ to 9.21×10^4 . To the best of our knowledge, these values represent the highest TLS-limited quality factors reported to date for superconducting resonators on Si/SiO₂ substrates. Our results demonstrate that NbTi resonators on Si/SiO₂ substrates would provide a promising platform for developing advanced quantum devices, including gatemon and topological qubits.

Author contributions

Bongkeon Kim: Conceptualization, Device fabrications, Low-temperature measurements, Data analysis and calculation, Visualization, Writing. Yong-Joo Doh: Conceptualization, Project administration, Supervision, Validation, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data in this study are available on request.

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