Magnetic field resilient high kinetic inductance superconducting niobium nitride coplanar waveguide resonators

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We characterize niobium nitride $\lambda/2$ coplanar waveguide resonators, which were fabricated from a 10 nm thick film on silicon dioxide grown by sputter deposition. For films grown at 120 °C we report a superconducting critical temperature of 7.4 K associated with a normal square resistance of 1 kΩ leading to a kinetic inductance of 192 pH/fΩ. We fabricated resonators with a characteristic impedance up to 4.1 kΩ and internal quality factors $Q_i > 10^4$ in the single photon regime at zero magnetic field. Moreover, in the many photons regime, the resonators present high magnetic field resilience with $Q_i > 10^4$ in a 6 T in-plane magnetic field as well as in a 300 mT out-of-plane magnetic field. These findings make such resonators a compelling choice for cQED experiments involving quantum systems with small electric dipole moments operated in finite magnetic fields.

High quality superconducting microwave resonators are at the heart of circuit quantum electrodynamics (cQED) experiments. In recent years, high-impedance superconducting microwave resonators (HISMRs) have emerged as a new component allowing to explore regimes previously unattained. Such resonators are characterized by their characteristic impedance $Z_c = \sqrt{L_i/C_i}$, $L_i$ and $C_i$ being the inductance-capacitance per unit of length, close or even higher than the quantum of resistance $h/(2e)^2 \approx 6.5$ kΩ. To reach such a high impedance, the resonators need low stray capacitance and extremely high inductance. A large inductance can be achieved either with Josephson meta-materials or thanks to the kinetic inductance of disordered superconductors like TiN, NbTiN or granular aluminium. Through their large inductance, HISMRs generate large zero-point voltage fluctuations $V_{ZPF} \propto f_0\sqrt{Z_c}$ with $f_0$ the resonator fundamental frequency. This large $V_{ZPF}$ enables the coupling of microwave photons to small electrical dipole moments like polar molecule or charges in semiconductor quantum dot. Moreover, using disordered superconductors with a high critical magnetic field, it is possible for HISMRs to maintain their high quality factors up to several tesla opening cQED type experiments to quantum systems requiring magnetic field like spin or majorana fermion qubits.

In this prospect, we present superconducting microwave $\lambda/2$ coplanar waveguide (CPW) resonators made from 10 nm thick films of NbN. We first study the kinetic inductance of the films by four probe DC measurement and by two-tone spectroscopy on long resonators. We show that the substrate temperature during the film growth is a viable control knob to achieve a desired kinetic inductance value. We fabricate, in one etching step, resonators of different characteristic impedances ranging from 110Ω to 4.1 kΩ, just by varying the geometry of the CPW. We characterize the internal quality factor of the resonators as a function of the average photon number occupancy. Then we extend the investigation by studying the resilience of the resonators to in-plane and out-of-plane magnetic fields. Finally, we pinpoint that the 4.1 kΩ resonators, which induce the highest zero-point voltage fluctuations, show $Q_i > 10^4$ in the single photon regime, while preserving a high quality factor in both 300 mT out-of-plane and 6 T in-plane magnetic fields. This makes NbN HISMR a compelling choice for cQED experiments involving quantum systems with small electric dipole moments under sizable magnetic fields.

The resonators are fabricated on a 525 ± 25 µm thick p-type silicon wafer (1-15 Ωcm), covered by 400 ± 80 nm of thermally grown SiO₂. The NbN deposition is performed inside...
a sputtering chamber where the wafer is first heated during ~16 h at 120 °C at a base pressure of 2 × 10⁻⁹ mbar. Then, we perform a cleaning step of 30 s of Ar milling with a bias voltage of 350 V. The sputtering step lasts for 11 s to deposit 10 nm of NbN at 0.01 mbar with an Ar:N partial gas ratio of [60:40]. Afterwards the resonators are patterned in one e-beam lithography step using ZEP resist, followed by an O₂/SF₆ plasma etching.

Representative scanning electron microscopy (SEM) images of the resonators obtained after such a process are shown in Fig. [1](a). We designed arrays of resonators in a hanger type geometry allowing parallel measurement of 5 resonators in one experimental run. In Fig. [1](b), we show an instance of such a chip inside its sample box. The sample box is placed in a dry dilution refrigerator equipped with a 3D vector magnet (6 - 1 - 1 T) and connected to a standard microwave setup, see Fig. [1](c). The chip is then cooled down to a base temperature of 8 mK at zero magnetic field.

We characterize the NbN film by measuring its sheet resistance as a function of temperature, see Fig. [2](a). The inset shows the high temperature behaviour for which the sheet resistance increases while lowering the temperature from room temperature to ~ 19 K, typical of weak localization and Coulomb interaction in strongly disordered superconductors. From 19 to 5 K the resistance decreases, until zero resistance marking the superconducting transition. From this curve we extract the sheet resistance \( R_{\square} = 1033 \pm 1 \Omega/\square \) as the maximal value of the curve and the critical temperature \( T_c = 7.4 \pm 0.1 \) K at the inflexion point of the curve, see Fig. [2](a). From the sheet resistance and the critical temperature, we estimate the kinetic inductance of our NbN film\(^\text{[25]}\) as

\[
L_{\text{kin}} = \frac{\hbar R_{\square}}{k_B T_c},
\]

where \( \hbar \) is the reduced Planck constant and \( T_c \) is the superconducting gap at zero temperature. We assume that the superconducting gap for NbN is given by \( \Delta_0 = 1.76 k_B T_c \), where \( k_B \) the Boltzmann constant.\(^\text{[26]}\) From this DC measurement we obtain a kinetic inductance value of \( L_{\text{kin}} = 192 \pm 3 \) pH/\( \square \).

To confirm the kinetic inductance value extracted via DC measurements, we performed an independent RF measurement based on a two-tone spectroscopy.\(^\text{[27]}\) This method relies on measuring the dispersion relation of a resonator whose resonance frequency is set intentionally low, here \( f_0 = 750 \) MHz. This allows to probe a large number of its harmonics. To map the dispersion relation, a VNA is set to measure the transmission at a resonant frequency of the resonator \( f_{\text{VNA}} \) within the 4-8 GHz band of our measurement setup. We then sweep a second tone at a frequency \( f_{\text{MW}} \) and whenever that second tone matches a harmonic of the resonator, at a frequency \( f_h \), the measured resonance at \( f_{\text{VNA}} \) is dispersively shifted by the cross-Kerr effect\(^\text{[28]}\) and the transmission readout by the VNA is modified. By identifying all \( f_h \), the dispersion relation can be reconstructed. In Fig. [2](b) we show the dispersion relation for a probe frequency \( f_{\text{VNA}} = 5.22 \) GHz, the seventh harmonic of the resonator. Since the angular wavenumber of each resonance is given by \( k_n = \pi n/\ell \) where \( \ell \) is the length of the \( \lambda/2 \)

![FIG. 2. DC and RF method to extract the kinetic inductance. a) \( R(T) \) characteristics of the NbN film, \( T_c = 7.40 \) K and \( R_{\square} = 1033 \Omega/\square \). b) Dispersion relation of a NbN resonator measured by two-tone spectroscopy, only half of the data points to extract the phase velocity is plotted.](image)

resonator and \( n \) is the mode index, we can extract the kinetic inductance as follows:

\[
\nu_{\text{ph}} = \frac{\omega_n}{k_n} = \frac{1}{\sqrt{C_{\ell}(L_{\ell}^m + L_{\ell}^{\text{kin}})}},
\]

where \( \omega_n = 2\pi f_n \) is the angular resonance frequency, \( C_{\ell} \) is the capacitance per unit length and \( L_{\ell}^m \), \( L_{\ell}^{\text{kin}} \) are the geometric and the kinetic inductance per unit length respectively. \( L_{\ell}^m \) and \( C_{\ell} \) are purely geometrical quantities and can be estimated using a microwave simulation software like Sonnet (\( L_{\ell}^m = 2.13 \times 10^{-3} \) H/m and \( C_{\ell} = 2.82 \times 10^{-10} \) F/m) or conformal mapping calculations\(^\text{[29]}\) (\( L_{\ell}^{\text{kin}} = 2.13 \times 10^{-7} \) H/m and \( C_{\ell} = 3.13 \times 10^{-10} \) F/m). From this RF measurement and Sonnet simulations data we obtained a kinetic inductance value \( L_{\text{kin}} = 3.84 \times 10^{-4} \) H/m corresponding to \( L_{\text{kin}} = 192 \pm 3 \) pH/\( \square \), which is in excellent agreement with the DC measurement extraction. Our kinetic inductance is significantly higher than previous reports of kinetic inductance in NbN: \( L_{\text{kin}} \in [4.4, 8.2] \) pH/\( \square \).\(^\text{[30]}\) Note that the kinetic inductance can be tuned by varying the substrate temperature during the sputter deposition. We find that by tuning the temperature from room temperature to 275 °C the kinetic inductance changes from \( 220 \) pH/\( \square \) to \( 45 \) pH/\( \square \) as \( T_c \) evolves from \( 5.56 \) K to 10.5 K.

| TABLE I. Characteristic impedance of the resonators with different geometries |
|-----------------|---------|---------|
|                | 110 \( \Omega \) | 890 \( \Omega \) | 4.1 k\( \Omega \) |
| \( s \) (\( \mu \)m) | 50 | 2 | 0.2 |
| \( w \) (\( \mu \)m) | 2 | 2 | 2 |

From the NbN layer characterized previously (192 pH/\( \square \)) we have designed three sets of resonators with impedances of 110 \( \Omega \), 890 \( \Omega \) and 4.1 k\( \Omega \) by just varying the central conductor width \( s \) from 50 \( \mu \)m to 200 \( \mu \)m while keeping the gap width \( w = 2 \) \( \mu \)m, see Tab. I. We study the effect of the impedance...
inside the resonator as

\[
\langle n_{\text{ph}} \rangle = \frac{Q_i}{\omega_b} \left( \frac{Q_i}{Q_i + Q_c} \right)^2 \frac{P_{\text{in}}}{\hbar \omega_b},
\]

where \( P_{\text{in}} \) is the input power at the resonator and \( \omega_b = 2\pi f_0 \). Fig. 3(c) shows the internal quality factor as a function of the averaged number of photons. For each impedance, each data point corresponds to the mean value of 4 resonators of the same impedance but with different resonance frequencies. Before going into detail we precise that the 110Ω resonators stayed in ambient atmosphere for a few months during the COVID-19 pandemic between its fabrication and the characterization, which may explain its different behaviour from the two other sets of resonators. At low power we observe for the 900Ω and 4.5 kΩ resonators a clear saturation of the internal quality factor that may be explained by two-level system dynamics. At high photon number, \( \langle n_{\text{ph}} \rangle > 10^4 \), and for the same set of resonators, self-Kerr non-linearities lead to a strong asymmetry of the measured resonances rendering the analysis of the quality factors beyond the scope of our study.

We can only conclude that the internal quality factor saturation usually observed at such input power \([31]\) was not visible up to the power shown here. For the 110Ω resonators, whom we suspect had a different aging evolution than the other sets of resonators, we do not observe a saturation in the single photon regime while observing a clear saturation at high power around \( ~10^4 \) photons.

We now turn to the behaviour of the resonators in a static magnetic field. The internal quality factor and the relative frequency shift as a function of the applied magnetic field have been measured with an average of \( \approx 100 \) photons and the results can be seen in Fig. 4. For an out-of-plane magnetic field, see Fig. 4(a) and (b), the internal quality factor drops to \( 10^2 \) at 100 mT with an abrupt jump in resonance frequency around 0 T for the 110Ω and 890Ω resonators. For the narrowest resonators (4.1 kΩ) \( Q_i \) stays well above \( 10^4 \) up to \( B_\perp = 300 \) mT without any jump or hysteresis in the resonance frequency. We note a dip in \( Q_i \) around \( \sim 150 \) mT, which can be associated with a coupling of the resonator to magnetic impurities. The quadratic shift of the resonance is explained by the superconducting depairing under magnetic field and can be fitted following the expression\([33]\) \( \Delta f / f_0 = (\pi / 48) (D e^2 / (\hbar k^2 T_c)) B^2 s^2 \) with \( D \) the electronic diffusion constant. The extracted diffusion constant \( D \approx 0.58 \) cm\(^2\)/s is consistent with previous measurements\([34,35]\) on NbN thin films.

For the in-plane magnetic field resilience, see Fig. 4(c) and (d), we find \( Q_i > 10^4 \) for all resonators from 300 mT to 6 T. Finally, both out-of-plane and in-plane magnetic field studies show that the highest impedance have also the highest magnetic field resilience. As the losses induced in a magnetic field are mainly attributed to the creation of magnetic-flux vortices in the superconducting film, a smaller width of the central conductor minimizes vortices creation and dynamics, thus suppressing the quality factor degradation. For the 4.1 kΩ resonator for example, the central conductor width (200 nm) is shorter than the London penetration depth of NbN. Therefore, vortices are induced only in the ground plane, which explains its high \( Q_i \) in magnetic fields.

From a circuit model we derive the average photon number

\[
\frac{1}{S_{21}} = 1 + \frac{Q_i}{Q_c} e^{i\phi} \frac{1}{1 + i2Q_c\delta x},
\]

where \( Q_i, Q_c \) are the internal and coupling quality factor respectively, \( \phi \) is the rotation in the \( 1/S_{21} \) complex plane due to an impedance mismatches of the feedline of the resonators and \( \delta x = (f - f_0) / f_0 \) is the relative frequency to the resonance frequency \( f_0 \). The fit is performed in the \( 1/S_{21} \) complex plane to take into account the resonance response in magnitude and in phase simultaneously. A typical result of such a fit is shown in Fig. 3(b).

The transmission spectrum is normalized by setting the back-ical normalized transmission spectrum is shown in Fig. 3(a).
FIG. 4. Evolution of the resonators characteristics with a magnetic field. a) $Q_i$ as a function of $B_{∥}$; b) Normalized shift of the resonance frequencies with $B_{∥}$, where the lower impedance resonators show abrupt jumps around zero field while the highest impedance resonator shows no abrupt jumps neither a hysteresis. c) $Q_i$ as a function of $B_{⊥}$ for different impedances. For the resonators at 110 Ω and 4.1 kΩ, the measurement is performed from 0 to −6 T and for practical reasons it is plotted as positive values. At low magnetic field, the dip in $Q_i$ is due to coupling to magnetic impurities. Inset: $Q_i$ as a function of $B_{⊥}$. Around 200 mT for $Z_i = 4.5$ kΩ resonators resonating at different frequencies ($f_1 = 3.8$ GHz, $f_2 = 4.4$ GHz, $f_3 = 5.6$ GHz, $f_4 = 6.2$ GHz) all coupled to magnetic impurities of $g = 2$. d) Normalized shift of the resonance frequencies with $B_{⊥}$. Arrows in b) and d) indicate the sweep direction of the magnetic field.

Consequence shift in $B_{∥}$ in Fig. 4(d) shows that the 100 Ω resonances jump abruptly around 0 T, which is a signature of unstable magnetic-flux vortices in the superconducting film, while the 890 Ω and the 4.1 kΩ resonators show smooth shift of the resonance frequency and no hysteretic behaviour. Thus, even without complex microwave engineering to minimize vortices dynamics, a nanowire CPW design already improves the magnetic resilience by several orders of magnitude for both in-plane and out-of-plane magnetic field. In addition, we have verified that the excellent behaviour under a magnetic field of $B_{∥} = 6$ T with $Q_i > 10^4$ is preserved in the single photon regime.

Concerning the interaction between the resonator and magnetic impurities, the inset in Fig. 4(c) shows the internal quality factors of four 4.1 kΩ resonators with different resonance frequencies. The observed dip in the internal quality factor is shifting to a higher magnetic field as the resonator frequency is increased as expected for the resonant condition $g_m B = \hbar \omega$ with $g$ the Landé $g$-factor of the magnetic impurities. From all resonator measurements, we extract $g = 1.97 \pm 0.29$, which matches the $g$-factor of free electrons ($g = 2$).

In conclusion, we fabricate CPW resonators from a 10 nm thick NbN film in a single e-beam lithography step with a kinetic inductance of 192 pH/Ω on silicon oxide. The highest impedance reaches 4.1 kΩ, which should induce zero-point voltage fluctuation one order of magnitude higher than for a 50 Ω resonator. The high kinetic inductance enables the fabrication of superinductor with relaxed geometry constraints compared to previous reports. We find, at zero field, an internal quality factor $Q_i > 10^4$ in the single photon regime. The narrow center conductor of the 4.1 kΩ resonator made it highly resilient to magnetic fields with $Q_i > 10^4$ in a 300 mT out-of-plane and in a 6 T in-plane magnetic field without any hysteresis in the resonance frequency. Finally, NbN HISMR is a compelling choice for cQED experiments operating at finite magnetic fields and involving quantum systems with small electric dipole moments.

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1. A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, “Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation,” Phys. Rev. A 69, 062320 (2004).
2. A. Blais, S. M. Girvin, and W. D. Oliver, “Quantum information processing and quantum optics with circuit quantum electrodynamics,” Nature Physics 16, 247–256 (2020).
3. A. A. Clerk, K. W. Lehnert, P. Bertet, J. R. Petta, and Y. Nakamura, “Hybrid quantum systems with circuit quantum electrodynamics,” Nature Physics 16, 257–267 (2020).
4. N. Samkharadze, A. Bruno, P. Scarlino, G. Zheng, D. P. DiVincenzo, L. DiCarlo, and L. M. K. Vandersypen, “High-kinetic-inductance superconducting nanowire resonators for circuit qed in a magnetic field,” Phys. Rev. Applied 5, 044004 (2016).
5. L. Grünhaupt, M. Spiecker, D. Gusenko娃, N. Maleeva, S. T. Skacek, I. Takmakov, E. Valenti, P. Winkel, H. Rotzinger, W. Wernsdorfer, A. V. Ustinov, and I. M. Pop, “Granular aluminium as a superconducting material for high-impedance quantum circuits,” Nature Materials 18, 816–819 (2019).
6. D. Niepce, J. Burnett, and J. Bylander, “High kinetic inductance NbN nanowire superconductors,” Phys. Rev. Applied 11, 044014 (2019).
7. X. Mi, M. Benito, S. Putz, D. Zajac, T. J.M., G. Burkard, and J. Petta, “A coherent spin–photon interface in silicon,” Nature 555, 599–603 (2018).
8. N. Samkharadze, G. Zheng, N. Kalhor, D. Brousse, A. Sarmak, U. C. Mendes, A. Blais, G. Scappucci, and L. M. K. Vandersypen, “Strong spin–photon coupling in silicon,” Science 359, 1123–1127 (2018).
9. A. J. Landig, J. Koski, P. Scarlino, U. Mendes, A. Blais, C. Reichl, W. Wegscheider, A. Wallraff, K. Ensslin, and T. Ihn, “Coherent spin-photon coupling using a resonant exchange qubit,” Nature 560, 156–158 (2018).
10. N. A. Masluk, I. M. Pop, A. Kamal, Z. K. Minev, and M. H. Devoret, “Microwave characterization of josephson junction arrays: Implementing a low loss superinductor,” Physical Review Letters 109, 1–5 (2012).
11. M. T. Bell, I. A. Sadovskyy, L. B. Ioffe, A. Y. Kitaev, and M. E. Gershenson, “Quantum superinductor with tunable nonlinearity,” Physical Review Letters 109, 1–5 (2012).
12. B.D. Josephson, “Possible new effects in superconductive tunneling,” Physics Letters A, 7 (1962).
13. M. A. Castellanos-Beltran and K. W. Lehnert, “Wide-tunable parametric amplifier based on a superconducting quantum interference device array resonator,” Applied Physics Letters 91 (2007), 10.1063/1.2773988.
abled by a high impedance resonator,” Physical Review X 2, 041001 (2012).

A. André, D. DeMille, J. M. Doyle, M. D. Lukin, S. E. Maxwell, P. Rabl, R. J. Schoelkopf, and P. Zoller, “A coherent all-electrical interface between polar molecules and mesoscopic superconducting resonators,” Nature Physics 2, 636–642 (2006).

T. Frey, P. J. Leek, M. Beck, A. Blais, T. Ihn, K. Ensslin, and A. Wallraff, “Dipole coupling of a double quantum dot to a microwave resonator,” Phys. Rev. Lett. 108, 046807 (2012).

A. Stockklauser, P. Scarlino, J. V. Koski, S. Gasparinetti, C. K. Andersen, C. Reichl, W. Wegscheider, T. Ihn, K. Ensslin, and A. Wallraff, “Strong coupling cavity QED with gate-defined double quantum dots enabled by a high impedance resonator,” Physical Review X 7, 1–5 (2017), arXiv:1701.03433.

M. R. Delbecq, V. Schmitt, F. D. Parmentier, N. Roch, J. J. Viennot, G. Fève, B. Huard, C. Mora, A. Cottet, and T. Kontos, “Coupling a quantum dot, fermionic leads, and a microwave cavity on a chip,” Physical Review Letters 107, (2011), 10.1103/PhysRevLett.107.256804, arXiv:1108.4371.

J. J. Viennot, M. C. Dartiailh, A. Cottet, and T. Kontos, “Coherent coupling of a single spin to microwave cavity photons,” Science 349, 408–411 (2015).

F. Borjans, X. G. Croot, X. Mi, M. J. Gullans, and J. R. Petta, “Long-Range Microwave Mediated Interactions Between Electron Spins,” Nature 577, 195–198 (2020).

C. Müller, J. Bourassa, and A. Blais, “Detection and manipulation of Majorana fermions in circuit QED,” Physical Review B - Condensed Matter and Materials Physics 88, 1–11 (2013), arXiv:1306.1539.

K. Yavilberg, E. Ginossar, and E. Grosfeld, “Fermion parity measurement and control in Majorana circuit quantum electrodynamics,” Physical Review B - Condensed Matter and Materials Physics 92, 1–7 (2015), arXiv:1411.5699.

M. C. Dartiailh, T. Kontos, B. Douçot, and A. Cottet, “Direct Cavity Detection of Majorana Pairs,” Physical Review Letters 118, 1–7 (2017), arXiv:1702.01637.

B. Sacépé, Spectroscopie tunnel dans des films minces proche de la transition supraconducteur-isolant, Ph.D. thesis (2007).

M. Tinkham, Introduction to superconductivity (Dover Publications Inc., 2004).

E. A. Antonova, D. R. Dhurau, G. P. Motulevich, and V. A. Sukhov, “Superconducting energy gap of niobium nitride,” Soviet Physics - JETP 53, 1270–1271 (1981).

Y. Krupko, V. D. Nguyen, T. Weißl, É. Dumur, J. Puertas, R. Dassonneville, C. Naud, F. W. J. Heikking, D. M. Basko, O. Buisson, and N. Roch, “Kerr nonlinearity in a superconducting Josephson metamaterial,” Physical Review Applied 094516, 1–12 (2018).

O. Suchoi, B. Abdó, E. Segev, O. Shemtov, M. P. Blencowe, and E. Buks, “Intermode dephasing in a superconducting stripline resonator,” Phys. Rev. B 81, 174525 (2010).

R. N. Simons, Coplanar Waveguide Circuits, Components, and Systems (John Wiley & Sons, Inc., 2001).

A. J. Annunziata, D. F. Santavicca, L. Frunzio, G. Catelani, M. J. Rooks, and A. Friedman, “Tunable superconducting nanodisorders,” Nanotechnology 21 (2010), 10.1088/0957-4484/21/44/445202.

A. Meigrant, C. Naud, F. W. J. Hekking, D. M. Basko, O. Buisson, and N. Roch, “Superconducting nanowire circuits using a neon focused ion beam,” Phys. Rev. Applied 8, 014039 (2017).

A. Engel, K. Inderbitzin, A. Schilling, R. Lusche, A. Semenov, H. Hübers, D. Henrich, M. Hofherr, K. Il’in, and M. Siegel, “Temperature-dependence of detection efficiency in nbn and tan snp,” IEEE Transactions on Applied Superconductivity 23, 2300505–2300505 (2013).

E. Knehr, A. Kuzmin, D. Y. Vodolazov, M. Ziegler, S. Doerner, K. Ilin, M. Siegel, R. Stolz, and H. Schmidt, “Nanowire single-photon detectors made of atomic layer-deposited niobium nitride,” Superconductor Science and Technology 32, 125007 (2019).

A. Kamplapure, M. Mondal, M. Chand, A. Mishra, J. Jesudasan, V. Bagwe, L. Benfatto, V. Tripathi, and P. Raychaudhuri, “Measurement of magnetic penetration depth and superconducting energy gap in very thin epitaxial nbn films,” Applied Physics Letters 96, 072509 (2010).

J. Kroll, F. Borsoi, K. van der Enden, W. Uijlhoorn, D. J. de Jong, M. Quintero-Pérez, D. van Woerkom, A. Bruno, S. Plissard, D. Car, E. Bakkers, M. Cassidy, and L. Kouwenhoven, “Magnetric-field-resilient superconducting coplanar-waveguide resonators for hybrid circuit quantum electrodynamics experiments,” Phys. Rev. Applied 11, 064053 (2019).