Film-thickness dependence of 10 GHz Nb coplanar-waveguide resonators

Kunihiro Inomata,1,∗ Tetsuya Yamamoto,1,2 Michio Watanabe,1 Kazuki Matsuba,3 and Jaw-Shen Tsai1,2

1RIKEN Advanced Science Institute, 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
2NEC Nano Electronics Research Labs., 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
3Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, 226-8503, Japan

(Dated: April 14, 2009)

We have studied Nb λ/2 coplanar-waveguide (CPW) resonators whose resonant frequencies are 10 – 11 GHz. The resonators have different film thicknesses, t = 0.05, 0.1, 0.2, and 0.3 µm. We measured at low temperatures, T = 0.02 – 5 K, one of the scattering-matrix element, S21, which is the transmission coefficient from one port to the other. At the base temperatures, T = 0.02 – 0.03 K, the resonators are overcoupled to the input/output microwave lines, and the loaded quality factors are on the order of 105. The resonant frequency has a considerably larger film-thickness dependence compared to the predictions by circuit simulators which calculate the inductance of CPW taking into account Lg only, where Lg is the usual magnetic inductance determined by the CPW geometry. By fitting a theoretical S21 vs. frequency curve to the experimental data, we determined for each film thickness, the phase velocity of the CPW with an accuracy better than 0.1%. The large film-thickness dependence must be due to the kinetic inductance Lk of the CPW center conductor. We also measured S21 as a function of temperature up to T = 4 – 5 K, and confirmed that both thickness and temperature dependence are consistent with the theoretical prediction for Lk.

J. Vac. Sci. Technol. B 27, 2286 (2009) [DOI: 10.1116/1.3232301]

I. INTRODUCTION

Microwave resonators (for example, Chap. 7 of Ref.[1]) are one of the key components in a variety of circuits operated at GHz frequencies, and their new applications continue to emerge. A simple example is band-pass filters, which are based on the fact that the microwave transmission through resonators is frequency sensitive. The same idea is also used for more complex devices, such as oscillators, tuned amplifiers, and frequency meters. Actually, having high-quality filters and oscillators is critical in mobile communications, where available bands keep getting overcrowded as demand grows rapidly.

Another application of microwave resonators is radiation detectors, which often consist of sensor heads and read-out circuits, and resonators can be used in the readout circuit. When one would like to detect at the single-photon level, one needs to have detectors with high enough energy resolutions. In this respect, superconducting sensor heads can be advantageous, and may be the only solution at present depending on the energy range of the object. Once one decides to use superconducting sensor heads, it makes sense to fabricate the read-out circuit with superconducting materials as well. Superconducting microwave resonators allow one to obtain higher quality factors, which are favorable for frequency multiplexing. In addition, one type of photon detector is designed to probe the change in the kinetic inductance of superconducting thin-film resonator due to the absorbed photons. In this device concept, the resonator works as a sensor head rather than a part of the readout circuit.

Recently, superconducting resonators are used for the non-demolition readout of superconducting qubits as well. Since the demonstration by Wallraff et al.[8] this type of readout scheme has been one of the main topics in the field of superconducting qubits, and we are also developing a similar readout technique. In superconducting resonators, kinetic inductance, which is essentially the internal mass of the current carriers, plays an important role especially when the superconducting film is thin. In our circuit, for example, a Nb λ/4 coplanar-waveguide (CPW) resonator is terminated by an Al dc SQUID, and the total thickness of the Al layers is 0.04 µm. In order to avoid a discontinuity at the Al/Nb interface, we usually choose the Nb thickness to be 0.05 µm, which is much thinner than a typical thickness of ≥ 0.3 µm for superconducting integrated circuits fabricated by the standard photolithographic technology. Fabricating circuits with thinner films is actually important from the viewpoint of miniaturization as well. Therefore, for designing resonators, quantitative understanding of the kinetic inductance in the CPW is important.

There have been a number of reports on kinetic inductance for a variety of materials.[8-13] In general, however, kinetic inductance is indirectly measured by assuming a theoretical model, and as a result, the uncertainties are relatively large. Thus, although kinetic inductance is a well established notion and the phenomenon is qualitatively understood, the quantitative information is not necessarily sufficient from the point of view of applications, especially at high frequencies, ≥ 10 GHz. When we would like to precisely predict the resonant frequency, the best solution would be to characterize the actual CPW in a simple circuit. Such characterization should also improve the knowledge of superconducting microwave circuits. Very recently, Göppl et al.[14] measured a series of Al CPW resonators with nominally the same film thickness of 0.2 µm, and investigated...
TABLE I: List of resonators. \( t \) is the thickness of Nb film; \( f_r \) is the resonant frequency; \( Q_L \) is the unloaded quality factor; \( C_c \) is the coupling capacitance; \( v_p \) is the phase velocity, and its ratio to the speed of light \( c \) is listed in percent. The values for \( f_r \) and \( Q_L \) are obtained at the base temperatures. \( C_c \) and \( v_p \) are evaluated by least-squares fitting (see Fig. 1) with \( C = 1.6 \times 10^{-10} \, \text{F/m} \), and their uncertainties are determined by changing the value of \( C \) by \( \pm 10\% \), where \( C \) is the capacitance per unit length.

| Resonator | \( t \) (\( \mu \text{m} \)) | \( f_r \) (GHz) | \( Q_L \) \((\times 10^3)\) | \( C_c \) (fF) | \( v_p/c \) (%) |
|-----------|----------------|--------------|----------------|-------------|-------------|
| A1        | 0.05           | 10.01        | 1.6            | 7.0±0.4    | 39.31±0.03 |
| A2        | 0.1            | 10.50        | 1.4            | 7.3±0.4    | 41.28±0.04 |
| A3        | 0.2            | 10.74        | 1.4            | 7.2±0.4    | 42.21±0.04 |
| A4        | 0.3            | 10.88        | 1.6            | 6.6±0.4    | 42.71±0.03 |
| B1        | 0.05           | 10.06        | 3.4            | 4.6±0.3    | 39.32±0.02 |
| B2        | 0.1            | 10.56        | 3.1            | 4.8±0.3    | 41.26±0.02 |
| B3        | 0.2            | 10.81        | 2.7            | 5.0±0.3    | 42.27±0.03 |
| B4        | 0.3            | 10.94        | 3.3            | 4.5±0.3    | 42.72±0.02 |

![FIG. 1: Schematic diagram of coplanar-waveguide (CPW) resonators. A CPW of length \( l \) is coupled to the microwave lines through capacitors \( C_c \).](image)

the relationship between the loaded quality factor at the base temperature of 0.02 K and the coupling capacitance. For this purpose, it is justified to neglect kinetic inductance because the kinetic inductance should be the same in their resonators and estimated to be about two orders of magnitude smaller than the usual magnetic inductance determined by the CPW geometry. In this work, on the other hand, we paid close attention to the resonant frequency as well, and characterized Nb CPW resonators as a function of film thickness rather than a function of coupling capacitance. We also looked at the temperature dependence in order to discuss kinetic inductance in detail.

II. EXPERIMENT

We studied two series of Nb \( \lambda/2 \) CPW resonators listed in Table I. Each resonator consists of a section of CPW and coupling capacitors, as shown schematically in Fig. 1. The resonators were fabricated on a nominally undoped Si wafer whose surface had been thermally oxidized. On the SiO\(_2\)/Si substrate, a Nb film was deposited by sputtering and then patterned by photolithography and SF\(_6\) reactive ion etching. Figure 2(a) represents the cross section of CPW. The center conductor has a width of \( w = 10 \, \mu\text{m} \), and separated from the the ground planes by \( s = 5.8 \, \mu\text{m} \), so that the characteristic impedance becomes \( \sim 50 \, \Omega \). The thickness of Nb is \( t = 0.05, 0.1, 0.2, \) or \( 0.3 \, \mu\text{m} \) (see Table I), and that of SiO\(_2\)/Si substrate is \( h = 300 \, \mu\text{m} \). The SiO\(_2\) layer, whose thickness is \( 0.3 \, \mu\text{m} \), is not drawn in Fig. 2(a). We employed interdigital coupling capacitors as shown in Fig. 2(b). The finger width is \( w_f = 9 \, \mu\text{m} \), the space between the fingers is \( s_f = 2 \, \mu\text{m} \), and the finger length is \( l_f = 78 \, \mu\text{m} \) for Resonators A1–A4 and \( l_f = 38 \, \mu\text{m} \) for Resonators B1–B4. Here, we quoted designed dimensions for the Nb structures. The actual dimensions differ by about \( 0.2 \, \mu\text{m} \) due to over-etching; for example, \( w \) and \( w_f \) are \( \sim 0.2 \, \mu\text{m} \) smaller, whereas \( s \) and \( s_f \) are \( \sim 0.2 \, \mu\text{m} \) larger. In this paper, we define the resonator length \( l \) as the distance between the center of the fingers on one side and that on the other side, and \( l = 5.8 \, \text{mm} \) for all resonators. Because our chip size is 2.5 mm by 5.0 mm, our CPWs meanander as in Fig. 3.

The resonators were measured in a \( ^3\text{He} - ^4\text{He} \) dilution refrigerator at \( T = 0.02 - 5 \, \text{K} \). A typical measurement setup is shown schematically in Fig. 3. The boxes in the figure represent attenuators. The amount of attenuation was not the same because the microwave lines in our refrigerator had been designed for several different purposes. The attenuation was \( x = 10 \, \text{dB} \) for Resonators A2, B3, and B4, and \( x = 20 \, \text{dB} \) for the others; \( y = 10 \, \text{dB} \) for all resonators except A1 and A3. For Resonators A1 and A3, we used a line with no attenuators (\( y = 0 \, \text{dB} \)) but with an isolator and a cryogenic amplifier at 4.2 K. The gain of the cryogenic amplifier was 40 dB for Resonator A1 and 34 dB for A3. We measured the transmission coefficient.
The solid curves in Fig. 4 are calculations based on the transmission \((ABCD)\) matrix (for example, Sec. 5.5 of Ref. 1), and they reproduce the experimental data well. The matrix for the resonators is given by
\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} = T_{cc} \cdot T_{cpw} \cdot T_{cc} ,
\]
where
\[
T_{cc} = \begin{pmatrix} 1 & (j\omega C_c)^{-1} \sin \beta l \\
0 & 1 \end{pmatrix} ,
\]
j is the imaginary unit,
\[
T_{cpw} = \begin{pmatrix} 
\cos \beta l & jZ_{cpw} \sin \beta l \\
\sin \beta l / \cos \beta l & \cos \beta l/n \end{pmatrix}
\]
for lossless CPWs, \(\omega = 2\pi f\), \(\beta = \omega / v_p\),
\[v_p = 1/\sqrt{LC}\]
is the phase velocity, which is strongly related to \(f_r\),
\[Z_{cpw} = \sqrt{L/C}\]
is the characteristic impedance, \(L\) is the inductance per unit length, and \(C\) is the capacitance per unit length. From these transmission-matrix elements, the scattering-matrix elements are calculated, and \(S_{21}\) is given by
\[S_{21} = 2/(A + B/Z_0 + C/Z_0 + D) ,\]
where \(Z_0 = 50 \Omega\) is the characteristic impedance of the microwave lines connected to the resonator. Unit-length properties of CPW are determined when two parameters out of \(v_p\), \(Z_{cpw}\), \(L\), and \(C\) are specified. In the calculations for Fig. 4, we employed \(C = 1.6 \times 10^{-10} \text{ F/m}\) based on the considerations described in the following paragraph, and evaluated \(C_c\) and \(v_p\) by least-squares fitting.

We calculated CPW parameters using conformal mapping. Within the theory, \(C\) does not depend on \(t\), and it is given by
\[C = (\epsilon_r + 1) \epsilon_0 2K(k)/K(k') ,\]
where \(\epsilon_r\) is the relative dielectric constant of the substrate, \(\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}\) is the permittivity of free space, \(K(k)\) is the complete elliptical integral of the first kind, the argument \(k\) is given by
\[k = w/(w + 2s) ,\]
and \(k' = \sqrt{1 - k^2}\). For our CPWs, we obtain \(C = 1.6 \times 10^{-10} \text{ F/m}\) when we employ \(\epsilon_r = 11.7\) for Si (p. 223 of Ref. 16) neglecting the contribution from the SiO\(_2\) layer, which is much thinner compared to \(w\), \(s\), or \(h\). Circuit simulators [Microwave Office from AWR (#1) and AppCAD from Agilent (#2)] also predict similar values of \(C\). The simulators calculate CPW parameters from

Figures 4 shows the amplitude of \(S_{21}\) as a function of frequency for (a) Resonators A1–A4, and (b) Resonators B1–B4. A typical incident power to the resonator was −40 dBm. For each resonator, we confirmed that the measurements were done in an appropriate power range in the sense that the results looked power independent.

\[S_{21}\] by connecting a vector network analyzer to the “IN” and “OUT” ports in Fig. 3. A typical incident power to the resonator was −40 dBm. For each resonator, we confirmed that the measurements were done in an appropriate power range in the sense that the results looked power independent.

### III. RESULTS

#### A. \(S_{21}\) at the base temperatures

Figure 4 shows the amplitude of \(S_{21}\) at the base temperatures, \(T = 0.02 – 0.03 \text{ K}\), as a function of frequency \(f\) for all resonators. The resonant frequency \(f_r\) has a rather large film-thickness dependence. Our interpretation is that this is due to the kinetic inductance of the CPW center conductor. Before discussing the thickness dependence in detail, let us look at the quality factors.

What we obtain by measuring \(S_{21}\) as a function of \(f\) is the loaded quality factor \(Q_L\), which is related to the external quality factor \(Q_e\) and the unloaded quality factor \(Q\) by
\[Q_L^{-1} = Q_e^{-1} + Q^{-1} .\]

In general, \(Q_e\) is determined mainly by \(C_c\), whereas \(Q\) is a measure of the internal loss, which arises not only from the dielectric but also from the superconductor in the high-frequency regime. Our resonators should be highly overcoupled to the input/output lines at the base temperatures, that is, \(Q \gg Q_e\), and thus, \(Q_L \sim Q_e\). As listed in Table 1, \(Q_L\) of our resonators is on the order of 10\(^3\). These values are not only reasonable for the designs of our finger-shaped coupling capacitors but also much smaller than typical values of \(Q\) below 0.1 K for superconducting microwave resonators.\(^{13,14}\) When \(Q \gg Q_e\), the maximum \(|S_{21}|\) is expected to be 0 dB. We have confirmed by taking into account attenuators, amplifiers, and cable losses, that our measurements are indeed consistent within the uncertainties of gain/loss calculations, 1–2 dB. Based on this confirmation, the experimental data in Fig. 4 are normalized so that the peak heights equal 0 dB.
TABLE II: Dependence of coplanar-waveguide parameters on the film thickness \( t \). For capacitance \( C \) and inductance \( L \) per unit length, the normalized variations \( \Delta C(t)/C^* \) and \( \Delta L(t)/L^* \) are listed in percent, where \( \Delta C(t) = C(t) - C^* \), \( C^* \sim 1.6 \times 10^{-10} \text{ F/m} \) is the value at \( t = 0.3 \text{ µm} \), and the definitions of \( \Delta L(t) \) and \( L^* \sim 4 \times 10^{-7} \text{ H/m} \) are similar. The predictions by circuit simulators \#1 and \#2 are compared. Regarding \( L \), experimental values for “A”=Resonators A1–A4 and for “B”=Resonators B1–B4 are also given, and they are obtained from the values of \( v_p \) in Table I using Eq. (1) and by neglecting the \( t \) dependence of \( C \).

| \( t \) (µm) | \( \Delta C(t)/C^* \) (%) | \( \Delta L(t)/L^* \) (%) |
|--------------|--------------------------|--------------------------|
|              | \#1 | \#2 | \#1 | \#2 | A  | B  |
| 0.05         | 1.7 | 3.9 | 18.0| 18.0|     |    |
| 0.1          | 1.4 | 3.0 | 2.2 | 7.1 | 7.2 |    |
| 0.2          | 0.8 | 1.4 | 1.2 | 2.4 | 2.1 |    |

FIG. 5: (Color online) Amplitude of the transmission coefficient \( S_{21} \) as a function of frequency for Resonators A1 at different temperatures.

FIG. 6: (Color online) Normalized quality factors, \( Q/Q_e \), and \( Q_L/Q_e \), as functions of temperature for Resonators A1–A4 (Nb thickness \( t = 0.05, 0.1, 0.2, \) and 0.3 µm), where \( Q_L, Q_e, \) and \( Q \) are loaded, external, and unloaded quality factors, respectively, and \( Q_e \) is assumed to be temperature independent. The markers are data points, whereas the curves are guides to the eyes.

B. Temperature dependence of \( S_{21} \)

We also measured \( S_{21} \) vs. \( f \) at various temperatures up to \( T = 4 \) – 5 K for Resonators A1–A4. We show the results for Resonator A1 in Fig. 5. With increasing temperature, \( f_r, Q_L, \) and the peak height decrease. As in Sec. IIIA, let us look at the quality factors first. In our resonators, \( Q_e \sim Q_L \) at the base temperatures as we pointed out in Sec. IIIA. Thus, when we assume that \( Q_e \) is temperature independent, we can calculate \( Q \) from measured \( Q_L \) using Eq. (1). We plot \( Q_L(T)/Q_e \) and \( Q(T)/Q_e \) vs. \( T \) in Fig. 6 for all of the four res-
onators. With increasing temperature, $Q$ decreases in all resonators. A finite $Q^{-1}$ means that the resonator has a finite internal loss, which is consistent with a peak height smaller than unity in Fig. 5. The internal loss at high temperatures must be due to quasiparticles in the superconductor, as discussed in Ref. 6. The reduction of quality factors becomes larger as the Nb thickness is decreased. This trend also suggests that we should take into account the kinetic inductance.

As in earlier works,9,13,14 as well. The $T$ dependence of $L_k$ arises from the fact that $L_k$ is determined not only by the geometry but also by the penetration depth $\lambda$, which varies with $T$. Meservey and Tedrow5 calculated $L_k$ of a superconducting strip, and when the strip has a rectangular cross section like our CPWs, $L_k$ is written as

$$L_k = \frac{\mu_0}{\pi^2} \frac{\ln(4w/t)}{\sinh(t/\lambda)} \frac{\lambda(t)}{\cosh(t/\lambda) - 1},$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space. The relationship between $L_k$ and $\lambda$ is expressed in a much simpler form in the thick- and thin-film limits; $L_k \propto \lambda$ for $t \gg \lambda$, and $L_k \propto \lambda^2$ for $t \ll \lambda$. When we assume Eqs. (10) and (11), we obtain $\lambda(t, T)$ numerically, once $L_g(t)$ is given. Below, we discuss $\lambda(t, T)$ in our Nb films in order to confirm that the model represented by Eq. (10) is indeed appropriate.

In Fig. 5(a), we plot $[\lambda(t, T^*)/\lambda(t, T)]^2$ vs. $T/T_c(t)$ for Resonators A1–A4, where $T_c(t)$ is the superconducting transition temperature, which is assumed to be also $t$ dependent in this paper. We have found that with a reasonable set of parameters, $L_g(t)$ and $T_c(t)$, the experimental data for all resonators are described by a single curve. This kind of scaling is expected theoretically in the limits of $\zeta_0/\lambda_L \gg 1$ and $\zeta_0/\lambda_L \ll 1$, where $\zeta_0$ is the coherence length and $\lambda_L$ is the London penetration.
TABLE III: Inductance per unit length at the base temperatures in Resonators A1–A4. \( t \) is the thickness of Nb film; \( \Delta L_g(t) = L_g(t) - L_g^0 \), where \( L_g \) is the usual magnetic inductance per unit length determined by the CPW geometry, and \( L_g^0 \equiv L_g(0.3 \text{ mm}) = 3.75 \times 10^{-7} \text{ H/m} \); \( L_k \) is the kinetic inductance per unit length, and \( L = L_g + L_k \).

| \( t \) (\( \mu \text{m} \)) | \( \Delta L_g(t)/L_g^* \) (%) | \( L_k/L \) (%) |
|-------------------------|-----------------|-----------------|
| 0.05                    | 4.3             | 13.1            |
| 0.1                     | 3.4             | 4.9             |
| 0.2                     | 1.7             | 2.2             |
| 0.3                     | –               | 1.6             |

Although \( \xi_0/\lambda_L \sim 1 \) in Nb (p. 353 of Ref. 16) at temperatures well below \( T_c \), it would be still reasonable to expect a scaling in our Nb resonators because at a given normalized temperature \( T/T_c(t) \), the relevant quantities should be on the same order of magnitude in all resonators, and thus, two parameters, \( \lambda(t, T^*) \) and \( T_c(t) \), are probably enough for characterizing \( \lambda(t, T) \) of our resonators. The values of \( L_g(t) \) and \( T_c(t) \) employed in Fig. 8(a) are summarized in Table III and Fig. 8(b), respectively. The relative change of \( L_g(t) \) in Table III is similar to the predictions by circuit simulators in Table II which do not take into account the kinetic inductance. The magnitude of \( L_g(t) \) is also reasonable because \( \sqrt{L_g(t)/C} \sim 49 \text{ } \Omega \) for all thickness. In Table III we also list the ratio of kinetic inductance \( L_k \) to the total inductance \( L \). With decreasing thickness, \( L_k/L \) indeed increases rapidly. In Fig. 8(b), \( T_c(t) \) and \( \lambda(t, T^*) \) are plotted together with the theoretical curves in Figs. 1 and 6 of Ref. 12 where Gubin et al. determined some parameters of the curves by fitting to their experimental data. The values of \( T_c(t) \) are reasonable, and \( \lambda(t, T^*) \) is on the right order of magnitude.

The solid curve in Fig. 8(a) is the theoretical \( T \) dependence based on the two-fluid approximation.  

\[
[\lambda(0)/\lambda(T)]^2 = 1 - (T/T_c)^4.
\]

This theoretical curve reproduces the experimental data at \( T/T_c < 0.4 \), when we assume that \( \lambda(t, T^*) \sim \lambda(t, 0) \) in Resonators A1–A4. At \( T/T_c \geq 0.4 \), on the other hand, the experimental data deviate from Eq. (12), but according to Ref. 17, the expression for \( \lambda \) vs. \( T \) depends on the ratio of \( \xi_0/\lambda_L \), and thus, Eq. (12) cannot be expected to apply to all materials equally well. Indeed, although the temperature dependence of Eq. (12) has been observed in the classic pure superconductors, such as Al with \( \xi_0/\lambda_L \gg 1 \) at temperatures well below \( T_c \), it does not seem to be the case in the high-\( T_c \) materials, whose typical \( \xi_0/\lambda_L \) is in the opposite limit \( \xi_0/\lambda_L \ll 1 \), and for example, Rauch et al. employed for a high-\( T_c \) material \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \), an empirical expression of 

\[
[\lambda(0)/\lambda(T)]^2 = 1 - 0.1(T/T_c) - 0.9(T/T_c)^2,
\]

which is the broken curve in Fig. 8(a), instead. Because \( \xi_0/\lambda_L \sim 1 \) in Nb even at \( T/T_c \ll 1 \), and because the experimental data at \( T/T_c \geq 0.4 \) are between Eqs. (12) and (13), we believe that the deviation from Eq. (12) at \( T/T_c \geq 0.4 \) is reasonable.

From the discussion in this section, we conclude that the model represented by Eq. (10) explains the film-thickness and temperature dependence of our resonators.

V. CONCLUSION

We investigated two series of Nb \( \lambda/2 \) CPW resonators with resonant frequencies in the range of \( 10 \sim 11 \text{ GHz} \) and with different Nb-film thicknesses, \( 0.05 \sim 0.3 \mu \text{m} \). We measured the transmission coefficient \( S_{21} \) as a function of frequency at low temperatures, \( T \sim 0.02 \sim 5 \text{ K} \). For each film thickness, we determined the phase velocity in the CPW with an accuracy better than 0.1% by least-squares fitting of a theoretical \( S_{21} \) curve based on the transmission matrix to the experimental data at the base temperatures. Not only the film-thickness dependence but also the temperature dependence of the resonators are explained by taking into account the kinetic inductance of the CPW center conductor.

Acknowledgment

The authors would like to thank Y. Kitagawa for fabricating the resonators, and T. Miyazaki for fruitful discussion. T. Y., K. M., and J.-S. T. would like to thank CREST-JST, Japan for financial support.
8 R. Meservey and P. M. Tedrow, J. Appl. Phys. 40, 2028 (1969).
9 W. Rauch, E. Gomik, G. Sölkner, A. A. Valenzuela, F. Fox, and H. Behner, J. Appl. Phys. 73, 1866 (1993).
10 T. Kisu, T. Inuma, K. Enpuku, K. Yoshida, and K. Yamafuji, IEEE Trans. Appl. Supercond. 3, 2961 (1993).
11 K. Watanabe, K. Yoshida, T. Aoki, and S. Kohjiro, Jpn. J. Appl. Phys. 33, 5708 (1994).
12 A. I. Gubin, K. S. Il’in, S. A. Vitusevich, M. Siegel, and N. Klein, Phys. Rev. B 72, 064503 (2005).
13 L. Frunzio, A. Wallraff, D. Schuster, J. Majer, and R. Shoelkopf, IEEE Trans. Appl. Supercond. 15, 860 (2005).
14 M. Göppl, A. Fragner, M. Baur, R. Bianchetti, S. Filipp, J. M. Fink, P. J. Leek, G. Puebla, L. Steffen, and A. Wallraff, J. Appl. Phys. 104, 113904 (2008).
15 C. P. Wen, IEEE Trans. Microwave Theory Tech. 17, 1087 (1969).
16 C. Kittel, Introduction to Solid State Physics (John Wiley & Sons, New York, 1996), 7th ed.
17 M. Tinkham, Introduction to Superconductivity (MacGraw-Hill, New York, 1996), pp. 100–108, 2nd ed.