Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters

Citation: Appl. Phys. Lett. 100, 192601 (2012); doi: 10.1063/1.4710520
View online: http://dx.doi.org/10.1063/1.4710520
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v100/i19
Published by the American Institute of Physics.

Related Articles
Mapping inter-element coupling in metamaterials: Scaling down to infrared
Thermal nonlinearity in silicon microcylindrical resonators
High-Q silicon optomechanical microdisk resonators at gigahertz frequencies
Membrane metamaterial resonators with a sharp resonance: A comprehensive study towards practical terahertz filters and sensors
AIP Advances 2, 022109 (2012)
Analysis of dielectric loaded surface plasmon waveguide structures: Transfer matrix method for plasmonic devices

Additional information on Appl. Phys. Lett.
Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors
Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters

K. Geerlings, S. Shankar, E. Edwards, L. Frunzio, R. J. Schoelkopf, and M. H. Devoret
Department of Applied Physics, Yale University, New Haven, Connecticut 06520-8284, USA

(Received 27 March 2012; accepted 16 April 2012; published online 7 May 2012)

Applications in quantum information processing and photon detectors are stimulating a race to produce the highest possible quality factor on-chip superconducting microwave resonators. We have tested the surface-dominated loss hypothesis by systematically studying the role of geometrical parameters on the internal quality factors of compact resonators patterned in Nb on sapphire. Their single-photon internal quality factors were found to increase with the distance between capacitor fingers, the width of the capacitor fingers, and the resonator impedance. Quality factors were improved from 210 000 to 500 000 at \( T = 200 \text{ mK} \). All of these results are consistent with our starting hypothesis. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4710520]
Kaufmann source that shoots 500 eV argon ions at our wafer. Our source operates at a flow rate of 4.25 sccm and a pressure of about 10 μTorr, generating a current density of 0.67 mA/cm². A 200 nm layer of Nb was then dc magnetron sputtered on the wafer. Photolithography was performed by patterning directly onto S1808 resist using a 365 nm laser. After development, the Nb was etched using a 1:2 mixture of Ar:SF₆ at 10 mTorr for 3 min. The wafer was then diced into individual chips for measurement.

In the systematic variation of compact resonator parameters, we chose to optimize the following parameters shown pictorially in Figure 1: the gap $g_C$ between two adjacent capacitor fingers, the distance $g_L$ between two adjacent inductor meanders, the distance $g_R$ between the resonator and the surrounding ground plane, and the width $w$ of the resonator traces. In addition, we also varied the characteristic impedance $Z_0$ of the resonator. This set of parameters is relevant for surface losses.

We formed a benchmark set of resonators with parameter values: $g_C = 10 \mu m$, $g_L = 20 \mu m$, $g_R = 10 \mu m$, $w = 5 \mu m$, and $Z_0 = 100 \Omega$. Resonators with this set of parameters will now be called “design A” resonators. We measured 25 design A resonators with an average $Q$, of 160 000 (±20 000) and a maximum of 210 000 at single-photon power. Additionally, one chip with 6 resonators inexplicably had quality factors ranging from 40 000 to 70 000, much lower than the rest; we did not include this chip in the benchmark. $Q$, typically increased to around $1 \times 10^6$ at a “high” power corresponding to an average of $10^8$ photons in the resonator. The resonant frequency typically decreased as the temperature passed below 1.3 K, consistent with TLS loss. These results are consistent with the hypothesis that our benchmark $Q$, is controlled by surface losses.

We measured 24 geometrical variants of design A, with each “mutant” resonator having only one parameter value that is changed. For example, the mutant values of $g_C$ were: 3, 5, 20, 30, and 40 μm. The results of the mutant resonators are shown in Figure 3; percent changes in $Q$, are given with respect to the design A resonator benchmark.

For $g_C$, small values lead to lower $Q$, and larger values lead to higher $Q$. The effect of changing $g_L$, on $Q$, is at least a factor of three smaller than for $g_C$. Thus, the gaps where electric fields are present (the capacitor and not the inductor), partially control $Q$, consistent with a surface loss mechanism coupled to the electric field. Similarly, $Q$, increases for larger $w$, again consistent with surface loss, since wider traces lead to decreasing electric field strength at surfaces. Next, we find that $Q$, drops by roughly 25% if $g_R \geq 50 \mu m$, suggesting that the ground plane prevents electric fields from reaching lossy materials such as the copper box or printed circuit board (PCB) dielectric. Lastly, the trend indicating that larger values of $Z_0$ are beneficial to $Q$, appears to contradict the usual hypothesis that dissipative mechanisms have a constant tanδ. The results for $g_C$, $g_L$, and $w$ are all consistent with a loss dominated by surface electric field participation.

We chose two new sets of parameters from these results with the goal of improving the $Q$,. Resonators with these parameters are called designs B and C resonators. Design B values were chosen to be relatively modest changes from design A, while design C values were chosen to maximize $Q$,.

<table>
<thead>
<tr>
<th>$g_C$ (μm)</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_i$</td>
<td>-31%</td>
<td>-14%</td>
<td>0%</td>
<td>16%</td>
<td>0%</td>
<td>18%</td>
</tr>
<tr>
<td>$g_L$ (μm)</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>$\Delta Q_i$</td>
<td>-6%</td>
<td>-10%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>$g_R$ (μm)</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>50</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>$\Delta Q_i$</td>
<td>28%</td>
<td>0%</td>
<td>-2%</td>
<td>-28%</td>
<td>-24%</td>
<td>-36%</td>
</tr>
<tr>
<td>$w$ (μm)</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>$\Delta Q_i$</td>
<td>-16%</td>
<td>0%</td>
<td>17%</td>
<td>16%</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>$Z_0$ (Ω)</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>$\Delta Q_i$</td>
<td>-12%</td>
<td>26%</td>
<td>33%</td>
<td>19%</td>
<td>33%</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 3. Dependence of $Q$, on parameter values. The changes in $Q$, for a given mutant value are reported in reference to the average $Q$, (160 000) of design A with positive values representing improvements. The shaded column indicates the design A value of that parameter; $\Delta Q_i$ in this column is zero by definition. The square in each row with a bold border shows the value chosen for design B. Parameters for design C cannot easily be shown on this figure as explained in the main text.

FIG. 2. Two extreme examples of resonator response curves fit with Eq. (1). Responses typically fall in between (a) symmetric and (b) strongly asymmetric about the resonant frequency.

FIG. 1. Schematic of compact resonator and inset showing resonator parameters. The compact resonator is coupled inductively to the CPW feedline. The parameters indicated in the inset directly affect the participation of the insulator and metal surfaces to the reactive elements of the resonator.
chosen values were: $g_C = 20 \, \mu m$, $g_L = 5 \, \mu m$, $g_R = 10 \, \mu m$, $w = 10 \, \mu m$, and $Z_0 = 200 \Omega$. Resonator size increases rapidly with $g_L$ since the larger $Z_0$ requires twice the inductance. Therefore, to limit the overall size to roughly $700 \, \mu m \times 500 \, \mu m$, we reduced $g_L$ to $5 \, \mu m$, despite the fact that this may lower $Q_i$ by 10%. Design C chosen values were: $g_C = 80 \, \mu m$, $g_L = 10 \, \mu m$, $g_R = 10 \, \mu m$, and $Z_0 = 3000 \Omega$. Note that $g_C$ was chosen beyond the range of tested mutant design A resonators. Also in design C, the trace width $w$ was different for the capacitor (40 $\mu m$) and inductor (10 $\mu m$) halves in order to benefit from the larger capacitor width while keeping the resonator from being larger than $1000 \, \mu m \times 1000 \, \mu m$.

The results of all 49 design A, 73 design B, and 28 design C resonators are shown in Figure 4. Designs B and C each show significantly higher $Q_i$ than design A, with design C on average better than design B. While there exists a spread in $Q_i$ for each design, we observed an overall increase in the range of measured $Q_i$. The maximum/median $Q_i$ rose from 210 000/160 000 for design A to 370 000/280 000 for design B and 500 000/380 000 for design C.

When ion-milling was not performed, the maximum/median $Q_i$ was reduced to 50 000/30 000 for design A and 190 000/80 000 for design B (design C was not measured without ion-milling). For both designs A and B, the median quality factor was reduced by roughly a factor of four when ion-milling was left out during fabrication. Since this type of cleaning affects only the substrate-air interface and substrate-metal interface, we infer that these two surfaces participate strongly. The dominating participation of these surfaces has also been predicted by simulation.13 This $Q_i$ dependence on ion-milling also suggests that while the geometry controls the resonator sensitivity to the surface loss mechanism, the surface preparation determines the strength of the loss.

When re-measured in a dilution refrigerator with a lower base temperature (15 mK), we found that resonator $Q_i$ drops by roughly a factor of 2, which is consistent with TLS loss.14 We have measured similar resonators coupled to a qubit and found that their temperatures would not reach below 50 mK, as also reported by other groups.14 However, directly measuring the linear resonator temperature without a qubit to add nonlinearity is outside the scope of this study. Reassuringly, the increase of $Q_i$ from design A to B to C resonators remains even at lower temperatures; indicating that the geometric variation affects only the sensitivity to loss, not the absolute strength.

In conclusion, we have shown that the $Q_i$ of compact resonators depends strongly on geometrical factors controlling where electric fields are stored. In addition, substrate surface preparation prior to metal deposition is crucial. Using our results indicating that surface loss is dominant, we have been able to increase, at our point of reference temperature of 200 mK, the maximum internal quality factor of our resonators from 210 000 to 500 000.

The authors thank Danielle Braje at MIT-LL for an independent measurement of our resonators. This research was supported by IARPA under Grant No. W911NF-09-1-0369 and ARO under Grant No. W911NF-09-1-0514.