Magnetic Shielding Effect of Grounded Superconducting Niobium Layers

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Abstract. Magnetic isolation is an important issue in the realization of superconducting LSIs including more than ten thousands Josephson junctions. In this paper, we present mutual inductances of two superconducting strip lines coupled through a grounded shield layer. A conventional dc-superconducting quantum interference device (dc-SQUID) method on Nb/AlO$_x$/Nb Josephson IC chips is employed. We have tested one dc-SQUID layout with a floating shield layer for reference, and ten dc-SQUID layouts with grounded shield layers. Four superconducting niobium layers are used as a ground plane, a SQUID line, a shield layer, and a control line from bottom to top. We have confirmed that the number, positions, and dimensions of ground contacts make differences in the mutual inductances. Ground contacts should be placed to enhance the shielding current for effective magnetic isolation.

1. Introduction

Single flux quantum (SFQ) logic composed of superconducting Josephson devices is a promising technology for future digital LSI because of its high speed operation with low power dissipation [1, 2]. For example, the state-of-the-art SFQ microprocessor comprising more than ten thousands Josephson junctions is designed to operate at 20 GHz clock frequency with a power consumption of 3.3 mW [3].

Since they are operated with current-biasing, larger integration scale of SFQ circuits requires greater bias current. The total bias current of the SFQ processor described above is estimated to be more than 1 A [3]. Large bias current induces nonnegligible amount of undesirable magnetic flux in circuits, which reduces operation margins [4].

One of the most effective designs for magnetic isolation between bias lines and Josephson devices is the subterranean power line structure [5], where bias lines and Josephson devices are placed beneath and above a superconducting ground plane, respectively. In this structure, the Meissner effect of the superconducting ground layer is utilized for magnetic isolation. It should be noted, however, that unless the ratio of a film thickness to a magnetic penetration depth is sufficiently large, part of applied magnetic flux penetrates through the superconducting thin film. In fact, Suzuki et al. demonstrated by using a scanning superconducting quantum interference device (SQUID) microscope method that approximately 10% of magnetic flux penetrated through a superconducting Nb thin film [6]. One of the authors (YM) also investigated magnetic coupling between two superconducting strip lines, one of which was covered by a superconducting layer [7]. The mutual inductance between the lines was reduced to 23% of that of the uncovered...
The authors recently reported numerical and experimental results of mutual inductances between two superconducting strip lines coupled through a superconducting shield layer [8, 9, 10]. It has been confirmed that the mutual coupling is reduced more effectively by a thicker and wider shield layer [8, 9], and that grounding positions of the shield layer are crucial [10]. Grounding the shield layer at one point or at two points located perpendicular to the line direction does not improve the shielding effect, whereas grounding at two points located parallel to the line direction reduces the mutual inductance by 67%.

In this paper, the authors present experimental evaluation of the mutual inductances between two superconducting strip lines coupled through a superconducting shield layer with various grounding conditions. We have tested one dc-SQUID layout with a floating shield layer for reference, and ten dc-SQUID layouts with grounded shield layers fabricated using a niobium integration technology.

2. Experiments

In the same manner as our previous works [8, 9, 10], the NEC standard Nb process [11] is used in the experiments. Four superconducting layers are available in the NEC process. In this paper, they are referred to as Nb1, Nb2, Nb3, and Nb4 from bottom to top. The Nb1 and Nb3 layer are used as a ground plane and a shield layer, respectively. The mutual inductance between strip lines of the Nb2 and Nb4 layer is evaluated. A dc-superconducting quantum interference device (dc-SQUID) method [12] is employed to measure the mutual inductances.

Figure 1(a) shows the layout of a reference dc-SQUID (the layout 1) used for measurements of the mutual inductance with a floating shield layer. A dc-SQUID composed of the Nb1 ground plane and the 10-µm-wide and 120-µm-long Nb2 strip line with two $2 \times 2 \mu m^2$ Nb/AlOx/Nb structure, but not to zero. Consequently, mutual coupling in multilayer structures is one of the three-dimensional problems that we have to solve for future Josephson LSI.
Figure 2. Grounding the Nb3 shield layer. (a) CAD layout. The Nb3 shield layer is contacted to the Nb1 ground plane via the Nb2 layer. (b) Cross sectional schematic view of the grounding structure along the B–B’ line section. (c) Simplified presentation used in figure 3.

Josephson junctions is used for measuring the mutual inductance. The Nb3 layer with the dimension of $110 \times 50 \mu m^2$ is used as a shield layer, which is not grounded in the layout 1. Shown in figure 1(b) is a cross sectional view along the A–A’ line section in figure 1(a). The widths of the Nb2 and Nb4 strip lines are 10 and 5 $\mu m$, respectively. The upper layers are not flat, although the NEC standard process includes the bias-sputtering technique for SiO$_2$ layers [13].

Ground contacting of the Nb3 shield layer is realized via the Nb2 layer as shown in figure 2. To secure the layer-to-layer contacts, the Nb1–Nb2 and Nb2–Nb3 contacts are separately placed. Hereafter, for simplicity, only the Nb2–Nb3 contact is displayed as “GC.”

To investigate the effects of grounding conditions to magnetic isolation, we have tested ten layouts shown in figure 3. The three layouts that have already been discussed in our recent paper are included (the layouts 3, 5, and 9) [10]. In figure 3, the layouts are sorted in descending order of the experimental values of the mutual inductances, which are presented in the next section.

3. Results and Discussion

Mutual inductances ($M$) obtained from the interference modulation periods of the dc-SQUIDs in a liquid helium bath are plotted in figure 4. The values of the mutual inductances are the averages of five or six test chips chosen from three or four wafers. The error bars represent their standard deviations (σ).

It is found in figure 4 that the mutual inductances for the layouts 1–5 are virtually identical. That is, grounding the shield layer either at one small contact or at two small contacts placed perpendicular to the strip lines does not reduce the mutual inductance. From the results for the layouts 6–11, we may state that grounding at two or more contacts placed parallel to the strip lines reduces the mutual inductance. Large contacts along the strip lines are also effective to reduce the mutual inductance.

The mutual inductance $M$ is generally expressed by $M = k \sqrt{L_{Nb2}L_{Nb4}}$, where $k$, $L_{Nb2}$, and $L_{Nb4}$ are the coupling coefficient, the self-inductance of the Nb2 strip line, and the self-inductance of the Nb4 strip line, respectively. Although we have not measured either $L_{Nb2}$ or $L_{Nb4}$, our previous calculation for the layout 9 demonstrates that the reduction of the coupling coefficient is approximately 60%, whereas that of the self-inductances is less than 10% [10]. Hence, we may attribute the reduction of $M$ to the reduction of $k$. That is, smaller $M$ means better magnetic isolation.
Figure 3. Ten tested layouts (the layouts 2–11) with a grounded Nb3 shield layer. Only the Nb4 strip line and the Nb3 shield layer with ground contacts (GCs) are displayed. In the real circuits, each layout includes a dc-SQUID same as the layout 1 in figure 1.

Figure 4. Experimental results of the measured mutual inductances ($M$). The error bars represent their standard deviations ($\sigma$).

It has been numerically confirmed that ground contacts of the shield layer affects the current distribution in the shield layer, which also affects the mutual coupling [10]. Magnetic isolation is expected to be improved by ground contacts that make shielding currents flow effectively. The descending order in figure 3 look consistent with the theory as a whole. For example, the layout 6 has two ground contacts along the strip lines, and hence, the mutual inductance is reduced in comparison with the layouts 1–5. The layout 7 has one but long (nine-fold in area) ground contact, of which the mutual inductance is only 8% smaller than that of the layout 6. It is interpreted that the central part of the ground contact in the layout 7 is not very effective to enhance the shield current in the shield layer. The layout 11 has the most effective ground contacts among the tested layouts. For large contacts are placed at the both edge of the shield layer. The mutual inductance is reduced to 8% of that of the layout 1.
4. Conclusion
In this paper, we presented the mutual inductances of two superconducting strip lines coupled through a grounded shield layer. We evaluated one dc-SQUID layout with a floating shield layer for reference, and ten dc-SQUID layouts with grounded shield layers fabricated using the NEC standard Nb process. Four superconducting niobium layers were used as a ground plane, a SQUID line, a shield layer, and a control line from bottom to top. Grounding a shield layer at one small contact or at two small contacts placed perpendicular to the strip lines did not improve magnetic isolation. Grounding at two or more contacts, or large contacts, placed parallel to the strip lines reduced the mutual inductance. The experimental results agreed to the theory that ground contacts making shield currents flow effectively should improve magnetic isolation.

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