

Weak Link Superconducting Quantum Interference Devices for High-Resolution Scanning Magnetometry

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Primary CNF Tools Used: AJA Sputter 1, Bruker DektakXT Profilometer, Heidelberg MLA 150 Maskless Aligner, JEOL JBX-6300FS, E-beam Lithography System, Oxford 82 RIE, SC4500 Even-Hour Evaporator, SC4500 Odd-Hour Evaporator, Unaxis 770 Deep Silicon Etch, Zeiss Gemini SEM, Zeiss Supra SEM, Zeiss Ultra SEM,

Abstract:

Magnetic imaging is a powerful tool for studying quantum materials. To make a sensitive magnetometer for use in a scanning probe microscope, a small superconducting loop is interrupted by two Josephson junctions to create a superconducting quantum interference device (SQUID), which converts the magnetic flux coupled into the loop into a measurable signal [1]. This research explores one way to increase the spatial resolution and maximum operating field of a SQUID, which is to replace conventional superconductor-insulator-superconductor (SIS) Josephson junctions with narrow constrictions (weak links) in the superconducting loop, which allow the size of the loop to be less than 1 μm [2]. Initial measurements have demonstrated the sensitivity of test SQUIDs to magnetic flux, with improvements in progress.

Summary of Research:

Figure 1(c) depicts a weak link SQUID, made of a patterned 50 nm niobium film on a silicon substrate with thermal oxide. For the weak links to behave like Josephson junctions, they must have dimensions comparable to the superconductor's coherence length [3], which necessitates the use of electron beam lithography to pattern a hard mask for the SQUID loop. A bilayer lift-off process patterns the SQUID loop in 20 nm of aluminum, and the pattern is then transferred to the niobium by dry etching in CF_4 and O_2 . In order to raster the SQUID loop across the surface of a sample like in Figure 1(a), a Bosch process deep etch (Figure 1(b)) defines the corner of the scanning probe where the SQUID will be patterned. This approach has been successfully applied to scan conventional SQUIDs [4].

A key parameter for the performance of these SQUIDs

is the maximum current that can flow through the weak links while they remain superconducting, which is known as the SQUID's critical current. Cryogenic measurements of several SQUIDs revealed an up to 50 variations in the patterned widths and lengths of the weak links. Since the critical current is expected to be a function of only the resistance of the weak link [3], the variation is likely due to differences in the thickness of the niobium grain where the weak link happens to be patterned. Such niobium grain size differences are depicted in Figure 2(a).

When a weak link SQUID is operated in the readout scheme used for conventional SQUIDs, heating of the weak links occurs, and as such the thermal as well as electrical characteristics of the SQUID become important to the design. As such, we are changing the silicon dioxide film under the niobium to be a bare silicon film instead, in order to increase the thermal conductivity from the SQUID to the substrate. Doing so required the development of a new dry etch that would not undercut the silicon or niobium weak links, as seen in Figure 2(b). Another avenue to reduce the noise and electrothermal behavior of these SQUIDs is to add an on-chip resistive shunt in parallel with the SQUID (Figure 3). As the shunt value must be comparable to the weak link resistance of a few Ohms, we optimized in-situ argon back-sputtering in the AJA 1 sputtering system to completely remove the native niobium pentoxide layer before sputtering the platinum. Weakly cleaned shunts had insulating contacts at cryogenic temperatures, while partially cleaned shunts had a contact resistance of a few Ohms, and fully cleaned shunts could reach 100–200 m Ω . The addition of a resistive shunt is also expected to eliminate destruction of the weak links by electrostatic discharge, as in Figure 4.

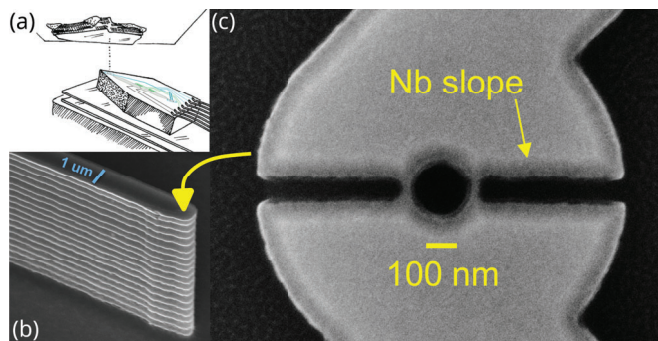


Figure 1: (a) A SQUID is a sensitive magnetometer that may be rastered over the surface of a sample. (b) By performing a deep silicon etch, a scanning probe at the etched tip may be brought within 1 μm of the sample. (c) Scanning electron microscope (SEM) image of a niobium (Nb) weak link SQUID. The narrow superconducting constrictions by the niobium slope make the device a sensitive tool for measuring the local magnetic flux through the loop.

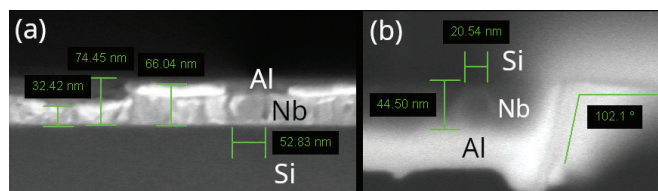


Figure 2: (a) SEM image of a cleaved niobium line, nominally 50 nm thick, with aluminum mask on top. Niobium grains as thin as 32 nm are visible. (b) Edge of an etched niobium line, with no undercutting of the niobium or silicon substrate, and little over-etching into the silicon.

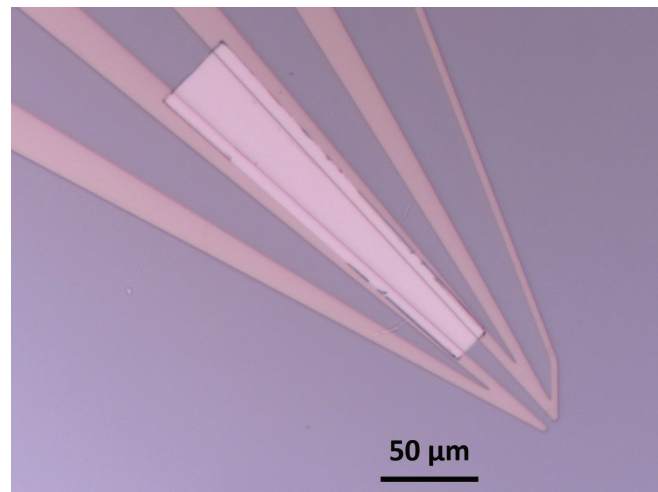


Figure 3: Bright-field microscope image of a platinum shunt center) on niobium traces. A SQUID would normally be patterned at the bottom right, but was omitted for testing the shunt. As the relevant contact occurs primarily through the covered niobium sidewall, the fencing along the perimeter of the platinum shunt has little impact on the shunt resistance.

Conclusions and Future Steps:

We are continuing to optimize the design and fabrication of these weak link SQUIDs. Future work will investigate managing a heat budget during the deposition of the platinum shunt and of the mask for deep silicon etching, as these process steps partially degrade the superconductivity of the niobium. Empirical optimization of the SQUID and shunt design is also in progress.

References:

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- [2] Vasyukov, D., et al. Nature Nanotech 8, 639-644 (2013).
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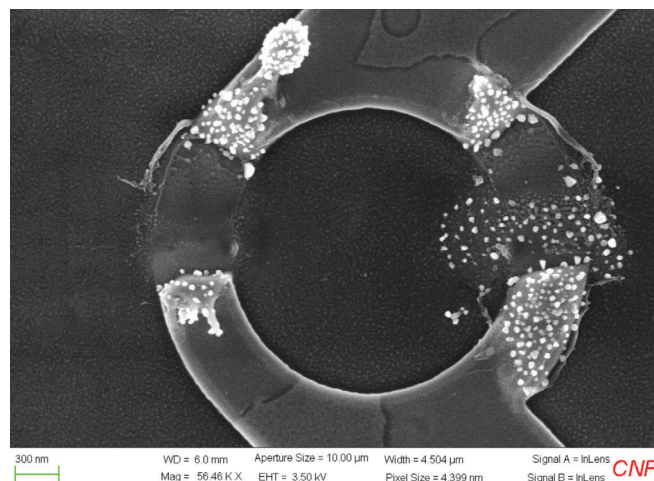


Figure 4: SEM image of a SQUID loop after a low-voltage electrostatic discharge event destroyed the weak links during electrical testing.