Investigation of Dayem Bridge NanoSQUIDs Made by Xe Focused Ion Beam

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***Abstract*—Superconducting QUantum Interference Devices (SQUIDs) based on nanobridge junctions have shown increasing promise for single particle detection. This paper describes the development of the fabrication of improved and reproducible nanobridge junctions fabricated by focused ion beam (FIB) milling from niobium thin films. Although the very low noise properties of nanobridge SQUIDs are well known, the nature of the milling process is little understood at the level of local superconducting properties. In this paper, we report the results for nanobridge Josephson devices and SQUIDs, which we believe are the first to be made by Xenon (Xe) FIB milling. Temperature-dependent current–voltage behavior, microwave-induced Shapiro steps, and SQUID response to magnetic fields have been measured. We make preliminary comparisons with nominally identical devices milled from Nb thin films using either Xe or Ga ions.**

***Index Terms*—Focused ion beam (FIB), microwave, nanoscale, nanoSQUID, superconducting QUantum Interference Devices (SQUIDs), Xe FIB.**

I. Introduction

SUPERCONDUCTING QUantum Interference Devices (SQUIDs) are macroscopic quantum devices that are capable of detecting and measuring a wide range of physical parameters with unequalled sensitivity [1], [2]. In addition to conventional trilayer SQUIDs whose performance has shown rapid improvements recently [3], [4], SQUIDs based on nanobridge Josephson junctions (also known as Dayem bridges) have returned to popularity in recent years, with the realization that their low capacitance and high critical current density can provide advantages of low intrinsic noise and potentially high-frequency operation [5]–[8]. In addition, their small scale in all three dimensions makes them particularly suitable for nanoSQUIDs [9]–[14]. The condition for low-noise operation of nanobridge junctions requires that the length L should be shorter or comparable with the temperature-dependent coherence length of the superconductor $\xi(T)$, i.e.,

$$L \leq \zeta\,(T)\,. \tag{1}$$

For pure Nb at low temperatures, $\xi(T)$ is around 35 nm and it proves difficult to fabricate bridges with length smaller than this, although 50 nm dimension is accessible to both focused ion beam (FIB) milling and electron beam lithography. $\xi(T)$ diverges as T approaches the critical temperature T_c so the above-mentioned condition will be satisfied if the temperature approaches T_c. However, the junctions cannot be operated very close to T_c without compromising the Josephson coupling energy and, thus, increasing the intrinsic noise of the device. Thus, for the present devices, there is only a limited temperature range over which these nanobridge SQUIDs operate optimally [15], [16].

Until recently, Ga ion beams were the main method for nanoscale milling. Over past years, other sources of ions (for example, various inert gases) have become available, including the massive atomic species Xe. Compared with Ga, Xe ions have larger mass and should provide higher milling rates, and the inert chemical nature of Xe may also produce less impact on the electrical properties of the underlying unsputtered thin-film surface. For specific comparison of the two ions, based on Monte Carlo simulation with an energy for both of 30 keV, Ga implanted into Nb will have a mean range of 11.6 nm and an absolute maximum around 37 nm. The sputter yield for a single ion with Ga is 3.9 atoms per ion on average. The threshold dose for amorphization is 2.56×10^{14} ion/cm^2. Xe at the same energy has a mean range of 8.4 nm with a maximum of range of 25 nm. The sputter yield is higher than for Ga at 5.7 atoms per ion and the threshold for amorphization is a little lower at 1.75×10^{14} ions/cm^2. The required dose to remove an equivalent volume would be less with Xe, but in both cases the amount of milling to produce a Dayem bridge junction is much higher than the threshold and is expected to be sufficient to amorphize the Nb film up to the maximum range. The Xe ions being inert can play no role other than damage and sputtering. Implanted ions will be present in the sample and being large and inert are likely to stabilize the damage. The Ga will also sputter and damage the sample, but Ga can alloy with Nb and occupy vacancies left behind in the damage cascade. The overall retained

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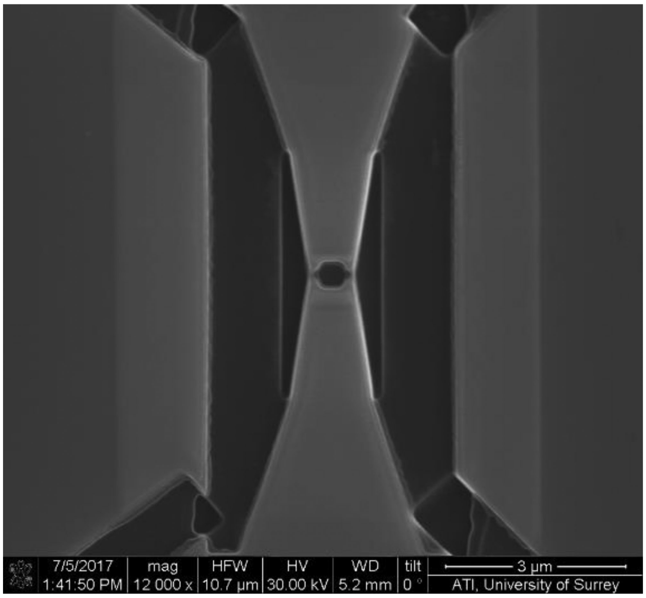

Fig. 1. SEM image of the nanoSQUID made by Xe FIB. NanoSQUID loop size is ∼500 nm.

damage in the Ga implanted sample may be less due to this mechanism. Beneath the damaged layer, a transition to pristine Nb is expected and the degree of damage should be influential on superconducting properties of the junctions [17].

In this paper, we report the first Xe FIB fabricated nanobridge SQUIDs showing that the properties are at least comparable with equivalent Ga milled devices, and the results are observed with those devices. Temperature-dependent current–voltage characteristics (IVCs) are reported along with the observation of microwave-induced Shapiro steps. The following sections describe fabrication, results, and future developments.

II. Fabrication and Test Procedure

Thin Nb films (150 nm) are first grown by sputtering on an SiO_2 (200 nm)/Si substrate and Nb tracks (with a width of 25 μm) were patterned by conventional optical lithography and reactive ion etching to produce a 8 mm × 8 mm chip design able to accommodate at least six SQUID devices. The SQUIDs with different loop sizes based on the nanobridge Josephson junctions have been milled using Xe FIB. For each device, four-terminal connections have been fabricated on the sample chip. Recently, for another set of devices with each of six tracks on the chip, a set of dc nanoSQUIDs (loop diameter 500 nm) is patterned using FIB milling, three of the devices are patterned with a Ga beam and the other three with a Xe beam, with identical milling patterns for each ion species. A SEM image of a Xe FIB nanoSQUID is shown in Fig. 1.

After fabrication, having attached the SQUID chip to a 24 pin chip holder, the nanoSQUIDs are individually wired up and the chip is cooled in a closed-cycle pulse-tube cooler having a temperature-controlled stage variable between 2.7 and 12 K, controlled to a precision of 1 mK or better. A variable magnetic field (up to 5 T) can be applied to the SQUIDs from a superconducting solenoid that surrounds the chip.

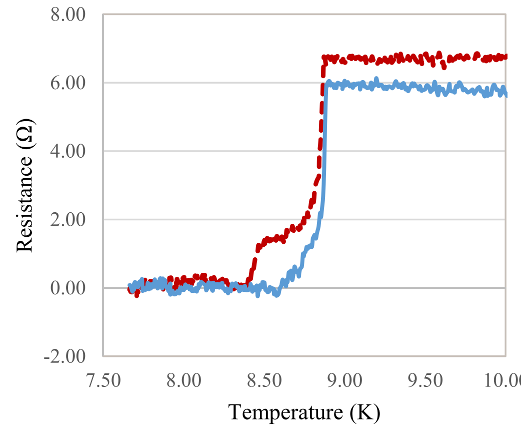

Fig. 2. Resistance versus temperature curves for *R(T)* for nanoSQUIDs fabricated by FIB. Dash line is for Xe nanoSQUID (deviceD30-1) and solid line is for Ga nanoSQUID (devices D30-2).

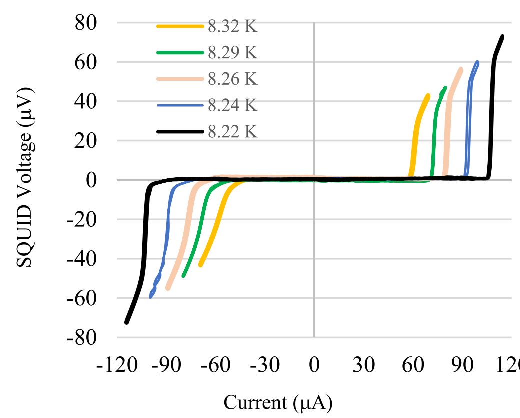

Fig. 3. Voltage versus current as function of the temperature for Xe FIB nanobridges SQUID. Temperature range is from 8.22 to 8.32 K.

Any one of the six devices can be measured in turn, and the initial tests measure the four-terminal SQUID resistance as a function of temperature from around 10 K down to a temperature of around 4 K. Typical curves for *R(T)* are shown in Fig. 2. Note that most devices show a large transition over a narrow temperature range followed by a slower smaller transition beginning around 0.5 K below the higher transition. We interpret the larger resistance drop as representing the main Nb transition to the superconducting state, whereas the broader and lower one is the junctions' transitions. It is notable that the Xe and Ga devices show rather different behaviors, especially the Xe *R(T)* variation shows a more pronounced junction transition.

III. Josephson Junction and SQUID Results

In addition to testing the *R(T)* behavior of the SQUID devices themselves, we also measure the variation of the critical currents of the two junctions in parallel (with zero applied magnetic field) as a function of temperature. Fig. 3 shows the IVCs as function of temperature for a Xe FIB SQUID. The temperature ranging varies from 8.22 to 8.32 K resulting in a critical current I_c variation from 50 to 100 μA. Note that the IVC shows the

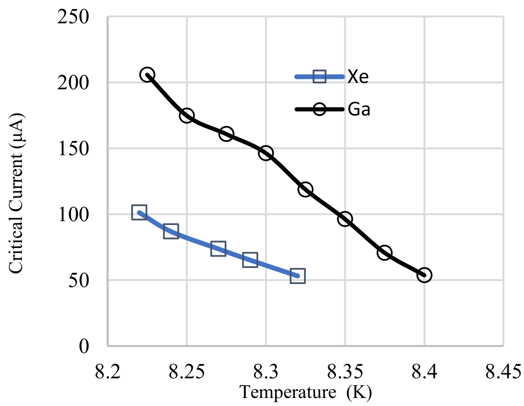

Fig. 4. Critical current versus temperature for both SQUIDs made by Xe FIB (line with square) and Ga FIB (the line with circle).

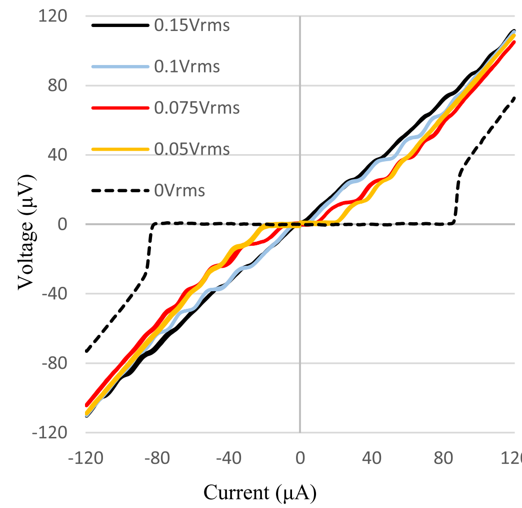

Fig. 5. Observed Shapiro steps for Xe nanobridge Josephson junction for different microwave power levels at fixed frequency 6 GHz and operating temperature 8.35 K.

normal resistively shunted junction behavior in this temperature range with no hysteretic regions.

Critical currents versus temperature have been measured for the Ga FIB SQUID for temperature in the range from 8.225 to 8.4 K. Over this range, the critical current changes from 60 to 200 μA. The SQUID junction critical currents for both methods of fabrication are plotted in Fig. 4 as a function of the operating temperature. The normalized slopes of the critical current with temperature are roughly similar to Xe FIB SQUID and Ga FIB SQUID, indicating that the bridge dimensions may be somewhat different but underlying superconducting properties seem the same.

The high-frequency properties of FIB milled microbridges are also an important property in view of the increasing importance of microwave readout of Josephson and SQUID circuits for parametric amplifiers and other inductively coupled circuits [18]. A straightforward test of the frequency response of the Dayem bridges employed in the SQUIDs described here is to measure the IVC in the presence of applied microwave radiation at a frequency *f*.

The zero-beat frequency between the internally generated Josephson current frequency f_J and the *n*th harmonic of the applied microwave signal gives rise to flat "Shapiro step" at a voltage *nfh/2e*, where *n* is an integer, *h* is the Planck constant, and *e* is the electronic charge. High-voltage (or equivalently high harmonic) steps are observed as the applied microwave power is increased, up to at least 100 μV. A measurement of the attenuation of the high-harmonic step amplitudes with increasing voltage gives an indication of the upper frequency limit for the Josephson effect generated microwave currents at which these junctions respond.

We have measured the high-frequency properties of nanobridge-based Josephson junctions fabricated by Xe FIB. As the 6 GHz applied microwave radiation power increases, higher harmonic steps appear in the characteristic. At an operating temperature of 8.35 K, the IVCs for four different microwave powers from 0.05 to 0.15 Vrms are shown in Fig. 5.

The measured circuit parameters for this device at the operating temperature yield a critical current I_c of 82 μA and a normal state resistance R of 1.1 Ω predicts an upper frequency cutoff f_c for the Josephson frequency of around RI_c/Φ_0, corresponding in this case to $f_c = 45$ GHz so it seems clear that these microbridge junctions show conventional Josephson behavior.

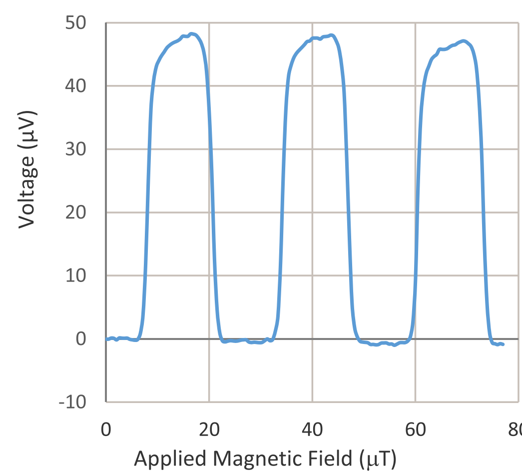

Fig. 6. SQUID voltage as a function of applied perpendicular magnetic field for Xe FIB SQUID at operating temperature T = 8.22 K.

Finally, to test the equality of the individual junctions' critical current in a SQUID, we measured the dc output voltage response to magnetic field *V(Φ)* of each SQUID when it is biased with a fixed dc bias current (slightly greater than the zero field critical current) as the applied magnetic flux is swept over a range of several flux quanta (see Fig. 6).

The maximum slope of the *V(Φ)* plot is a useful figure of merit for the gain of the SQUID device and is a measure of the minimum detectable flux or magnetization change that the SQUID can detect. The results shown here for a Xe milled SQUID show a flux-modulated voltage amplitude exceeding 45 μV and a maximum slope of the voltage versus flux response of *dV/dΦ* achieves a level as high as 0.65 mV/Φ_o, at least as good as we observe with typical Ga milled Nb nanoSQUIDs. An additional advantage of microbridge SQUIDs over some other types is that the stability of the voltage appearing across the direct current biased device is extremely high, perhaps due to the expected lack of two-level fluctuators. In this paper, the noise is dominated by the room temperature amplifier noise level (6 nV/(Hz)$^{1/2}$) so the intrinsic noise is not measurable. Elsewhere, in [10], we have shown that using a cooled preamplifier, sub $\mu\Phi_0/(\mathrm{Hz})^{1/2}$ flux noise is achieved with similar devices.

IV. Future Work and Conclusions

Having demonstrated that FIB milling with a Xe ion beam is capable of producing microbridge junctions with similar properties to those previously reported using a Ga beam, we plan to further investigate these devices. The observed similarity suggests that the chemical influence of implanted Ga ions on Nb films is small. Comparison of a larger set of devices milled by the different ion beams side by side on the same chip will allow us to more accurately assess the advantages and disadvantages of each process, while also providing better statistics on their reproducibility. Conventional Josephson analysis seems to apply to these junctions, even at operating temperatures within 1 K of the Nb superconductor T_c, reflected by the high-frequency response. We are particularly interested in determining the upper limit to frequency response of these nanoSQUIDs and have begun to model the Shapiro step amplitudes of the IVCs as a function of power, temperature, and applied magnetic field. Comparison of the observed and modeled thermal noise rounding of the IVCs provides a powerful method to estimate the upper frequency response of Josephson currents in these structures while also enabling us to estimate the effective noise temperatures of the junctions. We are also developing mechanisms in the fabrication of these milled SQUIDs to extend the useful operating temperature, particularly by inducing additional damage and/or doping to the nanobridge regions, combined with reducing film thickness [19].

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