

# Towards High Resolution Magnetic Microscopy

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**Abstract—** Sub – micron sized superconducting quantum interference devices (SQUIDs) based on Niobium nanobridges were produced by means of focused ion beam milling. By making use of the implantation of Gallium ions during the milling process, superconducting nanobridges with widths as small as 75 nanometers can be produced. The current – phase relationship in these bridges is the result of the nucleation of vortices in the device. Combination of two of these structures in a superconducting loop yields a SQUID. The smallest obtained effective sensor area was  $3.6 \times 10^{-2}$  squared microns, which, to our knowledge, is smaller than any superconducting quantum interference device reported in literature. Typical voltage – to – flux sensitivities of 100 to 200  $\mu\text{V}/\Phi_0$  and peak – to – peak voltages of up to 50  $\mu\text{V}$  were observed for these structures. Implementation of these sensors in a scanning SQUID microscope could result in a drastic improvement of the spatial resolution of such systems.

## 1. INTRODUCTION

Scanning SQUID Microscopy (S.S.M.) has proven to be a very valuable tool for studying small scale magnetic phenomena. Compared to other magnetic imaging techniques, such as scanning hall probe and magnetic force microscopy [1], state of the art scanning squid microscope systems boast unparalleled magnetic field sensitivities ( $<10^{-10}$  T/Hz<sup>1/2</sup>) and modest spatial resolutions (around 10 squared microns) [2]. An increase of this spatial resolution, which is limited by the effective sensor area and the separation between the sensor and the sample during imaging, could yield a magnetic microscopy technique with unprecedented imaging qualities. The first step towards realizing this would be the miniaturization of the effective sensor area.

The aim of the research described here was to create SQUIDs with sub – micrometer sized effective areas. Based on previous research within our group [3], superconducting nanobridges, produced by means of Focused Ion Beam (F.I.B.) milling, were chosen as the building blocks for these small sensors. The relationship between the current and the phase of the superconducting order parame-

ter is the result of the nucleation of vortices in these structures. These SQUID sensors could eventually be applied in a high – resolution, low – temperature, scanning microscope setup based on piezo scanners to establish a scanning SQUID microscope boasting unprecedented spatial resolution.

Following a brief introduction on nanobridge – based SQUIDS in the second section, in the third section of this article the preparation of the sensors will be described, followed by a brief overview of the sensor characteristics in the next section. The fifth section is dedicated to the limitations imposed by the implantation of Gallium ions in the superconducting structures during focused ion beam patterning.

## 2. NANOBIDGE – BASED SQUIDS

SQUID's are the most sensitive detectors of magnetic flux that are currently available. Any physical quantity that can be converted into a magnetic flux (i.e. magnetic field, magnetic field gradient, current, voltage or displacement) can be measured using a SQUID. SQUID's are used in a wide scope of applications, ranging from the detection of human brainwaves to the observation of single atomic spin – flips. In a SQUID two physical phenomena are combined:

- Flux quantization: the flux  $\Phi$  in a superconducting loop is quantized in units of the magnetic flux quantum  $\Phi_0 = h/2e$ .
- The Josephson effect.

As described by Likharev [4], the Josephson effect is not only a characteristic of the well – known tunnel junctions, but it is also exhibited in superconducting weak links of sufficiently small dimensions. These structures can be defined as conducting junctions between bulk superconducting electrodes, with the critical current of the weak link being a lot smaller than that of the electrodes. The second Josephson equation, describing the relationship between the first – order time derivative of the phase of the superconducting order parameter and the voltage across the electrodes, holds for any type of weak link. Many types of deviations from the classical sinusoidal form of the first Josephson equation can be observed for different kinds of weak links.

The SQUIDS described in this article are based on superconducting nanobridges. The current – phase relationship in these types of structures is dependent on the dimensions of the nanobridge. This dependence is schematically shown in Fig. 1, taken from Likharev [4]. The current – phase relationship is dependent on the ratio of the bridge – width ( $w$ ) and – length ( $l$ ) and the superconducting coherence length ( $\xi$ ). For short bridges ( $L < L_c$ ) an ideal Josephson effect is expected. Dependent on the width, the current – phase relationship in

longer bridges is based on either one – dimensional depairing of the superconducting order parameter or on the coherent motion of vortices across the structure. For bridges with widths that are larger than the superconducting penetration depth no current – phase relationship is expected.

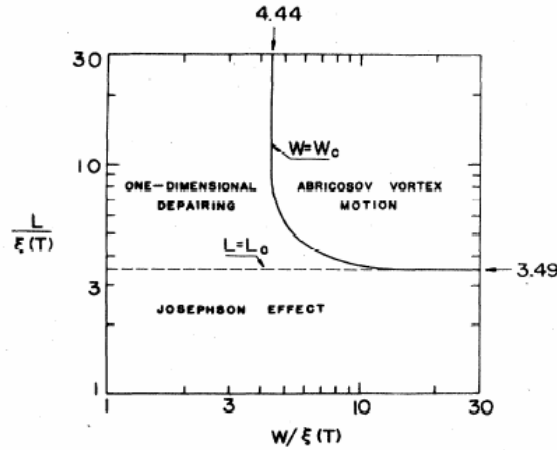


Fig. 1. The origin of the current – phase relationship in superconducting nanobridges is dependent on the dimensions of the weak link [4].

### 3. NANOSQUID FABRICATION

The patterning of nanobridges in a Niobium thin film is schematically shown in Fig. 2A. All devices were patterned in 50 nanometer thick Niobium films, produced by means of DC sputtering (Argon pressure:  $7.3 \times 10^{-3}$  mbar, power: 250 Watt), which were pre – defined using standard photolithography. A focused ion beam system, based on a 25 keV Gallium ion beam, was used. The typical full – width – half – maximum of the ion distribution profile for this beam was 50 nm. By patterning two nanobridges, separated by a small hole, in a Niobium lead, sub – micron sized SQUIDs were produced. Typical geometrical bridge – widths of 150 nanometers were used. A scanning electron micrograph of the smallest obtained working SQUID is shown in Fig. 2B. Characterization of this sensor, which is described in the next section, yielded that this device has an effective area of no more than  $3.6 \times 10^{-2}$  squared micrometers.

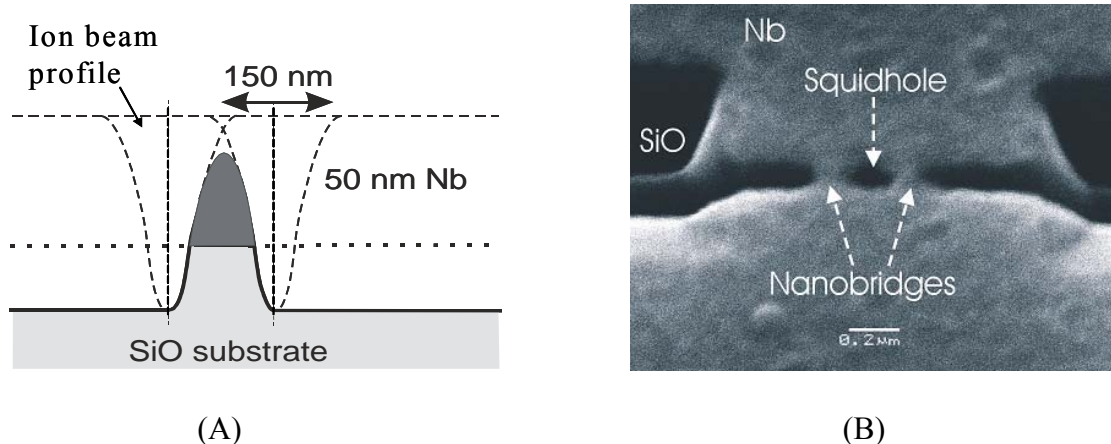
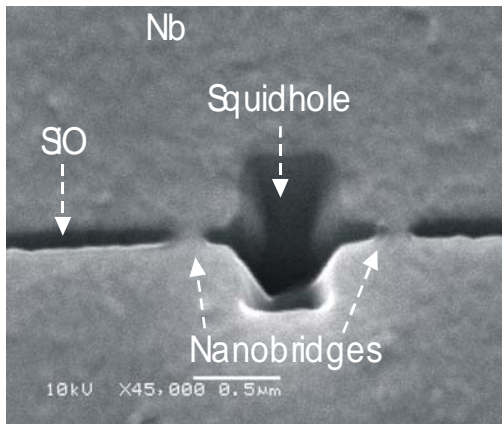


Fig. 2. (A) Scanning electron micrograph of a DC nanoSQUID patterned by means of focused ion beam milling. The effective area of this device was about  $3.6 \times 10^{-2}$  squared micrometers. (B) Schematic of nanobridge patterning by means of focused ion beam milling. By letting two beam profiles overlap Niobium bridges with widths smaller than the ion beam diameter can be produced.

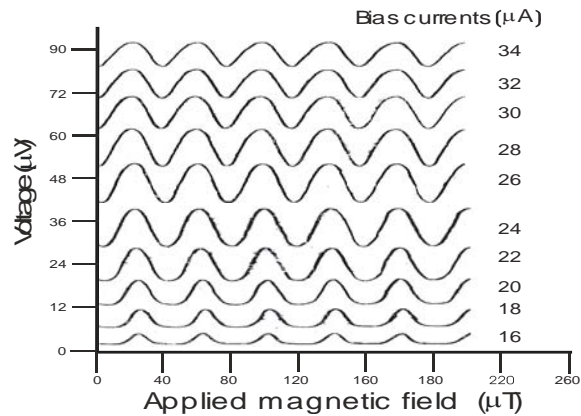
#### 4. NANOSQUID CHARACTERISTICS

Two SQUID voltage modulation characteristics are shown for different bias currents in Fig. 3B and Fig. 4. The voltage modulation shown in Fig. 3B belongs to a SQUID consisting of two 150 nm wide bridges patterned in a pre – defined Niobium loop, as shown in part (A) of this figure. The effective area of this structure is 5 squared micrometers. In Fig. 4 the same type of characteristic is shown for the SQUID structure shown in Fig. 2B. This device is also based on bridges with widths of 150 nanometers.

As mentioned before, the effective area of the latter SQUID proved to be about  $3.6 \times 10^{-2} \mu\text{m}^2$ , which, due to flux focusing effects [5], is somewhat larger than its geometrical area. This is the smallest SQUID we obtained thus far. Because of this very small size, the maximum amount of magnetic field that could be applied (75 mT) in the measurement setup corresponds to about 1.5 flux quantum ( $\Phi_0$ ). Since both devices only differ in effective area, it is presumable that, given the possibility to conduct the measurement in a larger applied field, this SQUID will also show typical oscillations over a range of several  $\Phi_0$ , such as the ones in Fig. 3B. Typical SQUID sensitivities of 50 – 100  $\mu\text{V}/\Phi_0$  and peak – to – peak voltages of up to 50  $\mu\text{V}$  were observed.



(A)



(B)

Fig. 3. (A) Scanning electron micrograph of a SQUID based on Niobium nanobridges with an effective area of about five squared microns. (B) Corresponding voltage – flux modulation characteristic.

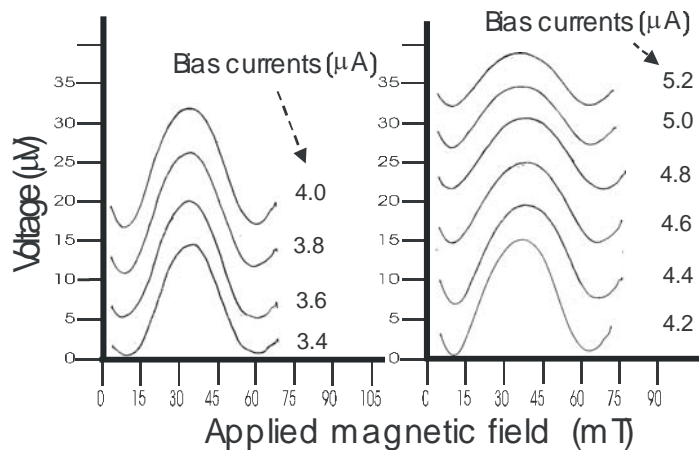


Fig. 4. Voltage modulation as a function of applied magnetic field for a SQUID based on Niobium nanobridges with an effective area of  $3.6 \times 10^{-2} \mu\text{m}^2$ .

## 5. THE EFFECT OF GALLIUM IMPLANTATION DURING THE PATTERNING PROCESS

The development of miniature SQUIDs based on superconducting nanobridges has been reported before, as in [6] and [7]. However, the SQUID loops reported in these studies were not miniaturized to the ultimate limits, and consequently these devices had areas that were about an order of magnitude larger than the ones described here. Furthermore, these SQUIDs showed hysteretic current – voltage characteristics.

The reason the devices reported here possess non – hysteretic characteristics, which allows for conventional SQUID measurements such as the ones shown in Fig. 3, is attributed to the fact that the actual width of the patterned supercon-

ducting nanobridges is strongly reduced by the implantation of Gallium ions during patterning.

It is well – known that the implantation of ions into interstitial sites in the Niobium lattice, which causes the lattice parameter to increase, suppresses the superconducting properties of the affected region [8]. Calculations with SRIM [9] and experiments (see Fig. 5.), where the remaining thickness of the Niobium film after focused ion beam etching is varied systematically, revealed that the implantation of Gallium ions extends as far as 35 nanometers inwards from the surface of a patterned structure.

It is believed that this reduction of the superconducting area in the designed nanobridges attributes to the relatively small critical currents (typically 20  $\mu\text{A}$ ) and non – hysteretic current – voltage characteristics observed. Structures designed to have a geometrical width of 150 nanometers are likely to behave as superconducting bridges with widths of only 75 to 80 nanometers. This effect is

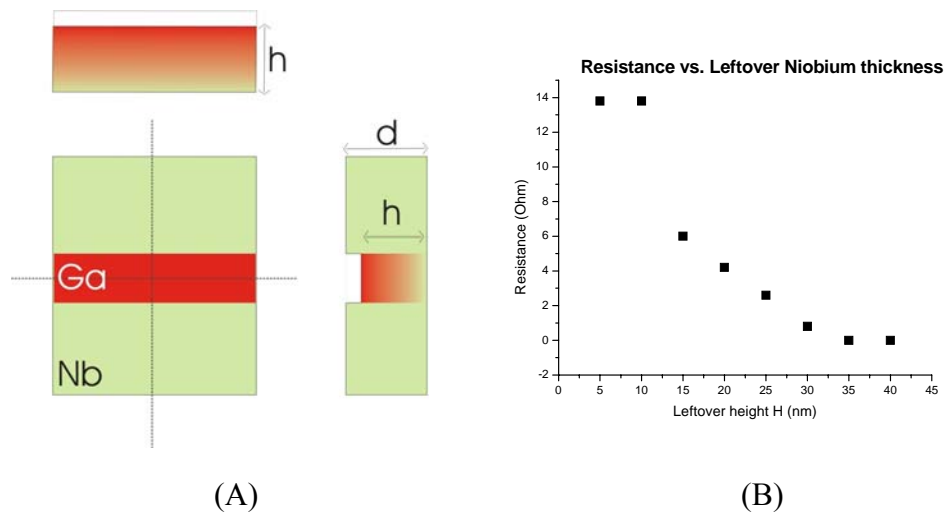


Fig. 5: The effects of the implantation of Gallium ions during F.I.B. etching of Niobium structures extend as far as 35 nanometers inwards from the patterned surface.

of primed importance because, given the dimensions of the focused ion beam, it is impossible to produce nanobridges with such small geometrical widths.

## 6. CONCLUSION AND OUTLOOK

We have described the successful realization of sub – micron sized SQUIDs based on Niobium nanobridges structured with a Gallium focused ion beam. In a next step of this research, these SQUIDs will be employed for high spatial resolution Scanning SQUID microscopy. For this purpose a high – resolution, low – temperature microscope insert based on piezo scanning stages has been acquired. Ultimately the goal of this research is to study novel magnetic phenom-

ena with the unprecedented magnetic flux sensitivity of SQUID sensors on a sub – micrometer scale.

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