Fabrication of arrays of nano-superconducting quantum interfernce devices using a double-angle processing approach

Peter Roediger, Robert C. Dynes
Department of Physics
University of California, San Diego
La Jolla, CA, 92093, USA
proediger@ucsd.edu

Shane Cybart, Robert C. Dynes
Lawrence Berkeley National Laboratory
Berkeley, CA, 94720, USA
sacybart@lbl.gov

Shane Cybart
Department of Physics
University of California, Berkeley
Berkeley, CA, 94720, USA
scybart@berkeley.edu

***Abstract*— Arrays of superconducting quantu interference devices (SQUIDs) from high-temperature superconductors such as YBCO have been shown to significantly improve the signal-to-noise ratio when compared to single SQUIDs from high-T_C material. This is based on the finding that the voltage response of a current biased array increases by the number of SQUID loops N while the noise only increases as $N^{1/2}$. It is therefore desirable to fabricate array structures with as many SQUIDs placed in series as possible. We present a fabrication technique for SQUID arrays based on ion-damage Josephson Junctions (JJ) that allows for creating virtually any SQUID-array design on any thin-film superconducting materials such as YBCO or MgB2. The fabrication employs electron beam lithography (EBL) to write the SQUID-array, electrical contact pads and JJ fine lines in a single lithography step. It is performed on a thick trilayer structure that allows for high-aspect ratio features. The superior resolution of EBL makes SQUID loop diameters down to a few hundred nanometers possible. Subsequent high-energy ion-implantion creates the JJ. Using low-energy argon ion milling at an angle to the sample shadows the fine lines used for creation of the JJ and transfers the EBL-defined SQUID-array and electrical contact pads into the thin-film superconductor.**

Keywords—SQUID array, YBCO, high-temperature superconductivity, Josephson junctions, electron beam lithography

I. Introduction

Superconducting interference devices (SQUIDs) from conventional superconductors can be found in many practical applications, most notably extremely sensitive magnetometers [1]. However, their characteristic ability to transduce magnetic flux into voltage is also of interest for many other applications, including the detection of electromagnetic waves.

Using high transition temperature Tc) superconducting material such as $YBa_2Cu_3O_{7-\delta}$ (YBCO) offers the possibility to integrate SQUIDs into mobile systems due to the significantly lower cooling requirements when compared to low-temperature superconductors. However, the thermal noise inform the increased operating temperature os high- Tc material is substantially higher [2]. One approach to improve the signal-to-noise ratio is to utilize arrays containing multiple SQUIDs in a

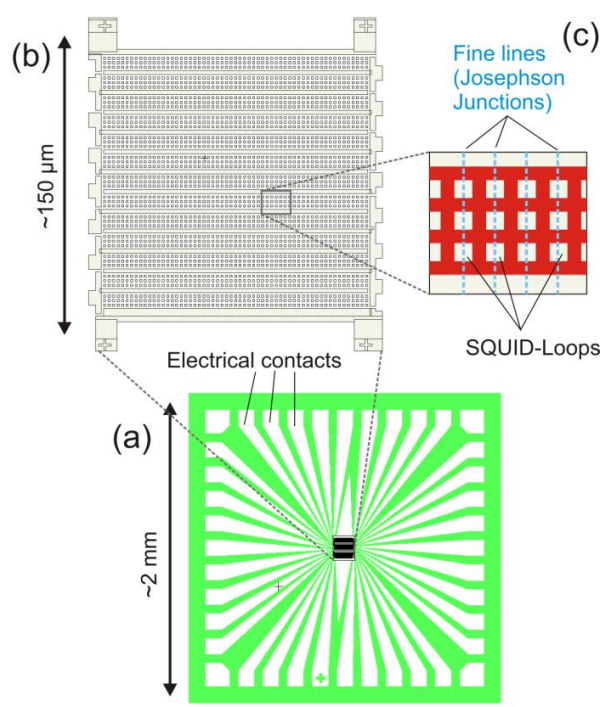

Fig. 1 Layout design of the electrode pattern (a) and embedded SQUID-array (b). The electrode pattern features in total 32 electrical contact pads used to measure individual portions of the SQUID array, which is situated in the center. The SQUID array is made up of several rows, each containing the actual SQUID loops (c). The SQUID loop areas are1 µm² and the loop width is 750 nm. The rows of the SQUID array are connected in series in a meander-like fashion.

series-parallel configuration. This is reasonable as the signal (i.e. the measured voltage response for a current biased device) increases as the number of SQUIDs N in series, while the noise

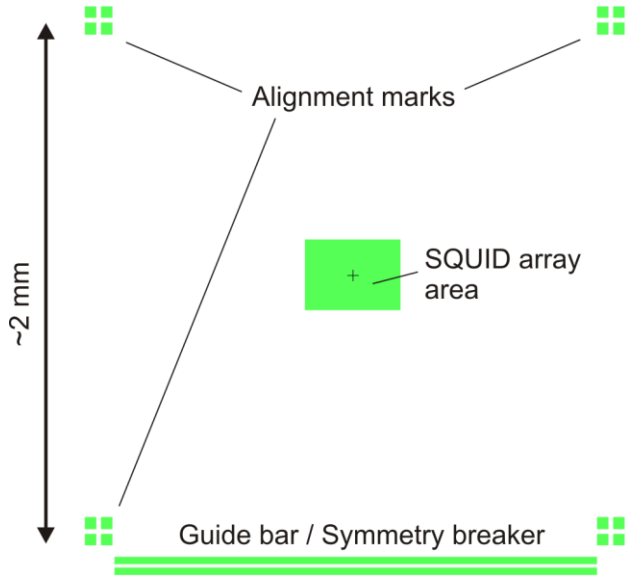

Fig. 2. Design pattern for the metal removal structure. It is used to align the center part of the pattern (shown in Fig.1) to the contact metal. The alignment marks and the bottom guide bar are necessary for later SQUID array pattern alignment to the structure.

only increases by $N^{1/2}$.

It has been shown recently that the fabrication of large-scale SQUID arrays containing thousands of loops using ion irradiated JJ is feasible, and that the devices are stable for several years.[cybart asc] These arrays have been made in a multi-step process based on photolithography that transfers the array design on the thin-film superconductor. In a second lithography step electron beam lithography (EBL) was used to pattern a mask used to define the Josephson Junctions. High-energy ions implanted through slits in the mask locally damage the YBCO film to form Josephson Junctions. The entire process is described in detail elsewhere [3-6].

In order to achieve a higher density of SQUID loops and an improved loop uniformity it is desirable to replace the photolithographic patterning approach by EBL which promises much smaller feature sizes. Also, it facilitates combining the writing of the SQUID loops and Josephson Junction (JJ) fine lines in a single lithography step which will significantly reduce turnaround times and amount of processing that any sample is subjected to. In this work we present a much-improved fabrication approach based on entirely EBL that aims to boost patterning resolution and also speed up and simplify the entire process. As opposed to the photolithographic patterning approach used previously because the JJ fine lines are written at the same time as the SQUID loops.

II. Fabrication Process

A. *SQUID array layout*

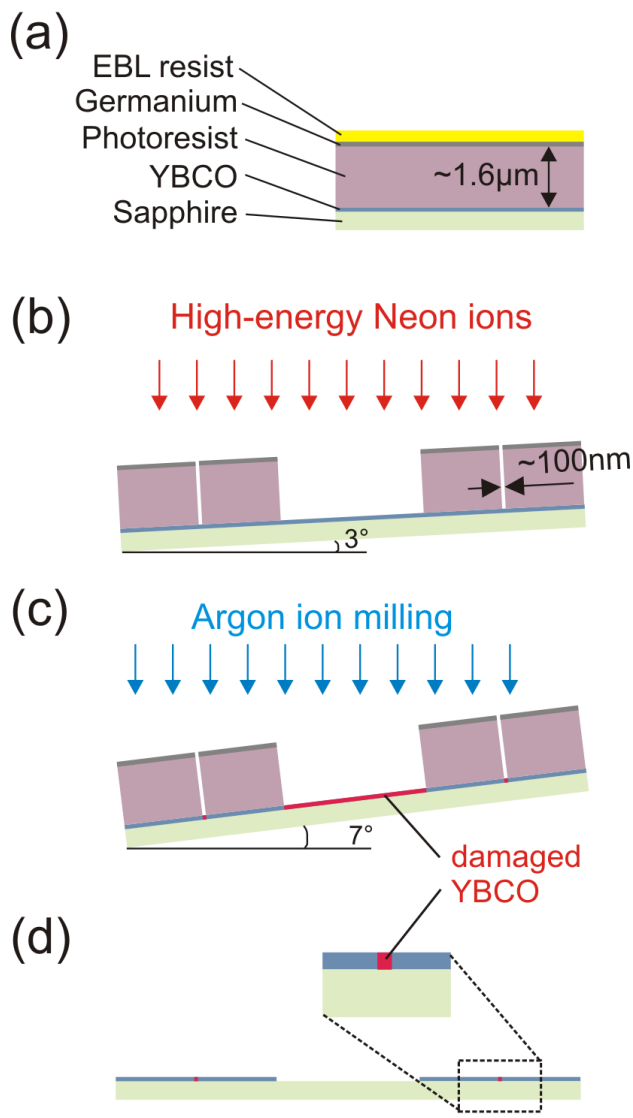

Fig. 3 Double angle fabrication process: (a) A trilayer consisting of ~120 nm PMMA resist, ~25 nm evaporated Germanium and ~1.6 µm of hard-baked photoresist is built on the substrate (150 nm YBCO on sapphire). After EBL and RIE the pattern is transferred into the trilayer forming a mask. (b) High-energy neon ion implant damages exposed material but leaves material undamaged that is covered by the trilayer mask. The 3° angle effectively narrows the 100 nm wide trenches to ~50 nm at the bottom. (c) Argon ion milling is performed at a 7° angle. This completely shadows the junction trenches and only removes large features (i.e. loops, interconnects, electrodes etc.) in the YBCO film. (d) The mask is stripped and the device is finished.

Fig. 1 shows the layout that has been used in this work. It is made up of a 2 × 2 mm² electrode structure for electrical characterization [Fig. 1(a)], and the SQUID array that is located in the center [Fig. 1 (b)].

The SQUID array features 1,020 closely packed parallel segments each consisting of 3 SQUID loops or 4 JJ in parallel [Fig. 1 (c)] totaling to 3,060 SQUIDs or 4,080 Josephson Junctions. The loop bridge width are 750 nm with a loop hole area of 1 × 1 µm². The rows of the SQUID array are linked in a meander-line.

B. Substrate preparation

As substrates, 7 × 7 mm² 150 nm YBCO films on *r*-planesapphire diced from 2”wafers. The YBCO films arecovered by a 15nm in-situ Ag to ensure low contact resistance.In order to allow for robust wire-bonding with good adhesion, an additional 10nm Ti sticking layer and 200nm Au

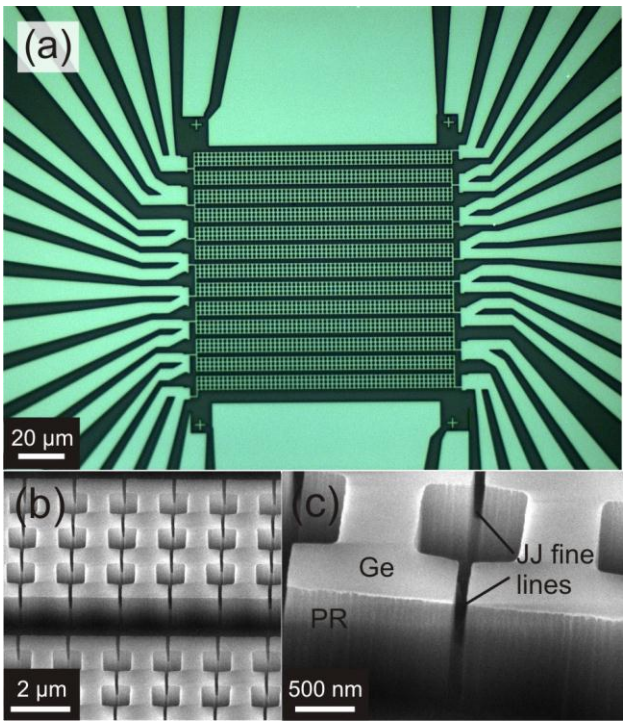

Fig. 4. Images of the SQUID array after mask fabrication, before neon implantion and ion milling. (a) Light-optical image of the entire SQUID array and electrodes. Dark regions correspond to the YBCO substrate, bright regions depict the mask (i.e. regions where the YBCO is covered). (b) and (c): Tilted SEM images showing magnified images of the loops with the Josephson junctions (JJ) fine lines. After etching the mask, the thin Ge film on top of the thick photoresist (PR) layer is still intact.

layer are sputtered ex situ.. The *TC* on an unpatterend film has been determined to be approximately90 K.

Before patterning of the SQUID array and electrodes, each substrate has to stripped of the metal where the SQUID array is to be placed in subsequent processing steps. This metal removal step is performed before the trilayer mask is applied [see Fig. 3 (a)] and is necessary to ensure the high-energy ion irradiation used to form the Josephson junctions reaches the YBCO SQUID array directly without traversing through the 200 nm metal layer first. If the incident ions were to travel through the metal layer, significant scattering would occur which would not only require a higher high-energy ion dose but would also result in considerable broadening of the damaged area from lateral ion straggle resulting in a low performance of the ion-damage Josephson junctions.

In order to perform the metal removal step, 1.8 µm thick 9 % 950k polymethylmethacrylate in chlorobenzene (PMMA C9) electron beam resist is spun on the substrates. Using a thick (as opposed to a thin) electron beam resist makes it easier to strip the metal-removal mask later. The substrates are then patterned using electron beam lithography using a high electron beam current (>5 nA) to allow for a short exposure time. After development an argon ion mill is used to remove the metal layer where the PMMA C9 mask does not cover it. Argon ion milling for this step is preferred over the widely used KI-I (potassium iodide-iodine) wet etch approach as ion

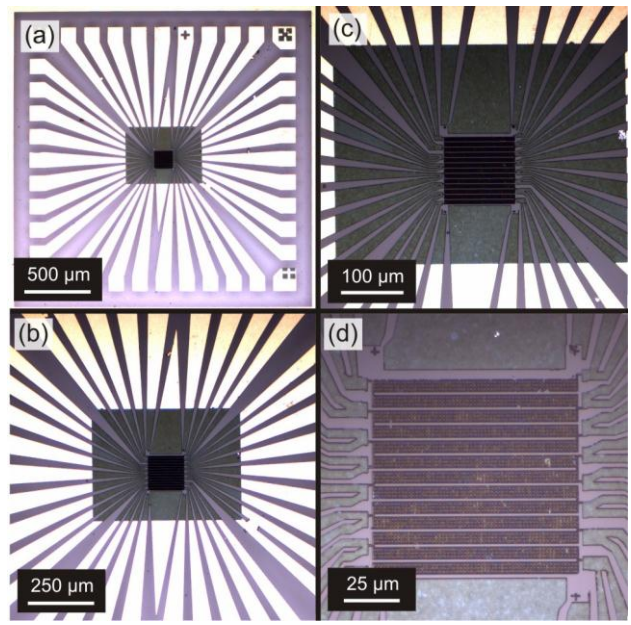

Figure 5. Light-optical images using different magnifications of the same SQUID array and electrode pattern after stripping the trilayer mask. (a) 5x magnification, (b) 10x magnification, (c) 20x magnification, (d) 50x magnification.

milling shows less undercutting and easily removes the underlying titanium layer, which cannot be etched using KI^{+}-I.

III. Fabrication of the SQUID array pattern

The fabrication process of the SQUID array and electrode pattern is illustrated in Fig. 3. A trilayer mask is built on the samples. It consists of a 1.6 µm hard-baked photoresist layer, 25 nm evaporated Germanium and a 120 nm layer of conventional PMMA C2 EBL resist. The PMMA layer was patterned by EBL performed on a RAITH50 EBL tool. It is important to note that the entire device layout including electrodes, SQUID array and Josephson Junctions fine lines are written in this single exposure.

In order to transfer the pattern into the photoresist, the samples were first reactively ion etched (RIE) in chlorine plasma to break through the Ge layer only where it is not protected by PMMA. A subsequent low-pressure oxygen RIE will remove the photoresist that is not covered by Ge. The creation of the Josephson junctions is performed by exposure to

200 keV Neon ions which was performed using a commercial ion implanter.

Argon ion milling is performed as the final step, with the sample mounted at a 7° angle to the incident argon beam. This shadows the narrow junction trenches but still etches the comparatively large SQUID loops andother features of the SQUID array (e.g. interconnects, contact pads, etc.).

After stripping the trilayer mask, the sample is ready to be wire-bonded and can be installed into a chip package. Fig. 5 shows light-optical images at different magnifications of the final chip. The pattern has been accurately transferred into the YBCO film. The bright areas show the metal contact layer while the bluish areas show the sapphire substrate that electrically isolates the electrodes from each other to form probing contacts to the SQUID array located in the center of the chip. Also of interest in Fig. 5 is the rectangular structure around the center SQUID array. This area shows the metal-stripped YBCO film that was previously covered by the trilayer mask and thus protected from ion milling. Finally, the tilting angle during ion milling ensured that the ion milling did not damage the SQUID array itself.

IV. Conclusion

In conclusion we have presented a fabrication process based on electron beam lithography that is able to easily create SQUID arrays consisting of sub-micron SQUIDs. Due to the double-angle processing approach, the whole pattern including the Josephson junctions can be written during a single exposure as opposed to individual processing steps as has been used previously. While this process may not be suitable for wafer-scale processing due to the comparatively slow electron beam exposure, it is superior to a photolithographic approach in almost any other respect. It is especially interesting to fundamental research in SQUID array technology as electron beam lithography does not require a photomask and is therefore very flexible and patterns can be adjusted easily in a timely manner.

Acknowledgment

This work was supported by AFOSR grant FA9550-07-1-0493, ONR grant N00014-11-1-0049, and the Office of Science and Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DEAC02-05CH11231.

References

[1] J. Clarke, “The SQUID Handbook”, Wiley, 2006

[2] D. Koelle, R. Kleiner, F. Ludwig, E. Dantsker, and J. Clarke, “High-transition-temperature superconducting quantum interference devices”, Rev. Mod. Phys. 71, 1999, pp. 631–686.

[3] S. A. Cybart, S. M. Anton, S. M. Wu, J. Clarke, and R. C. Dynes, “Very Large Scale Integration of Nanopatterned $YBa_2Cu_3O_{7-\delta}$ Josephson Junctions in a Two-Dimensional Array” Nano Lett. 9, 2009, pp. 3581-3585.

[4] S. A. Cybart, T. N. Dalichaouch, S. M. Wu, S. M. Anton, J. A. Drisko, J. M. Parker, B. D. Harteneck, and R. C. Dynes, “Comparison of measurements and simulations of series-parallel incommensurate area superconducting quantum interference device arrays fabricated from $YBa_2Cu_3O_{7-\delta}$ ion damage Josephson junctions” J. Appl. Phys. 112, 2012, 063911.

[5] S. A. Cybart, S. M. Wu, S. M. Anton, I. Siddiqi, J. Clarke, and R. C. Dynes, “Series array of incommensurate superconducting quantum interference devices from $YBa_2Cu_3O_{7-\delta}$ ion damage Josephson junctions” Appl. Phys. Lett. 93, 2008, 182502.

[6] S. A. Cybart, K. Chen, Y. Cui, Q. Li, X. X. Xi and R. C. Dynes, “Planar MgB_2 Josephson junctions and series arrays via nanolithography and ion damage” Appl. Phys. Lett. 88, 2006, 012509.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

DE-AC02-05CH11231