HEIDELBERG INSTRUMENTS

APPLICATION NOTE

MASKLESS LASER LITHOGRAPHY FOR JOSEPHSON JUNCTION FABRICATION

by

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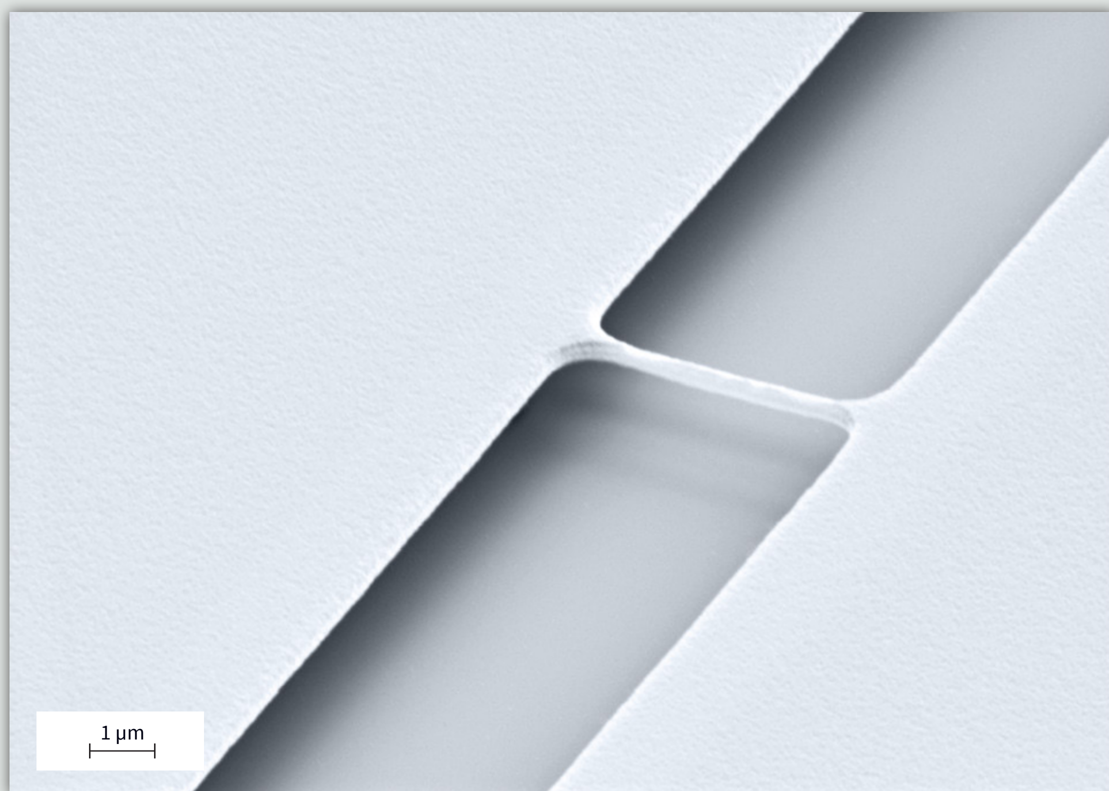

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INTRODUCTION

Josephson junctions (JJs) are fundamental building blocks for superconducting quantum circuits and advanced sensor technology. Historically, the fabrication of these precise, nanometer-scale structures has relied heavily on electron-beam lithography (EBL), which offers high resolution but suffers from low throughput and high cost for large-area patterning. Maskless laser lithography provides a flexible and efficient alternative by enabling direct-write patterning without physical masks. This approach accelerates prototyping and simplifies process flows while maintaining high resolution.

This application note details a robust fabrication process for JJs utilizing maskless lithography, focusing on two widely adopted geometries: the Niemeyer-Dolan-bridge technique, which employs suspended resist structures for shadow evaporation, and the Manhattan-style approach, which defines the junction area via orthogonal wiring layers.

For patterning, we utilize a MLA 300 from Heidelberg Instruments, a high-performance maskless lithography system capable of rapidly patterning substrates up to 300 mm in diameter, with a resolution down to 2 µm at a 405 nm exposure wavelength. However, the presented methodology is directly transferable to other laser lithography tools from Heidelberg Instruments like the DWL 66⁺ [1] or MLA 150, for applications requiring submicron critical dimensions.

1. PRINCIPLES OF JOSEPHSON-JUNCTION FABRICATION

Fundamentally, a JJ is realized by separating two superconducting electrodes by a non-superconducting barrier. In the context of standard thin-film technology, this structure is commonly realized using aluminum (Al) as a superconductor and a native aluminum oxide (AlO_x) tunnel barrier.

The definition of the critical junction area is achieved through liftoff lithography and an angled evaporation process known as shadow evaporation. To execute this precise angular deposition, the lithography step must reliably produce a suspended resist structure with a controlled and significant undercut profile.

1.1. NIEMEYER-DOLAN-BRIDGE GEOMETRY

The Niemeyer-Dolan-bridge geometry, or shadow evaporation technique, is a self-aligned fabrication method used to produce sub-micron JJs. This approach utilizes a suspended resist bridge—often termed a "Dolan bridge"—to act as a mask for successive thin-film depositions. By exploiting the geometric shadowing effect of this bridge, the junction is formed during a single lithographic step.

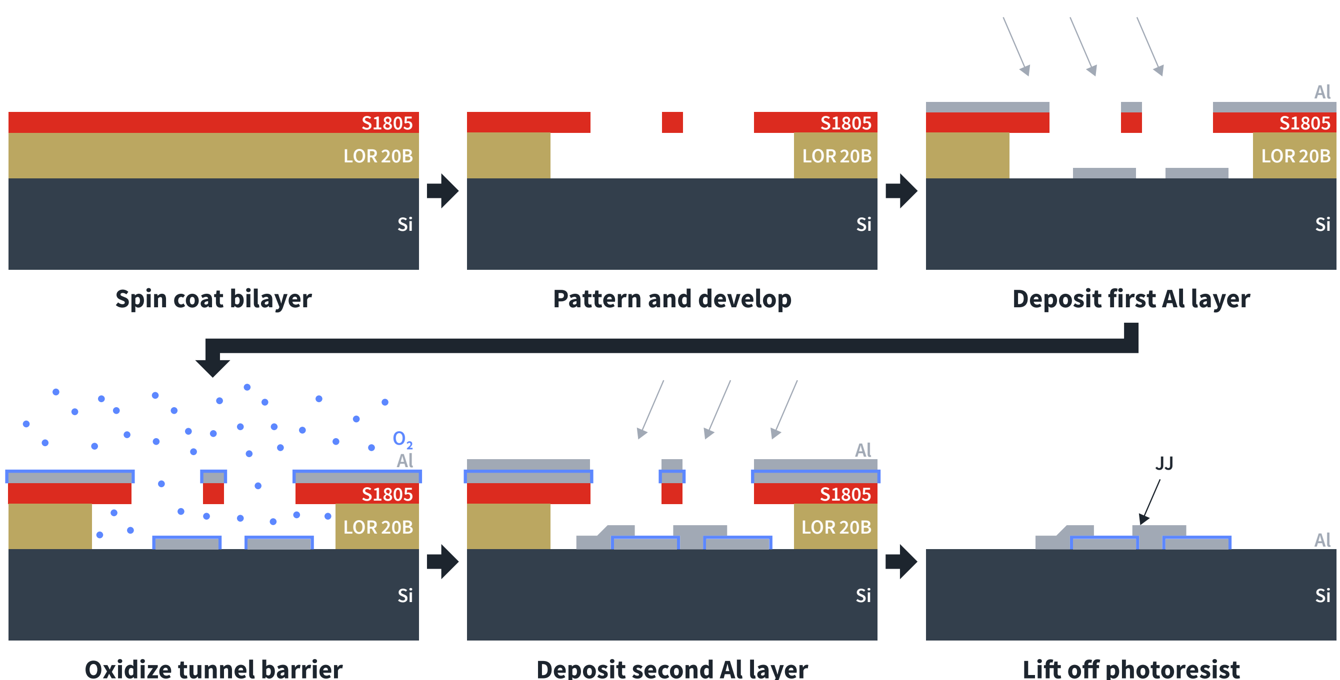


Figure 1: Cross-section schematic of the fabrication process of a Niemeyer-Dolan-bridge junction

The process begins with the patterning of a bilayer resist stack where the bottom layer is more sensitive than the top. Upon development, a significant undercut is formed, leaving a narrow strip of the top resist layer suspended over the substrate. Fabrication then proceeds via dual-angle evaporation. The initial deposition angle defines the base electrode, followed by in-situ oxidation of the exposed aluminum, and finally, the second deposition angle defines the counter electrode, creating the precise overlap area that constitutes the tunnel junction. A cross-sectional schematic of the processes is illustrated in Figure 1.

1.2. MANHATTAN-STYLE GEOMETRY

Manhattan-style geometry refers to a design architecture where all features are aligned along orthogonal axes, mimicking the rectilinear grid of a city. In microfabrication, this approach is favored for its simplicity and its seamless compatibility with standard lithography and etching protocols. In the context of Josephson junction fabrication, Manhattan geometry facilitates a two-step metallization process within a single lithographic step. This is achieved using a bilayer resist stack designed with a substantial undercut. During the initial evaporation, the superconducting metal is deposited along one axis (e.g., the X-direction); the undercut profile ensures that the orthogonal electrode remains "shadowed" and does not contact the substrate. Following an in-situ oxidation step to form the tunnel barrier, the substrate is rotated by 90°, and the counter-electrode is deposited along the Y-axis. This orthogonal intersection creates a precisely defined overlap region, which determines the junction's electrical characteristics. A 3D schematic of the process is depicted in Figure 2.

1.3. LITHOGRAPHIC PROCESS: BILAYER RESIST STACK

The liftoff process for both geometries necessitates a bilayer resist stack to ensure sufficient undercut for reliable shadow evaporation and subsequent metal liftoff. The following procedure details the preparation of the silicon substrate and the application of the resist stack utilized for this work:

Figure 2: Schematic of the fabrication process of a Manhattan-style-geometry junction

1. **Cleaning:** The silicon (Si) substrate is cleaned using acetone, methanol, and isopropanol.

2. **A dehydration bake** is performed at 180 °C for 10 minutes. No chemical priming (e.g. HMDS) was needed for the resists chosen.

3. **Spin coating:** The resist stack consists of two layers: LOR 20B (Kayaku Advanced Materials), a highly sensitive sacrificial layer, and Microposit™ S1805 (DuPont), a high-resolution imaging layer. The following parameters were used:

	Material	Spin speed/ rpm	Thickness/ µm	Soft bake
1.	LOR 20B	2000	2.0	180°C for 4 min
2.	S1805	3000	0.5	115°C for 1 min

4. **Exposure** was conducted at 405 nm using the MLA 300 with a dose of 90 mJ/cm^2. The pneumatic autofocus was employed with a 0% focus offset.

5. **Development:** The exposed resist was developed for **60 seconds** in MF-319 (DuPont) developer.

2. MLA 300 EXPOSURE RESULTS

The high sensitivity of the LOR 20B to the MF-319 developer facilitates a significant lateral development rate, resulting in the desired large undercut beneath the S1805 top layer. Scanning electron microscopy (SEM) images confirm the required resist profile and bridge formation. The wire (channel) width was varied to be between 2 µm and 4 µm and the resist bridge was varied from 2 µm down to sub-µm dimensions. With this process it was possible to fabricate a bridge as narrow as 560 nm (see Fig 3 c)).

Figure 3: SEM micrographs showing the photoresist after the development step, demonstrating the required retrograde profile. Panels a) and b) show the realization of bridges for Niemeyer-Dolan-bridge JJs and SQUIDs (superconducting quantum interference devices consisting of two JJs in parallel), including a detail measurement in panel c) illustrating a resist bridge with dimensions as narrow as 560 nm. Panel d) shows the structure for the Manhattan-style geometry.

3. SHADOW EVAPORATION AND LIFTOFF

The JJ fabrication concludes with the controlled deposition of the superconducting thin films and the formation of the insulating barrier. For both Niemeyer-Dolan-bridge and Manhattan-style junctions, 50 nm of Al was deposited at an angle of 45° to the substrate surface using electron beam evaporation with a deposition rate of 2 Å/s. After the first layer is deposited, an oxidation step is conducted by inserting oxygen or a mixture of oxygen and argon into the evaporation chamber at a pressure around a few Torr. Following the oxidation, a second 50 nm layer of Al is deposited, again at an angle of 45°, but from the opposite direction for the Niemeyer-Dolan-bridge JJ. For the Manhattan-style geometry the substrate was rotated by 90° (c.f. schematic in Figure 2). For liftoff, the substrate is immersed in Microposit™ Remover 1165 (DuPont). SEM images of completed, fully patterned JJs are available in Figure 4.

CONCLUSION & OUTLOOK

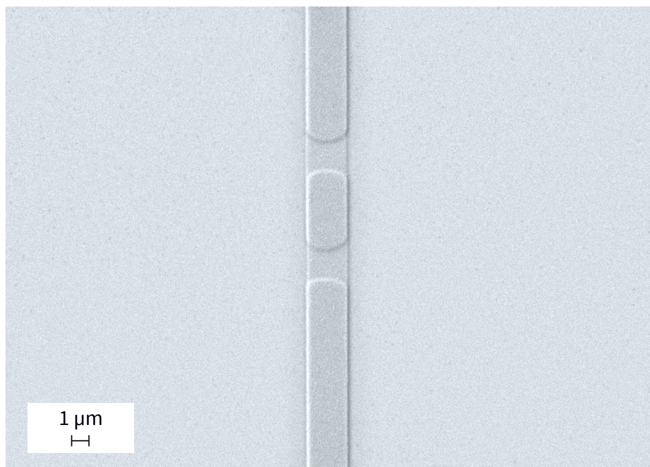
This application note successfully demonstrates the implementation of maskless laser lithography using the MLA 300 system as a highly efficient and versatile addition to traditional electron-beam lithography for the fabrication of superconducting devices. By leveraging a well-optimized bilayer resist stack and a standard shadow evaporation process, we achieved the high-aspect-ratio, retrograde resist profiles necessary for both the Niemeyer-Dolan-bridge and Manhattan-style geometries for JJ fabrication.

Furthermore, the high-precision overlay accuracy of the Maskless Aligner system allows for the reliable integration of these superconducting elements with larger-scale circuit features, such as coplanar waveguides. While the resultant junction dimensions are typically larger than required for state-of-the-art superconducting quantum chips, this approach is ideally suited for superconducting sensing applications and components like parametric amplifiers, high-frequency mixers, and superconducting classical circuits.

This maskless approach offers an alternative route for realizing superconducting quantum elements with a higher throughput compared to legacy EBL, thereby advancing the path toward scalable, cost-effective manufacturing of complex quantum circuits.

REFERENCE

[1] J. T. Monroe, D. Kowsari, K. Zheng, C. Gaikwad, J. Brewster, D. S. Wisbey, K. W. Murch; Optical direct write of Dolan–Niemeyer-bridge junctions for transmon qubits. Appl. Phys. Lett. 9 August 2021; 119 (6): 062601.



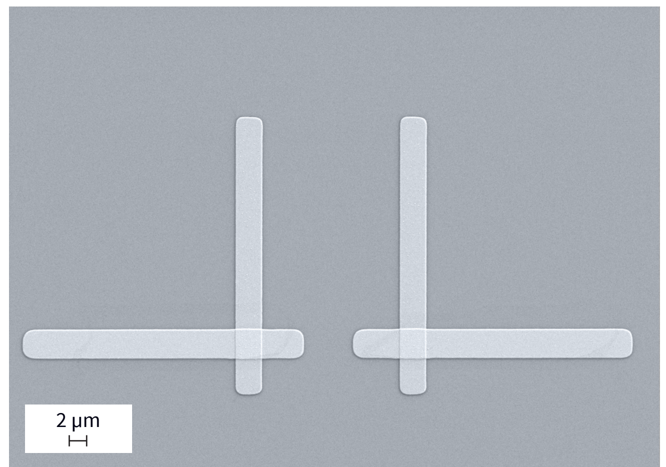


Figure 4: SEM micrographs of completed Josephson junctions after liftoff. Left shows the Niemeyer-Dolan version, right the Manhattan-style geometry.

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