IISER BHOPAL

DEVLOPMENT FOR ELECTRO-LITHOGRAPHY SYSTEM

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INTRODUCTION

What is Electro-Lithograhy?

The core principle of this lithography technique is Liquid Electromigration. This phenomenon is when material transport occurs due to electric current that leads to some deformation in the surface topology of the solid metallic conductor near cathode and anode. We apply this phenomenon to develop a scanning probe-based lithography technique where liquid electromigration driven material removal is used as a key step.
In electrolithography, we perform electromigration induced selective metal etching with the help of a conducting scanning probe, and then transfer the patterns to other materials using a polymer layer (PMMA). Electrolithography does not require UHV condition, high-power e-beam source or UV sources like conventional lithography techniques. In electrolithography, any polymer and corresponding developer can be used thereby, removing need of costly and toxic chemicals. Electrolithography can be used for drawing patterns having dimensions from a few nanometres to a few hundred micrometres.

How it works?

Setup

- A thin Cr film (10–30 nm) is deposited on the substrate (often over a sacrificial PMMA polymer layer for later pattern transfer).
- A fixed **anode** and a movable **cathode probe** are placed on the film.

Electric-Field–Induced Reaction

- High voltage is applied between the two probes.
- At the cathode tip, an **electrochemical oxidation reaction** occurs, producing liquid chromium trioxide ($CrO_3 \cdot H_2O$).

Water Bridge Formation

- In ambient conditions, water vapour in the air condenses to form a **nanoscale water bridge** between the probe tip and the sample surface.
- This water bridge acts as an **electrolyte**, allowing ions (OH^-) to migrate to the reaction site.
- The applied voltage drives the anodic oxidation process through this water bridge, aiding in oxide formation.

Material Removal

- The oxide is liquid and mobile under the electric field, allowing it to be **transported away** from the probe contact area.
- This is a **material removal** process rather than addition.

Pattern Writing

- By scanning the cathode tip across the film, **lines or shapes** are etched into the Cr layer.
- Ambient humidity, probe tip sharpness, and voltage affect resolution.
  - At higher humidity, the water bridge is larger, producing wider lines.
  - Resolutions down to **9 nm in PMMA** and **40 nm in Ti on Si** have been demonstrated.

Pattern Transfer

- The patterned Cr layer is removed, exposing the PMMA.
- PMMA is developed, the desired material is deposited, and lift-off is performed to transfer the pattern to the target substrate.

Some other types of Lithography

1. **Photolithography -** The most widely used technique in semiconductor industries. It uses ultraviolet (UV) light and a mask to pattern photoresist.
    - **UV Lithography:** For features ~1 μm.
    - **Deep UV (DUV):** 248 or 193 nm wavelength, enabling finer resolution down to 90 nm.
    - **Extreme UV (EUV):** Uses 13.5 nm light, enabling feature sizes below 10 nm.
2. **Electron Beam Lithography (EBL) -** A maskless technique using a focused electron beam to write patterns directly. It provides high resolution (down to a few nanometers) but is slower and suited for research or low-volume production.
3. **Scanning Probe Lithography (SPL):** Involves using an atomic force microscope (AFM) tip to create nanoscale patterns via local heating, oxidation, or mechanical contact.
4. **Maskless Lithography/ Direct-Write Technique:** Techniques like laser writing or electrolithography fall here—offering design flexibility without needing a photomask.

System Overview

Electro lithography is a cutting edge nanofabrication technique where a conductive probe is brought into contact with a surface to define patterns. The system uses precise motor controls and current-based contact detection to create lithographic patterns.
This project aims to provide:

- Automated probe movement in X, Y, and Z directions
- Real-time Z-axis feedback using current sensing from an SMU (Source Measurement Unit)
- Execution of custom lithographic patterns based on coordinate files
- Scalability toward nanometer precision and visual monitoring

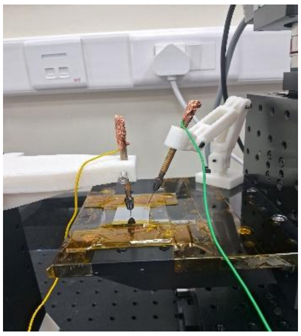
Technologies Used

- Python
- Serial Communication (pySerial Library)
- Holmarc motor controllers
- Source Measurement Unit (SMU)
- Micropositioner (XYZ Stage)

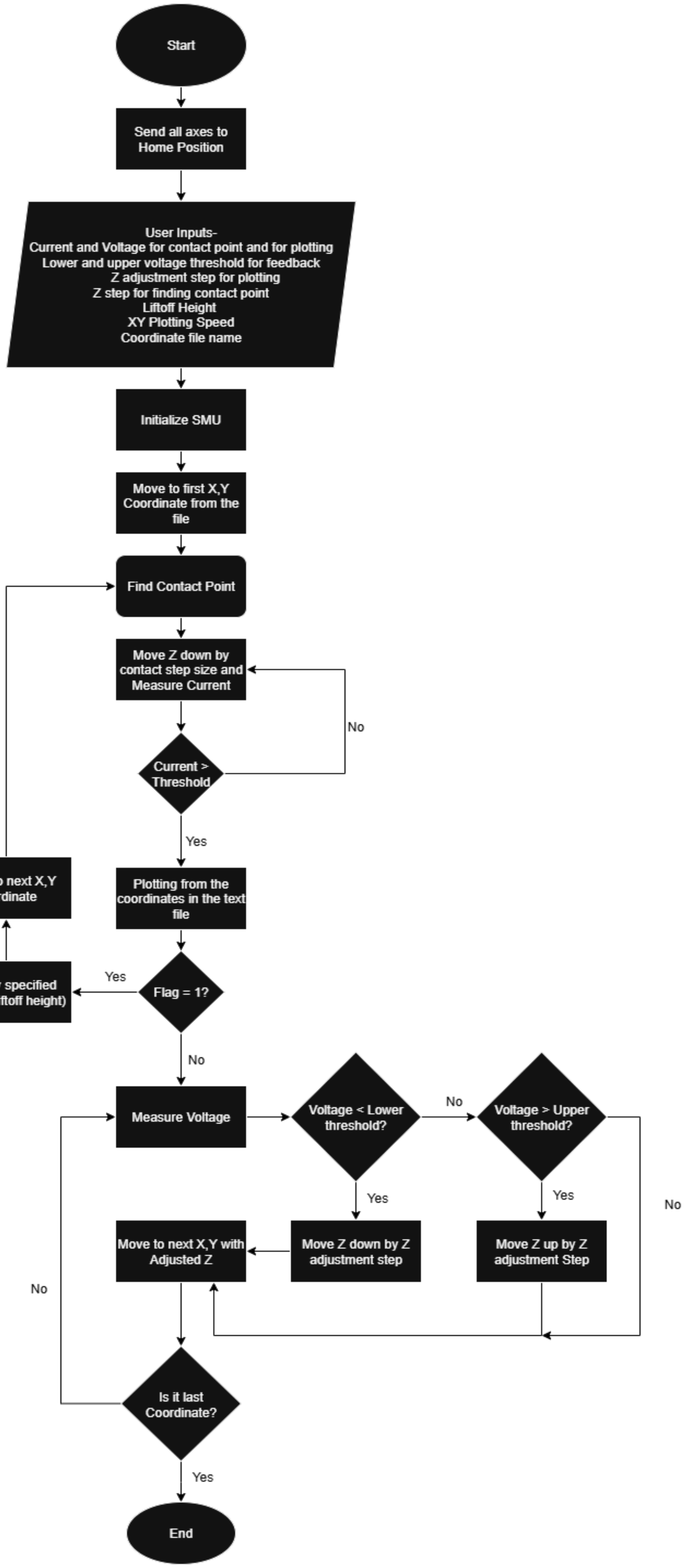
Hardware Setup

- **Source Measurement Unit (SMU)**

- **Holmarc micro positioner and XYZ Stage**



Algorithm



Start
Send all axes to Home Position
User Inputs-
Current and Voltage for contact point and for plotting
Lower and upper voltage threshold for feedback
Z adjustment step for plotting
Z step for finding contact point
Liftoff Height
XY Plotting Speed
Coordinate file name
Initialize SMU
Move to first X,Y Coordinate from the file
Find Contact Point
Move Z down by contact step size and Measure Current
No
Current > Threshold
Yes
Move to next X,Y coordinate
Plotting from the coordinates in the text file
Lift z by specified height (Liftoff height)
Yes
Flag = 1?
No
Measure Voltage
Voltage < Lower threshold?
No
Voltage > Upper threshold?
Yes
Yes
No
Move to next X,Y with Adjusted Z
Move Z down by Z adjustment step
Move Z up by Z adjustment Step
No
Is it last Coordinate?
Yes
End

Code Working Overview

The lithography control program was developed in Python to automate probe positioning, contact detection, and pattern plotting. It integrates motion control of the Holmarc micropositioner with real-time current and voltage measurements from the Source Measurement Unit (SMU), enabling closed-loop lithography operations.

1. Initialization

Upon execution, the program first detects available serial (COM) ports and establishes communication with the Holmarc motion controller. Instances of the motion control classes and the SMU control interface are initialized, ensuring that both subsystems are ready for operation.

2. User Input and Parameter Configuration

Before pattern execution, the user is prompted to provide key lithography parameters, including:

- Current and voltage settings for contact detection
- Voltage and current settings for lithography bias
- Upper and lower voltage thresholds for Z-axis feedback control
- Z-axis step size for plotting and contact detection
- Liftoff height for open-loop movements
- XY-axis plotting speed
- Name of the coordinate file to be executed

The coordinate file is expected in the format:

x, y, flag

where:

- **flag = 0** → Continue plotting in contact mode
- **flag = 1** → Lift probe before moving to the next position

```
10999.000, 10000.000, 0
11000.000, 10000.000, 0
11000.000, 10000.000, 1
10000.000, 10200.000, 1
10000.000, 10200.000, 0
10001.000, 10200.000, 0
10002.000, 10200.000, 0
10003.000, 10200.000, 0
```

3. Homing and Positioning

At the start of each lithography session, all three motion axes (X, Y, Z) are sent to their home positions. The probe is then positioned at the first X,Y coordinate from the provided file.

4. Contact Point Detection

The Z-axis is lowered incrementally using the specified step size while continuously monitoring current from the SMU. When the measured current exceeds the user-defined contact threshold, the system records this as the contact point and prepares for lithography.

User can adjust the step size for better precision during the motion.

5. Pattern Execution

The program processes each coordinate in sequence:

- **If flag = 1 (Liftoff)**:
  - The probe is raised by the liftoff height
  - Moved to the next X,Y coordinate
  - Contact point detection is performed again before plotting resumes
- **If flag = 0 (Contact Mode)**:
  - Voltage feedback control is applied during plotting:
    - If voltage < lower threshold → Z-axis is moved down by the adjustment step
    - If voltage > upper threshold → Z-axis is moved up by the adjustment step
    - If voltage is within range → Z position is maintained
  - The probe is then moved to the next plotting coordinate with the adjusted Z value

6. Real-Time Feedback Control
During the plotting phase, the SMU readings are continuously monitored to make fine Z-axis adjustments, maintaining optimal tip–sample interaction and ensuring pattern fidelity.

7. Completion and Safety
After all coordinates have been executed, the SMU output is disabled, motion commands are halted, and communication ports are closed, ensuring safe shutdown of the system.

Problems Faced and Solutions

During the development of the electro-lithography system, several technical challenges were encountered, ranging from critical hardware safety issues to efficiency improvements. The most severe issues were addressed first to ensure system stability and prevent equipment damage. The problems and their solutions are presented below in order of severity.

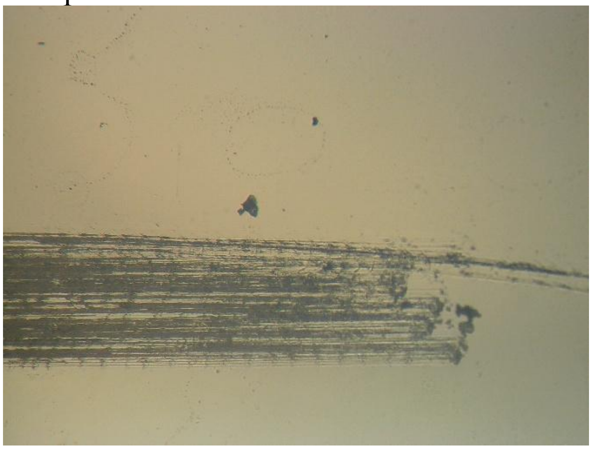
1. Controller Unresponsiveness on Limit Switch Triggers
Problem: Whenever a mechanical limit switch was triggered or a motion error occurred, the controller became unresponsive, requiring manual intervention. This posed a risk to both the probe and the sample.
Solution: Implemented automatic serial port reset procedures after every error encounter. Additionally, the code was modified to reject any user input that would move a motor more than 50,000 steps, effectively preventing accidental limit switch activation.

2. Command Execution During Motion
Problem: Sending a new motion command while the motors were still moving caused the controller to crash.
Solution: Added a control mechanism that blocks new commands until the current motion is fully completed.

3. Data Collision After Introducing Multithreading
Problem: Initial multithreading implementation caused simultaneous access to the serial port by multiple threads, resulting in corrupted data and unpredictable motion behavior.
Solution: Introduced a check to ensure that only one thread can send data at a time, starting a new thread only after the previous one has completed its data transmission.

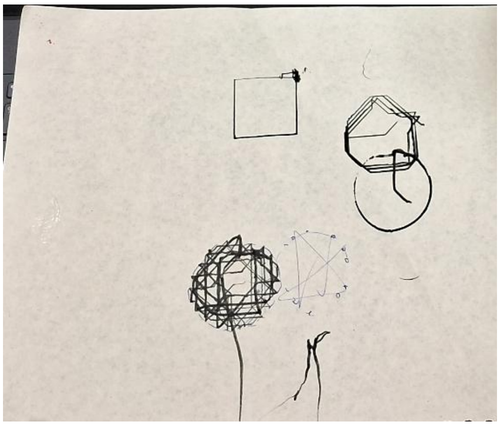
4. Probe Scratching in Open-Loop Movements
Problem: During open-loop patterning, the probe scratched the sample surface when

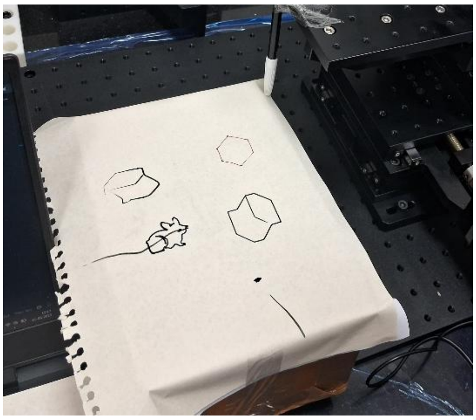
moving between patterns.
Solution: Introduced a flag system in the coordinate file that lifts the probe before moving to the next pattern position and reinitiates contact detection afterward.



At 10x Zoom

5. Non-Uniform Lines at Angles
Problem: When plotting angled lines by manually entering separate X and Y velocities, the system produced non-uniform patterns.
Solution: Modified the code to accept a single effective velocity as input and calculate proportional X and Y velocities internally, ensuring uniform line quality.





Skewed structure instead of a Hexagon being plotted

6. Step Size Adjustment During Contact Detection
Problem: Increasing the Z-axis step size during descent for contact point detection caused the controller to crash if the change was made mid-motion.
Solution: Implemented a secondary listener thread to accept updated step size values. When the user presses Enter, the motion temporarily stops, applies the new step size, and then resumes operation seamlessly.

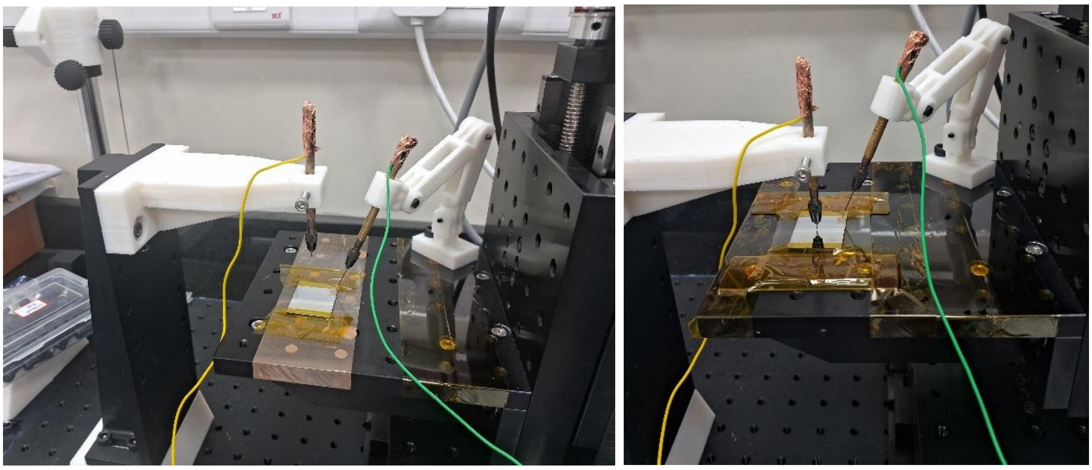
7. Erroneous SMU Readings Due to Static Charge
Problem: Static charges on the sample occasionally resulted in incorrect SMU readings.
Solution: Added a routine to reset the SMU whenever abnormal readings are detected.

8. Absolute vs. Relative Positioning
Problem: The controller did not accept absolute coordinate inputs, limiting direct

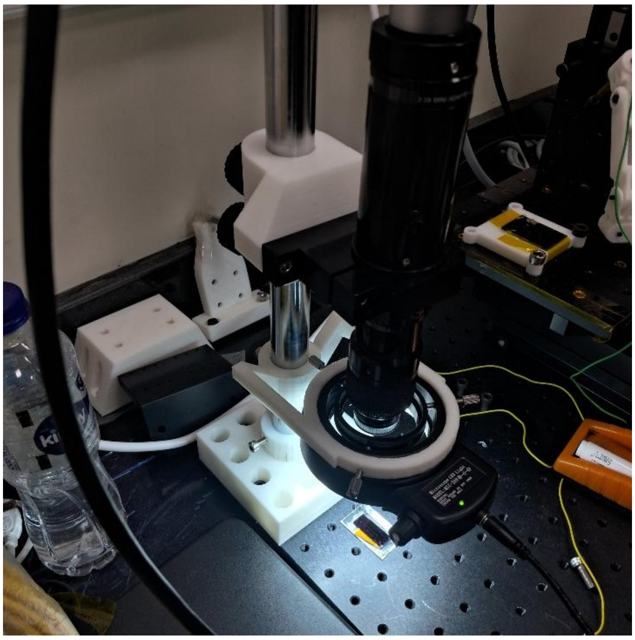
coordinate-based patterning.
Solution: Implemented a system to convert coordinates from the input file into relative movements, which are then sent to the controller.

9. Inverted Z-Axis Direction
Problem: The default controller configuration interpreted a positive Z value as a downward movement, which conflicted with our intended operational logic.
Solution: Inverted the Z-axis coordinate system so that positive values correspond to upward motion, aligning system behavior with lithography requirements.

3D Printed Components



3D Printed Stand and Probe Arms



3D Printed Lense and Light Holders

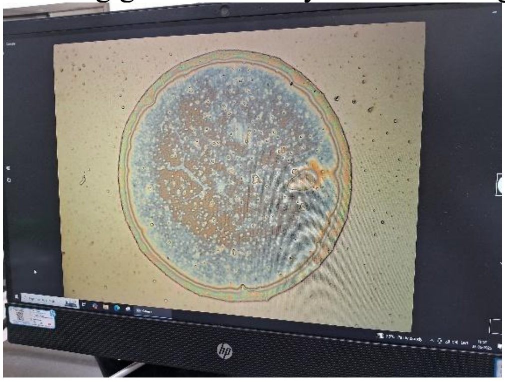
Results

1. Results and Observations
The developed electro-lithography system successfully integrated motion control, SMU feedback, and automated pattern execution.

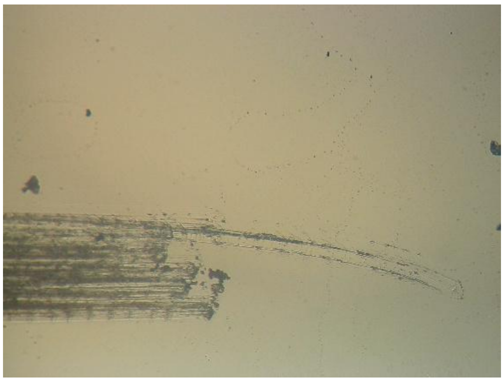
Key achievements during testing included:

- **Automated contact point detection** using current threshold monitoring.
- **Stable Z-axis feedback control** that maintained tip–sample interaction during plotting.
- **Execution of open-loop and feedback-controlled patterns** based on coordinate files.
- Real-time parameter adjustments for Z-step size and plotting speed without restarting the program.
- Implementation of a **liftoff system** to prevent probe scratching during inter-pattern movements.

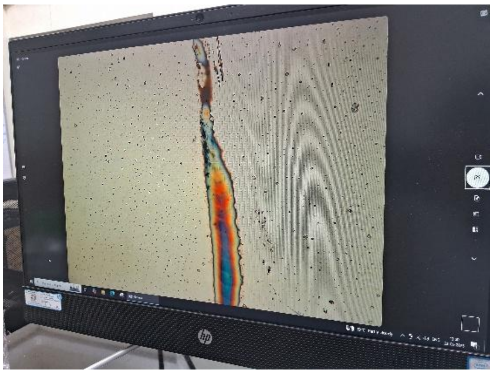
Test runs demonstrated that the system could accurately follow coordinate-based paths and dynamically adjust the Z position based on voltage readings. Both open-loop and feedback-controlled modes produced reproducible motion profiles, with feedback mode showing greater stability in maintaining contact conditions.



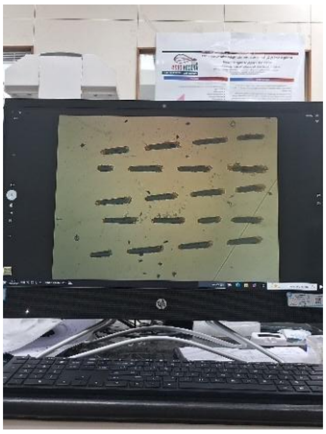
Chromium Deposition at Contact Point (100x)



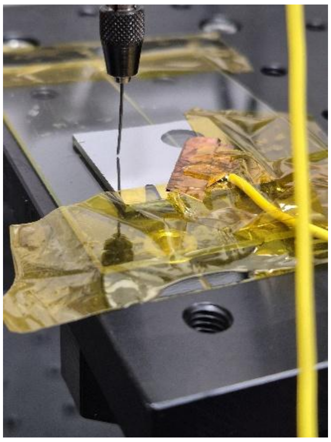
Probe Scratches on the Sample



Initial Patterning Attempts



After successive optimization



Lithography in progress

Conclusion

The development of the electro-lithography system successfully combined precision motion control, real-time SMU feedback, and automated pattern execution into a cohesive platform capable of micron-scale lithography. Through iterative problem-solving and optimization, the system achieved stable contact detection, reliable feedback-controlled Z-axis adjustments, and execution of both open-loop and closed-loop lithography patterns.

The integration of multithreading, error-handling routines, and real-time parameter adjustments significantly improved operational efficiency and system robustness. Safety measures, such as motion limits and liftoff mechanisms, minimized the risk of probe or sample damage during operation.

While the system currently operates at micron resolution, the modular nature of its design allows for future upgrades toward nanometer-scale precision, camera-based alignment, and enhanced automation. These improvements will further expand its applicability in advanced research and microfabrication tasks.

Overall, this project not only delivered a functional and adaptable electro-lithography platform for the laboratory but also laid a strong technical foundation for future enhancements in precision lithographic techniques.