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Design and experimental validation of a multi-beam electron source

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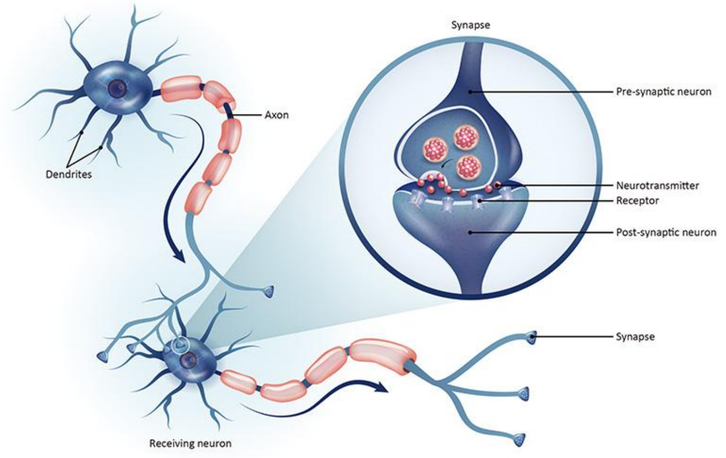
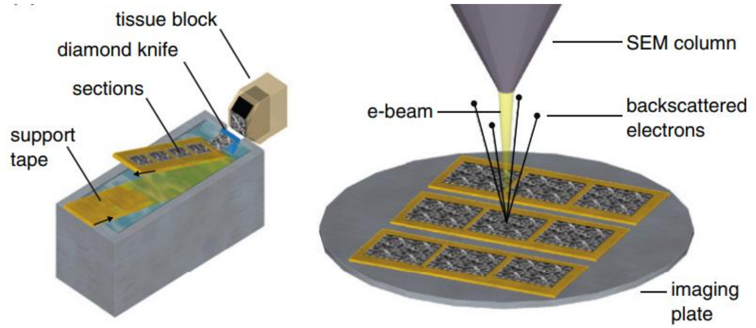
1. High-throughput demand for volume imaging

- **Application Scenario: Brain connectome Reconstruction**
  - The physical size of these structures are as small as 40–50 nm in diameter .
  - Volume size of 1 mm^3 is usually required.



Neuronal axons and dendrites and the synapses between them[1]

- **Conventional Solution: ATUM-SEM Serial Section Imaging**
  - Core Pain Point: Single-beam SEM requires over 500 days for tiny tissue volume, extremely low throughput.



Automated tape-collecting ultramicrotome scanning electron microscopy (ATUM-SEM)[2]

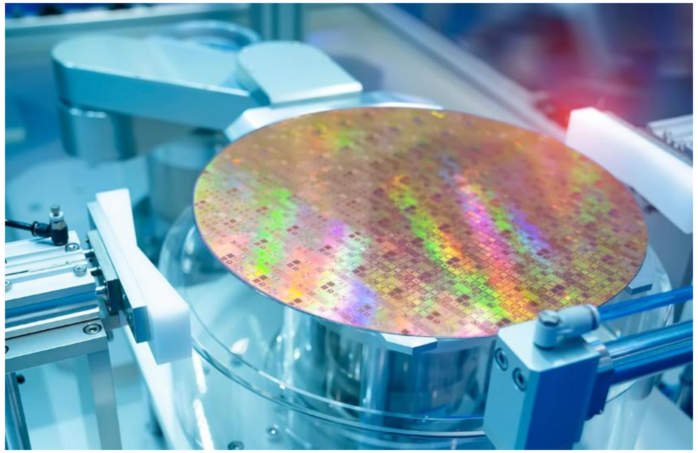
Mouse cortical column	400 μm× 400 μm× 1000 μm
Typical x, y resolution	4 nm
Typical z resolution	30 nm
Dwell time	0.1 μs
Total time (including overhead)	505 days

[1] https://www.genetex.cn/Research/Overview/neuroscience/neurites_synapses.
[2] Kevin L Briggman and Davi D Bock, 2012.

Background

2. High-throughput demand for wafer inspection and E-beam mask writing

➢ **Advanced Semiconductor Manufacturing Challenge**

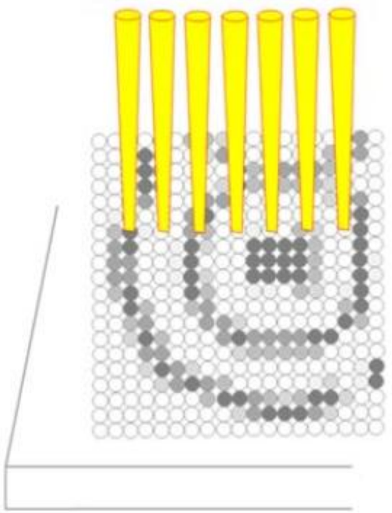


300 mm Wafer inspection[1]

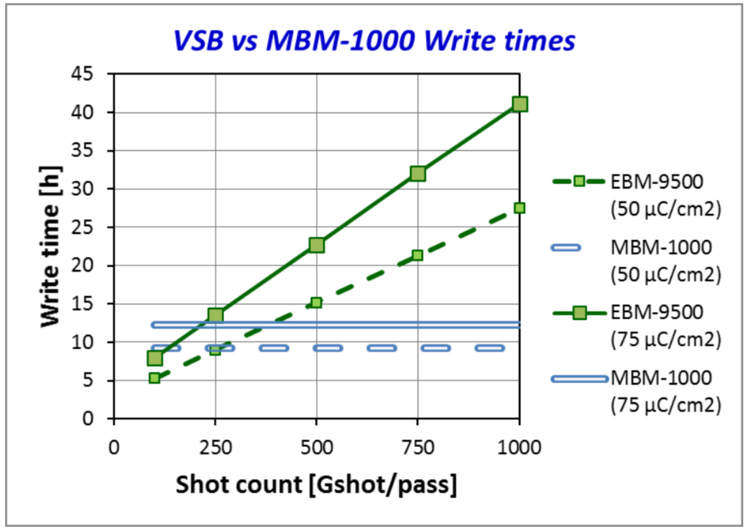
Full wafer	300 mm
Typical x, y resolution	10 nm
Pixels	7×10^{14}
Dwell time	20 ns
Single-beam sacn time	164 days

[1] https://ims-nl.com/2023/08/24/wafer-inspection/
[2] Jumpei Yasuda, et al., 2023
[3] Hiroshi Matsumoto, et al., 2016

➢ **Single-Beam vs Multi-Beam Mask Writing Comparison**



MB Writer: Parallel Writing Strategy[2]



Efficiency: VSB vs MBM Comparison[3]

- **Multi-beam is essential for nodes below 5 nm lithography;**
- **MB writing time is independent of pattern complexity;**
- **Significant advantage when shot counts exceed 200 Gshot/pass.**

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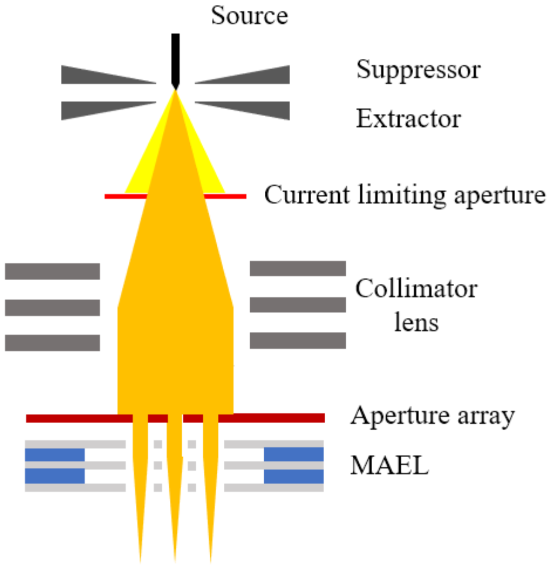
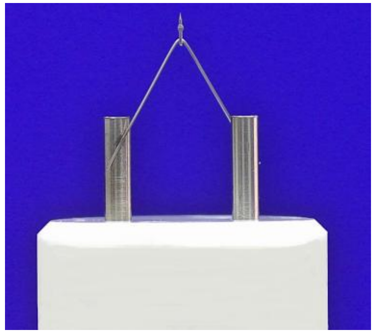
Multibeam electron source

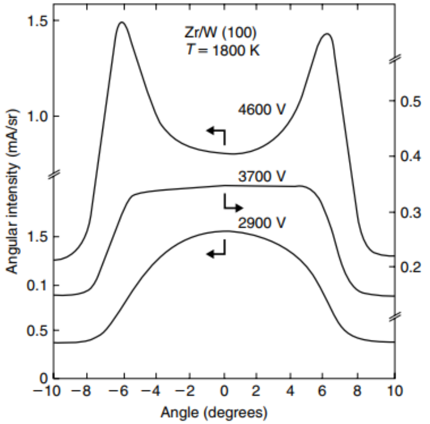
2.1 Overall Schematic of Multi-Beam Electron Source



Schematic design of multi-beam electron source. MAEL:micro-arrayed Einzel lens



Schottky Cathode



Measured angular intensity distribution of a Schottky electron source [1]

	Thermionic cathode (W)	Thermionic cathode (LaB6)	Schottky emission (ZrO/W)	Field emission (W)
Work function	4.5 eV	2.7 eV	2.7 eV	4.5 eV
Energy spread	1.5–3 eV	1–2 eV	0.3–0.7 eV	0.2–0.7 eV
Tip radius	60 µm	10 µm	0.5–1µm	<0.1µm
Cathode temperature	2500–3000 K	1400–2000 K	1800 K	300 K
Source diameter	20-50µm	10–20 µm	~15 nm	~2 nm
Reduced brightness (A/(m^2 sr V))	(1-5) ×10^4	(1-5) ×10^5	2×10^7-2×10^8	(2– 4) × 10^8
Lifetime	100 h	1000 h	>5000 h	>5000 h
Operating vacuum	<10^{-3} Pa	10^{-4} Pa	10^{-7} Pa	10^{-8} Pa

- **Schottky source is superior to other sources in terms of brightness, lifetime and stability.**
- **Schottky source can provide a limited emission half angle of about 100 mrad, in which the angular current density is reasonably constant.**

[1] Lyn W. Swanson and Gregory A. Schwind, "Review of ZrO/W Schottky Cathode" , in handbook of charged particle optics, 2nd edition, 2009, pp.1-28

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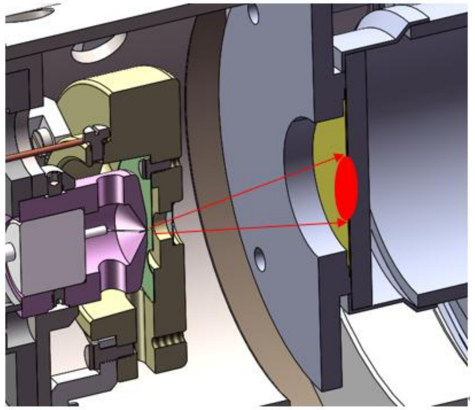
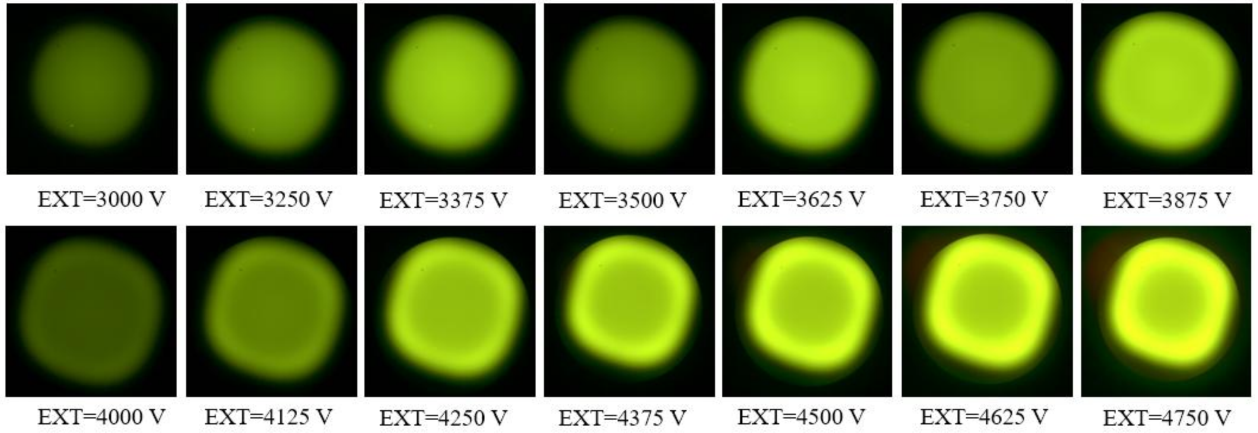
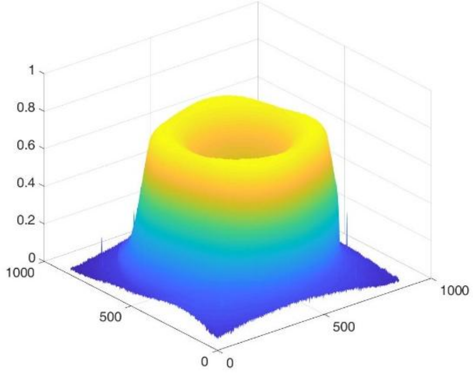
2.2 Angular Emission Characteristics & Per-Beam Current Calculation



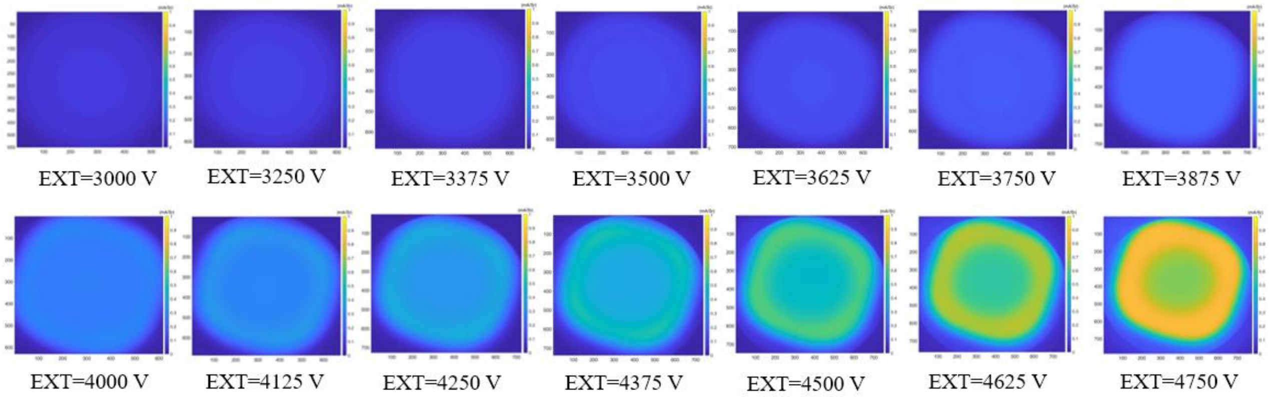
Angular current density measurement platform



Electron emission states from the filament with various extraction voltage. Tip radius: 0.7 μm, suppressor voltage = –300 V, filament heating current = 2.33 A.



3D plot of the angular distribution of emission current density from a Schottky source



The angular current density distribution after image processing.

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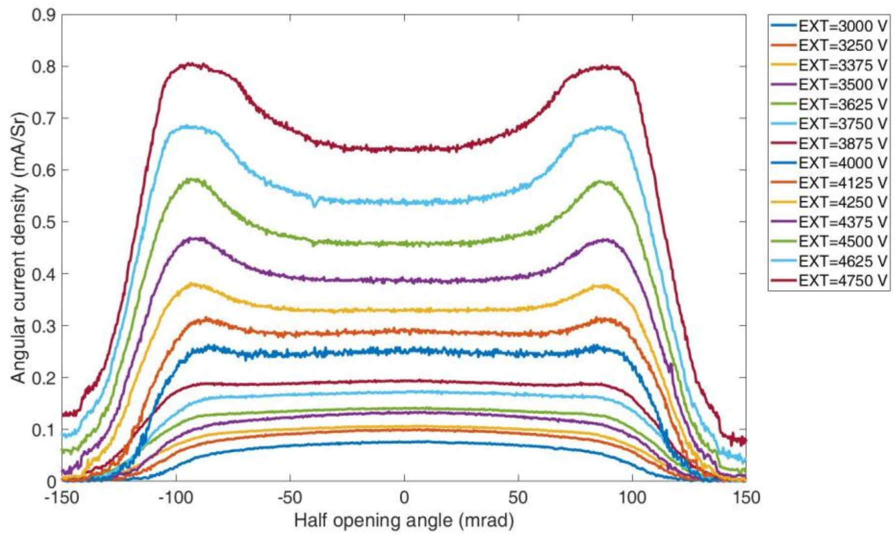
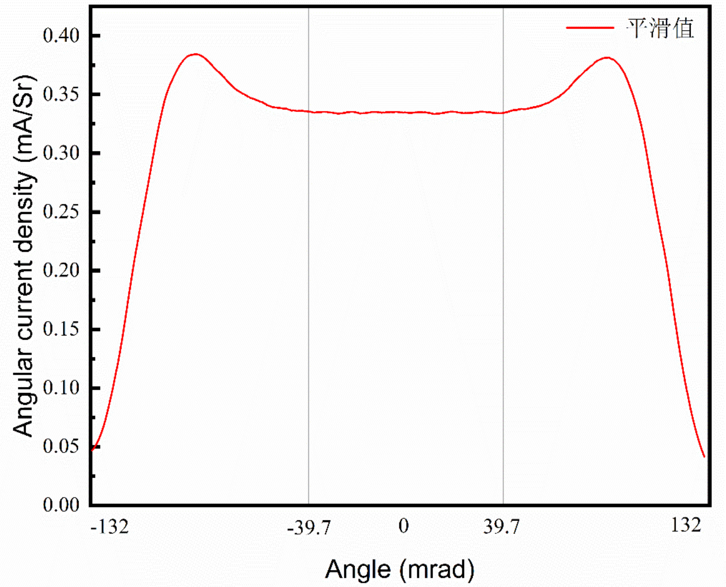
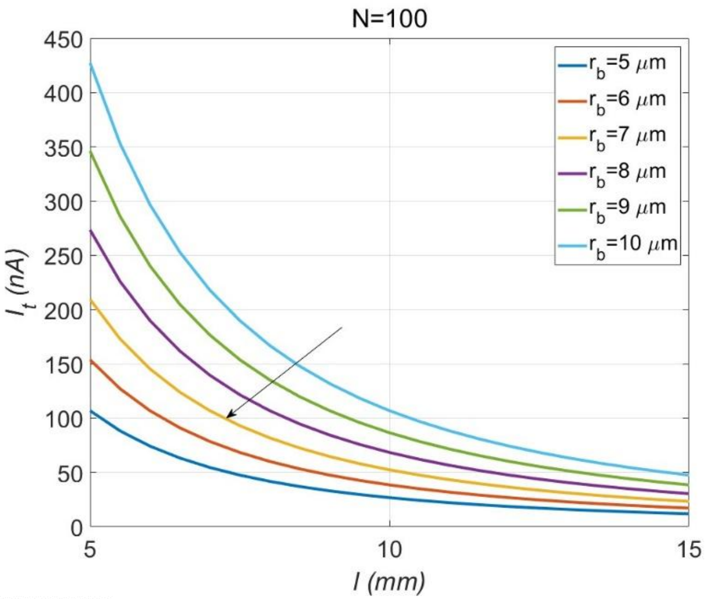
2.2 Angular Emission Characteristics & Per-Beam Current Calculation



Angular current density vs. extraction electrode voltage



At EXT = 4250 V, the angular current density is 0.34 mA/Sr， fluctuation is only 0.61% within a 39.7-mrad half-angle.



Total current calculation for a 10×10 aperture

It depends on the aperture size r_b and the distance l between source and collimator lens. If r_b=7 μm， l=7.5mm, the current per beam is about 1 nA when the current density is 0.34mA/sr.

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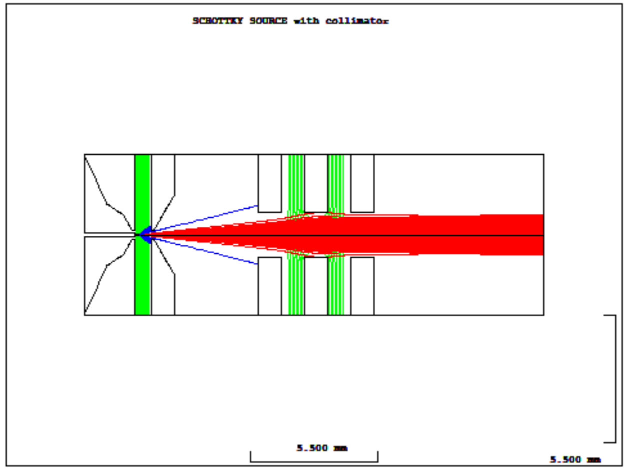
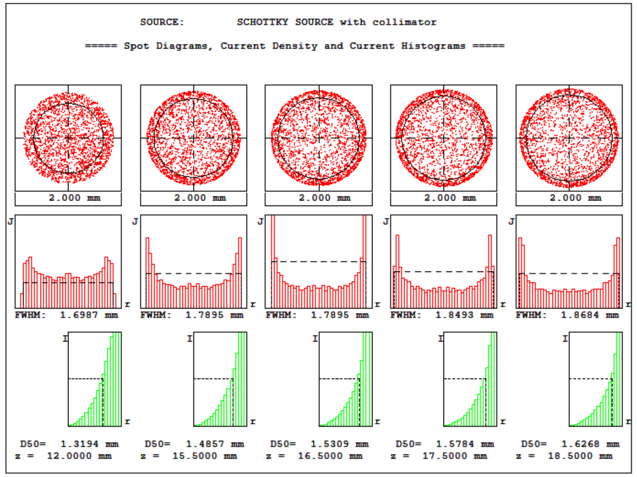
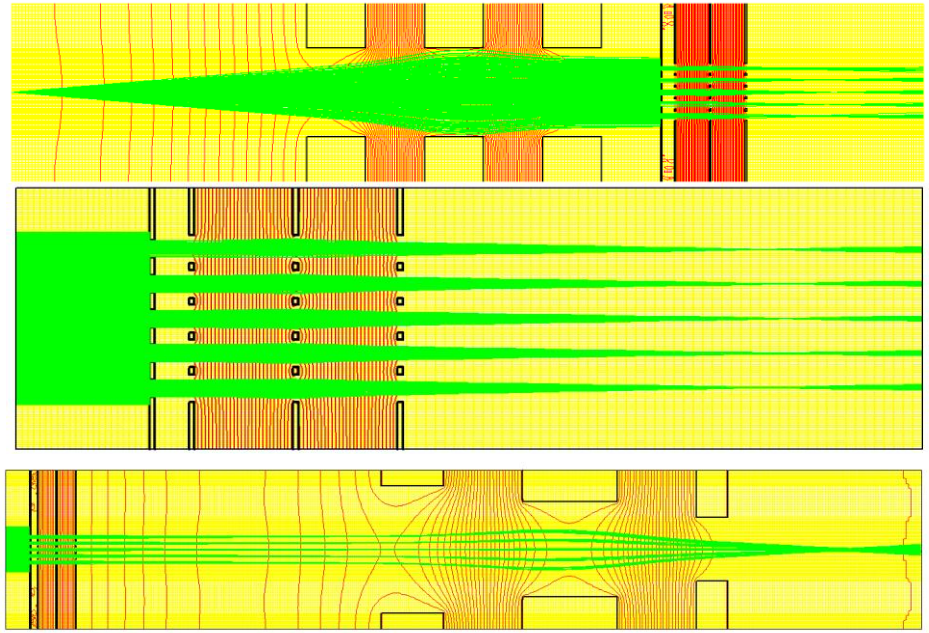
2.3 Electron Optical Simulation with Munro’ s Electron Beam Software (MEBS)





Simulation Setup: Schottky cathode + collimator lens optical path



Simulation of 3D trajectory trace

- **After collimation, the uniform current area on aperture plane covers ~1.2 mm diameter, suitable for 10×10 array layout;**
- **Virtual source size = 72 nm; final focused multi-beam spot diameter reaches 122 nm under ideal assembly (Emitter tip radius 0.9 μm).**

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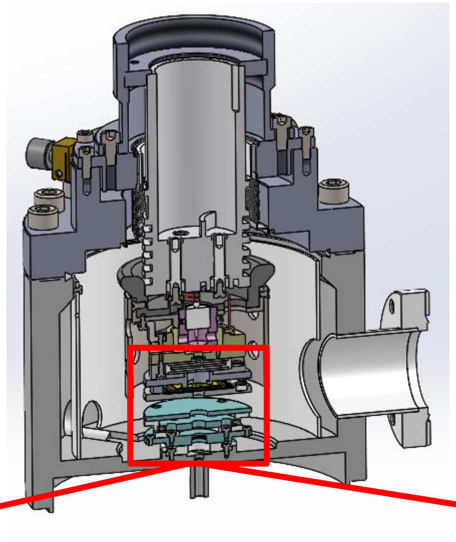
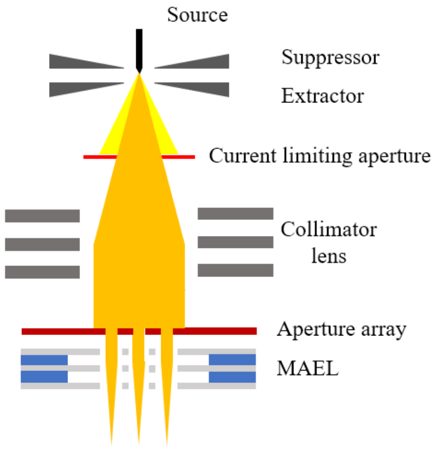
2.4 Mechanical Integration of Multi-Beam Electron Source

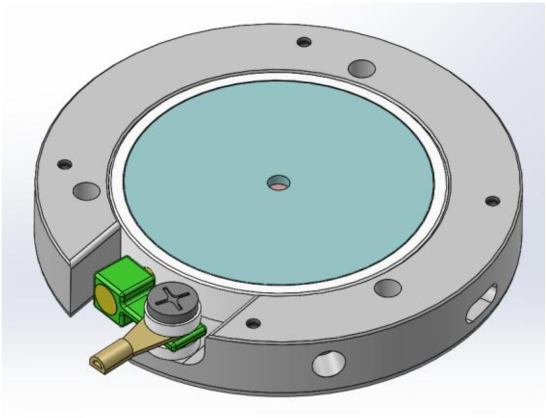
Main Engineering Challenges

- Ultra-precision MEMS micro-hole fabrication for aperture & MAEL arrays;
- Sub-micron level multi-layer electrode assembly alignment;
- High-voltage feedthrough design for stacked electrostatic lens electrodes.

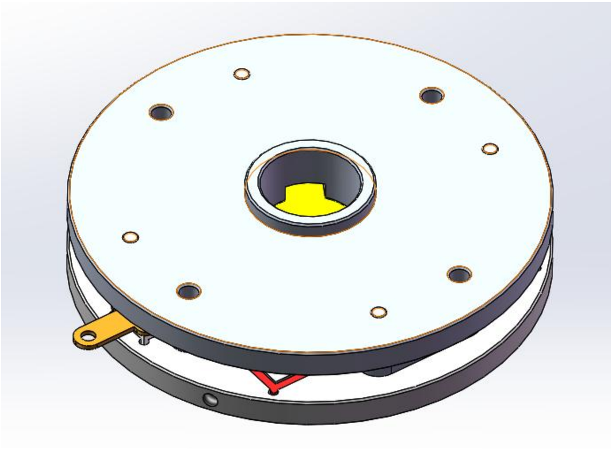




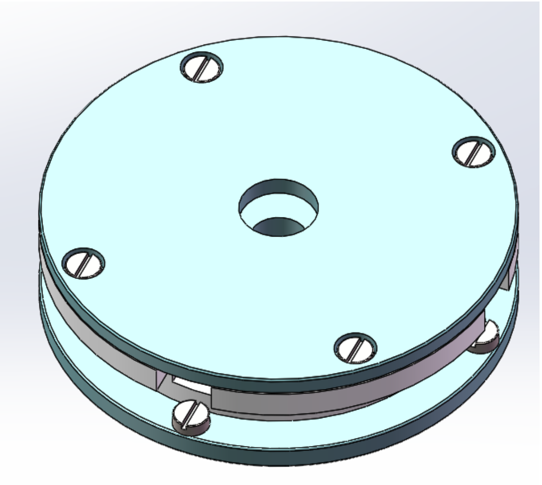
Three Core Integrated Modules



Collimator lens unit



MEMS based beam-splitting unit



Field lens unit

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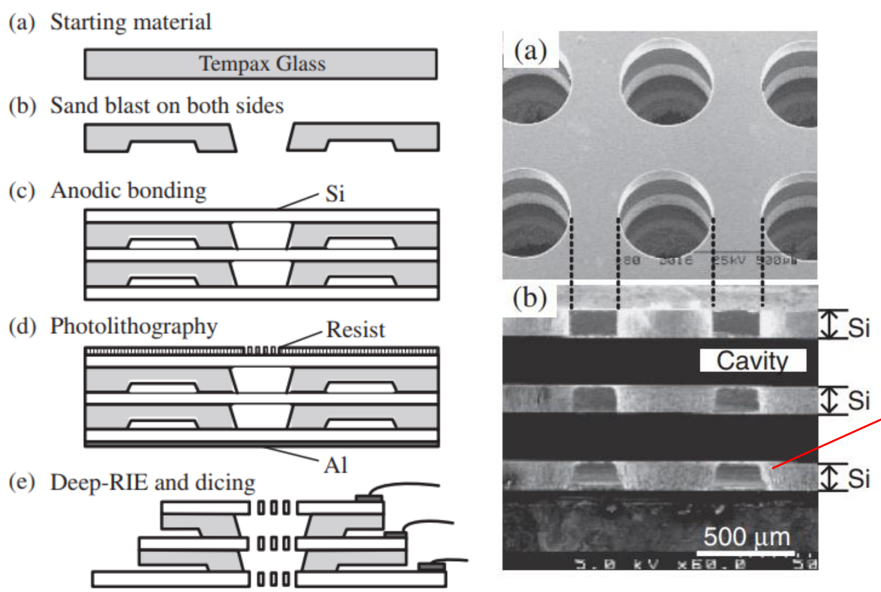
2.5 MEMS Fabrication Route Selection for MAEL Arrays

Route 1:Assemble first, then etch the micro-holes



Fabrication process of Einzel lens array[1]

The side wall of the hole appears trapezoid after processing .

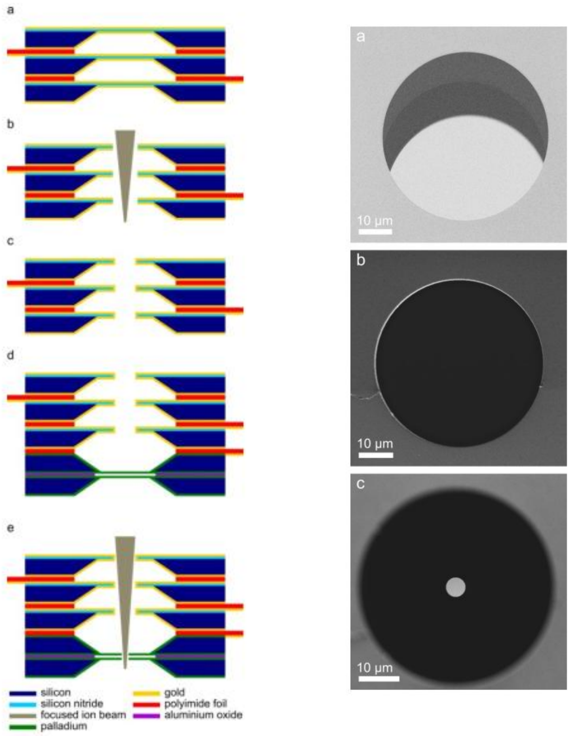


Illustration of the micro-column fabrication procedure[2]

Good quality, but slowly fabricate, not suitable for array hole processing

[1] Hidetoshi Miyashita et al., Japanese Journal of Applied Physics, 2011.
[2] Flavio Wicki et al., Ultramicroscopy, 2015

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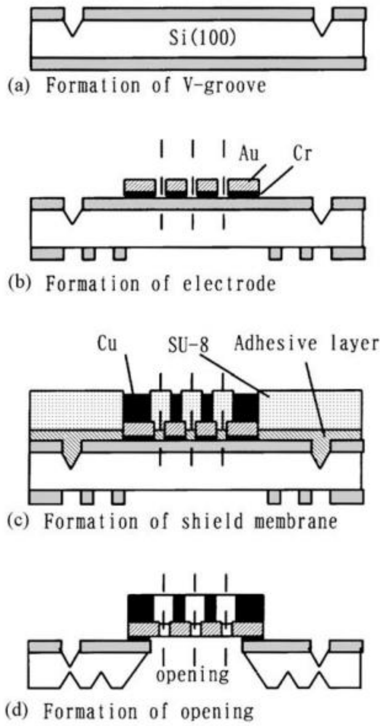
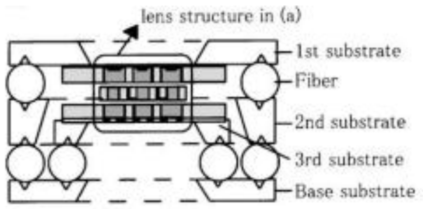
2.5 MEMS Fabrication Route Selection for MAEL Arrays

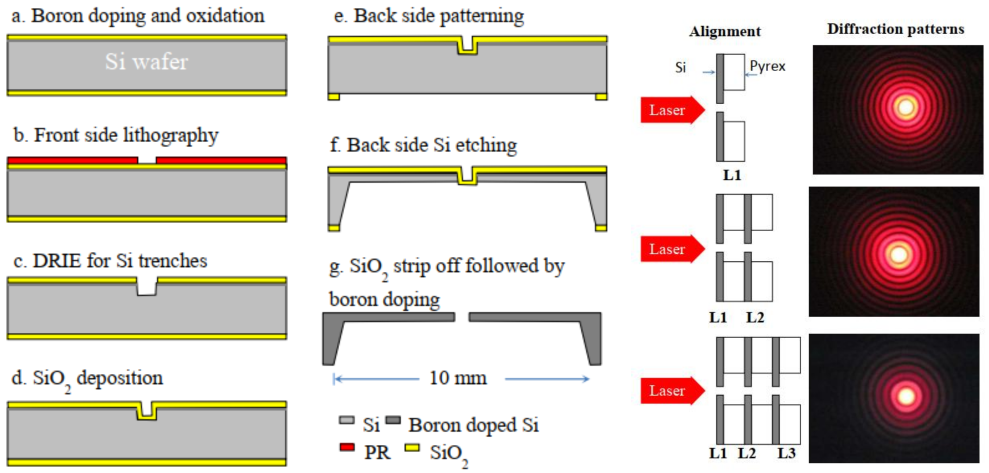
Route 2:Etch holes first, then precision assembly (Adopted in this work)



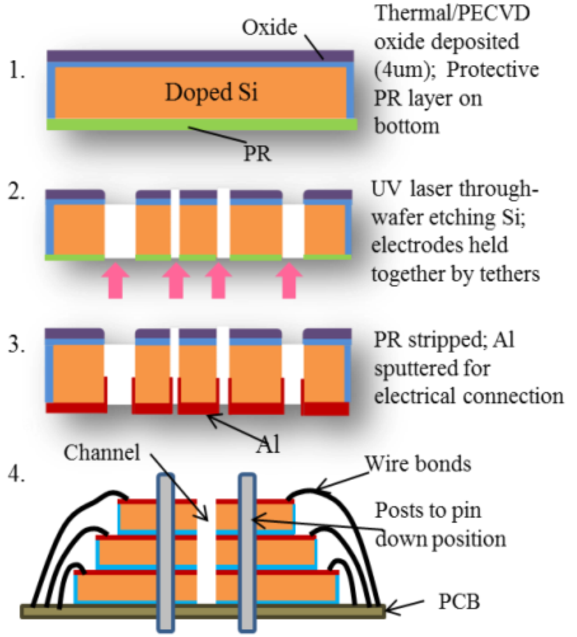


The fibres are put into the V-grooves between the electrodes, alignment accuracy is estimated to be ±5μm

Process sequence of the electrode based on MEMS technique [1]



Fabrication process of an electrostatic lens based on MEMS technique. Alignment technique based on laser diffraction pattern, the misalignment was measured to be ~0.75 μm [2]



Fabrication based on Laser-cut and assembly, the roughness of the side wall is about 10 μm [3]

In this work, we adopt this second route to keep high fabrication precision, and developed a dedicated high-precision assembly tool to solve the alignment.

[1] Haruhito Ono et al., Sensors and Actuators, 2002.
[2] Om Krishna Suwal et al., Advanced Materials Research, 2013
[3] Yue Shi et al., International conference on MEMS, 2013

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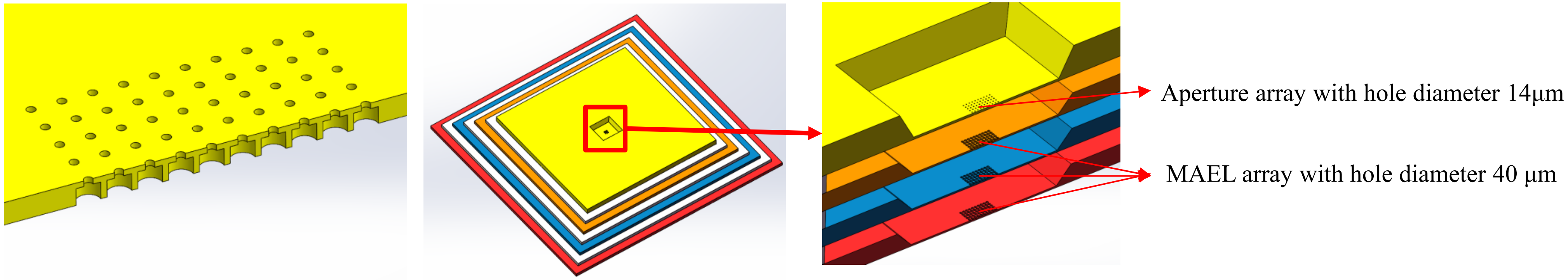
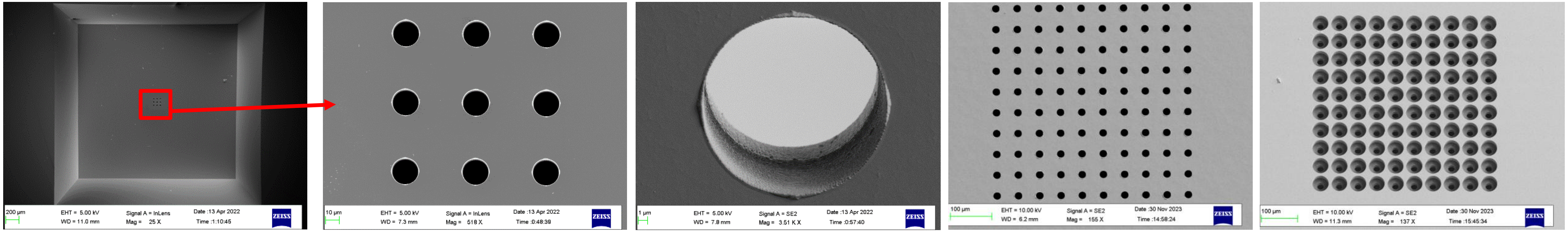
2.6 Fabricated MEMS Aperture & MAEL Array Characterization



Mechanical design of aperture and micro-arrayed Einzel lens



SEM images of 3×3 aperture array and 10×10 aperture array

Micro-holes exhibit circular vertical sidewalls with consistent diameter across the whole 10×10 array, no obvious dimensional deviation at edge units.

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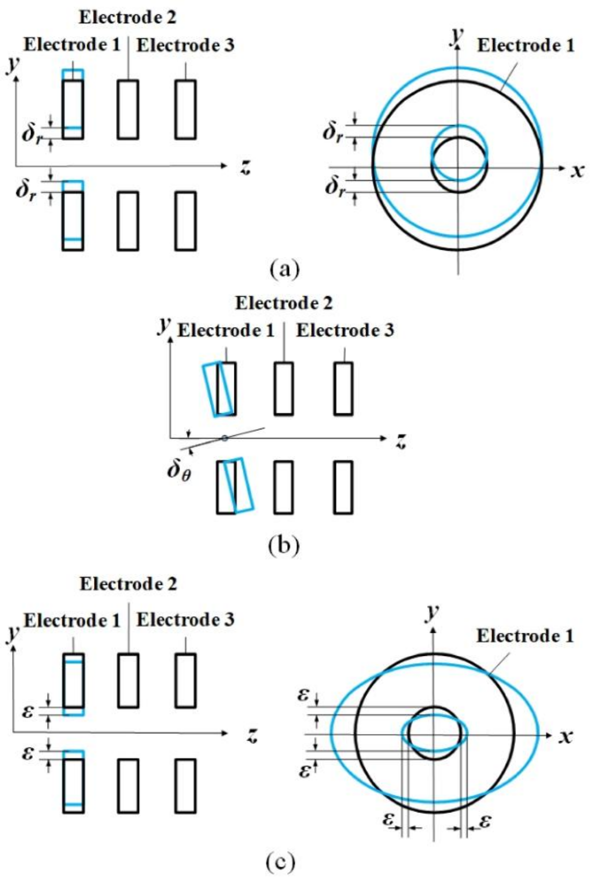
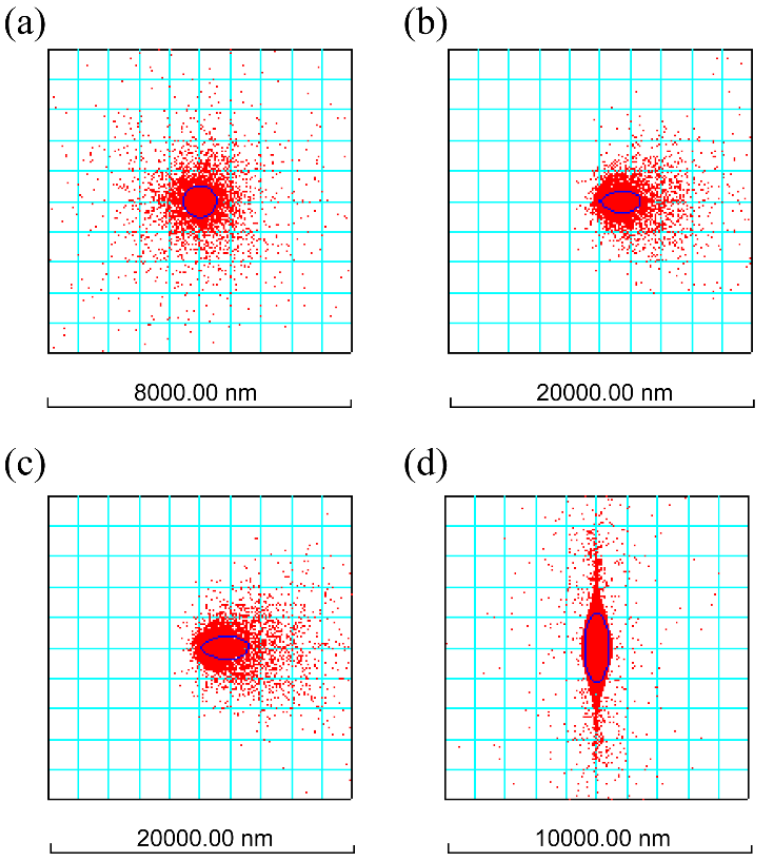
2.7 Influence of Assembly Errors on Multi-Beam Spot Quality

Three Typical MAEL Asymmetric Errors:

1. Lateral misalignment between electrode layers
2. Angular tilt of Einzel lens plates
3. Electrode hole ellipticity deformation



Schematic diagram of asymmetry error of MEL. (a) lateral misalignment; (b) angular tilt; (c) ellipticity .



The gaussian beam spots with and without asymmetry errors

[1] **Lixin Zhang*, et al.. "Accuracy requirements of the microarrayed Einzel lens," Journal of Vacuum Science and Technology B, vol. 40, p. 014203, 2022.**

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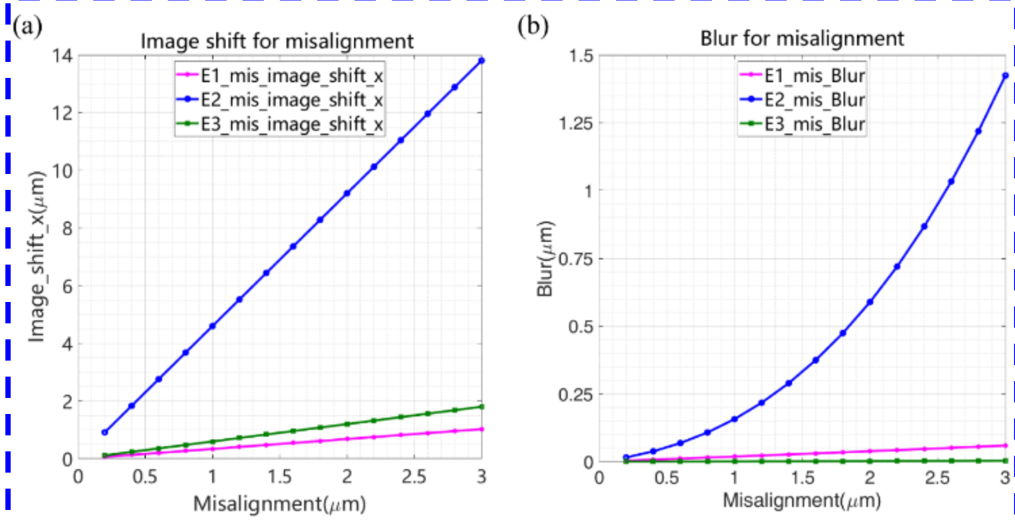
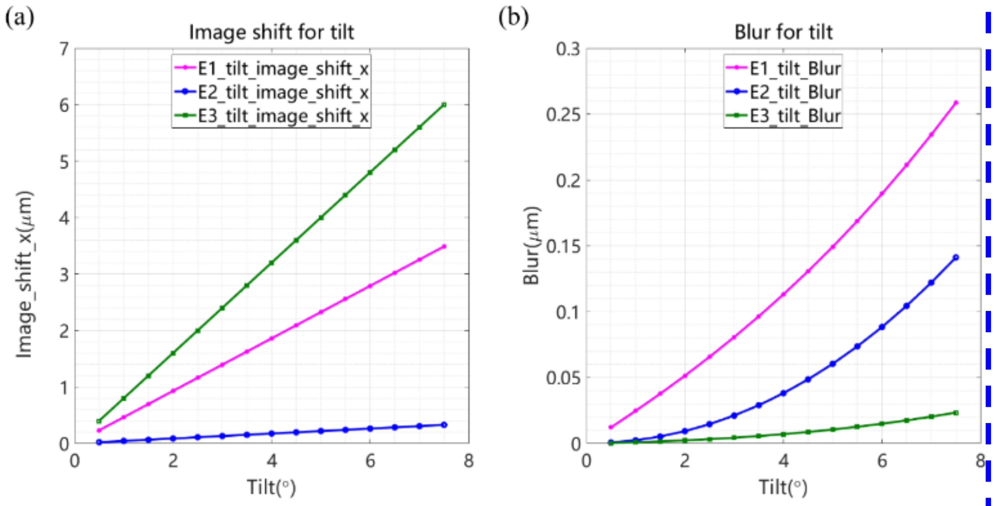
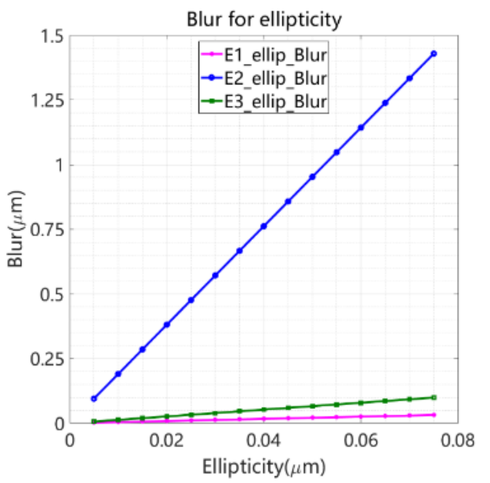
2.7 Influence of Assembly Errors on Multi-Beam Spot Quality



a)Image shift and (b) blur induced by misalignment of each electrode.



(a)Image shift and (b) blur induced by tilt of each electrode.



Blur induced by ellipticity of each electrode.

Quantitative Tolerance Conclusion：

- **Middle electrode alignment error dominates beam quality degradation;**
- **Target spot size 10 nm: max allowable misalignment=2.7 µm, tilt=1 mrad, ellipticity=60 nm;**
- **Target ultra-fine 1 nm probe: tolerance tightened to 0.8 µm shift, 0.7 mrad tilt, 6 nm ellipticity.**

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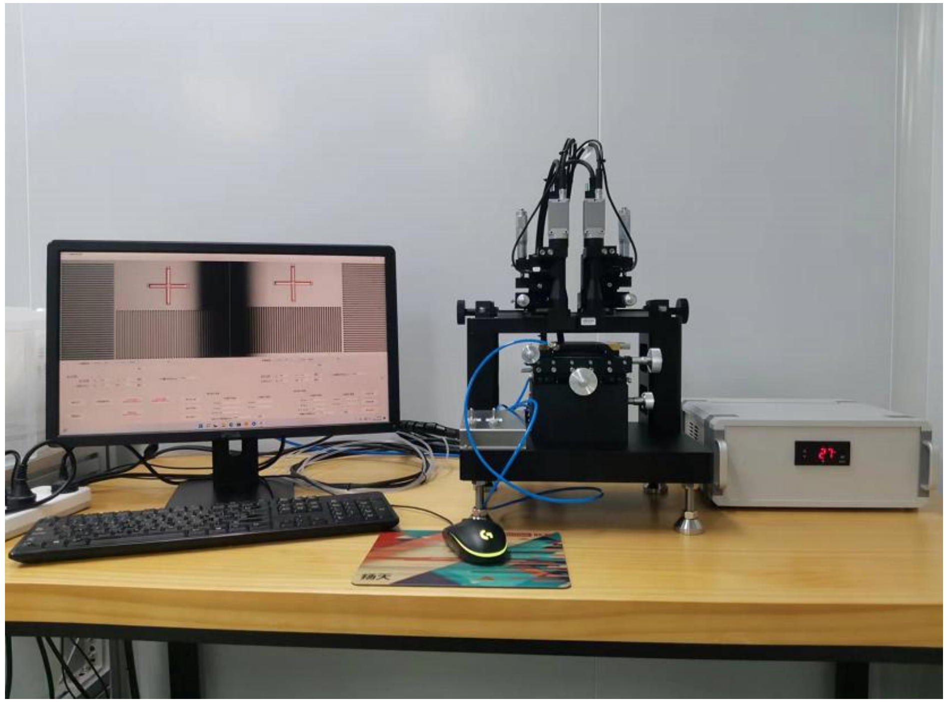
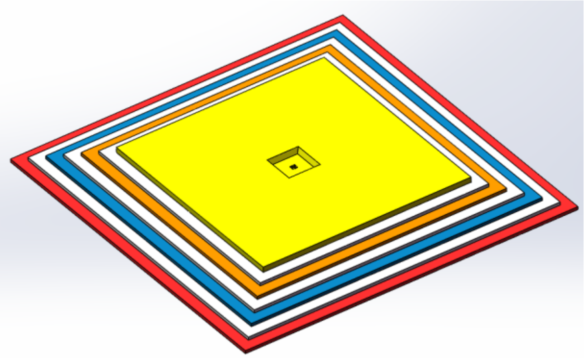
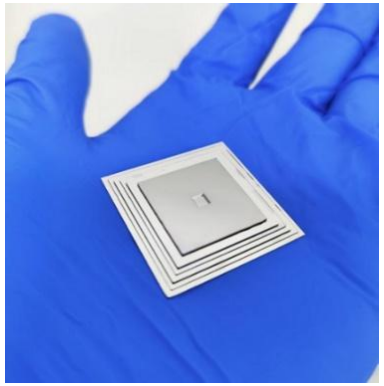
2.8 Dedicated High-Precision Assembly Platform Development



Design target:

- Lateral alignment accuracy: ≤ 500 nm;
- Azimuth angle accuracy θ: ≤ 0.1mrad;
- Parallelism between two plates : ≤ 3mrad;
- Applicable device dimension: 1 cm—5 cm;





Mechanical design and image of the assembly

The actual assembly error could be <200nm, exceeding original design target .

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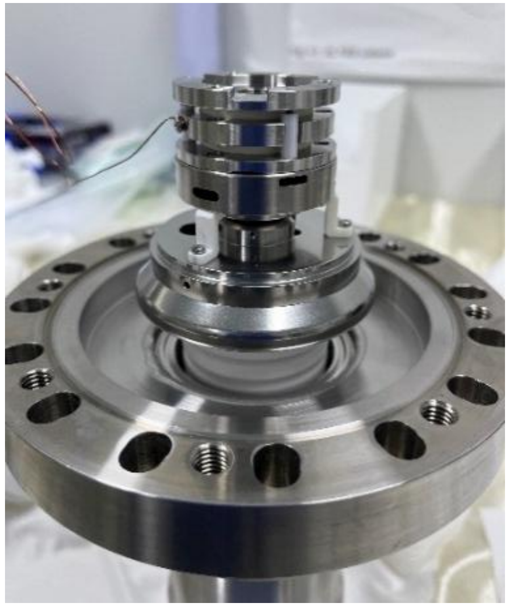
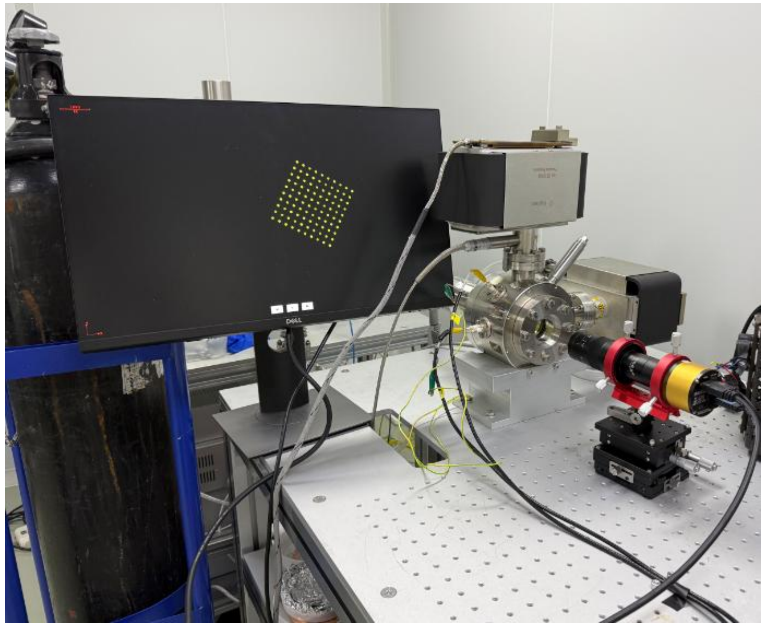
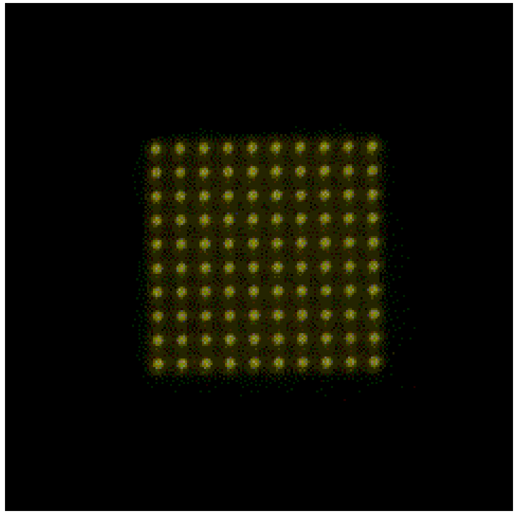
3.1 Experimental Setup & 10×10 Multi-Beam Observation



The multibeam electron gun



The experimental setup



Captured10×10 electron beams

Stable 10×10 uniform electron beam array was successfully extracted from single Schottky cathode for the first time in our lab in May, 2025.

Operating parameters:

- Filament heating current：2.35A；
- Suppressor voltage：-180V；
- Extractor voltage：5000V；
- Collimator voltage：4800V；
- Accelerating voltage：5000V；
- Focusing voltage tuning range:0 – 2600 V.

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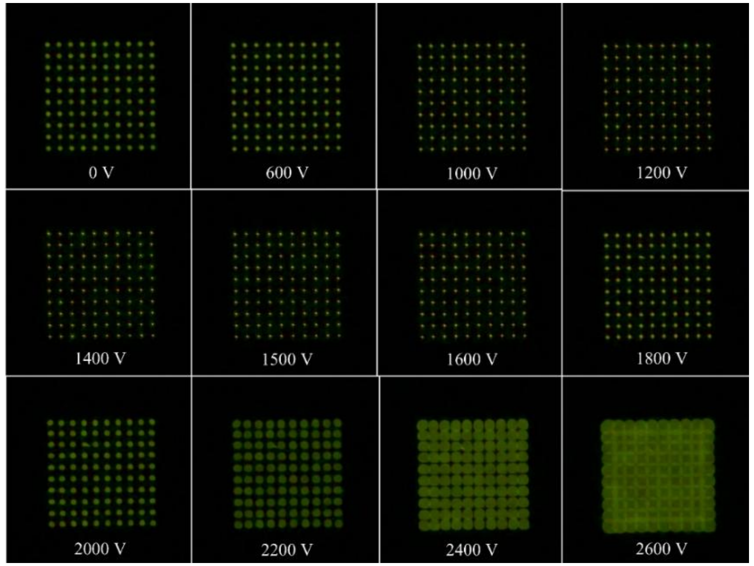
3.2 Influence of Focusing Voltage on Beam Spot Size & Uniformity

Quantitative Test Results

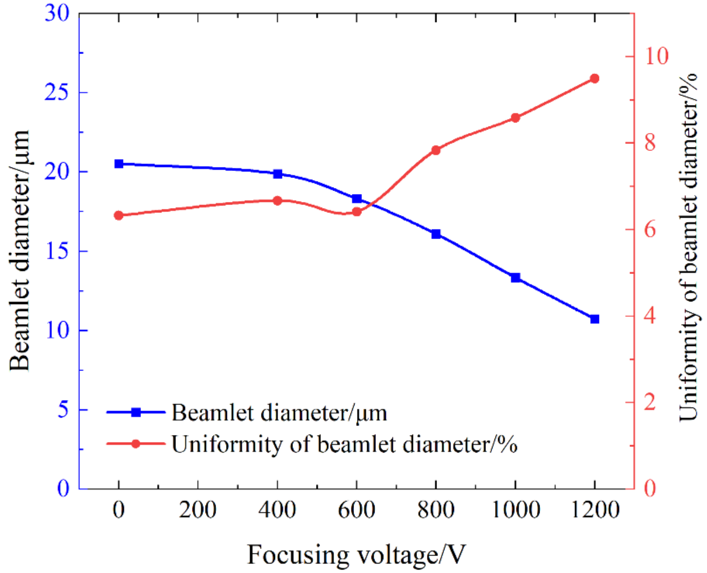
1. Sub-beam spot size evolution
- With focusing voltage rising from 0 V to 1200 V, the average diameter of each beamlet decreases from 20.88 μm to 10.74 μm.

2. Array uniformity performance
- The diameter uniformity of all 10×10 sub-beams is maintained within 10% across the entire focusing voltage tunning range.
- The measured current of a beamlet is about 0.23 nA.

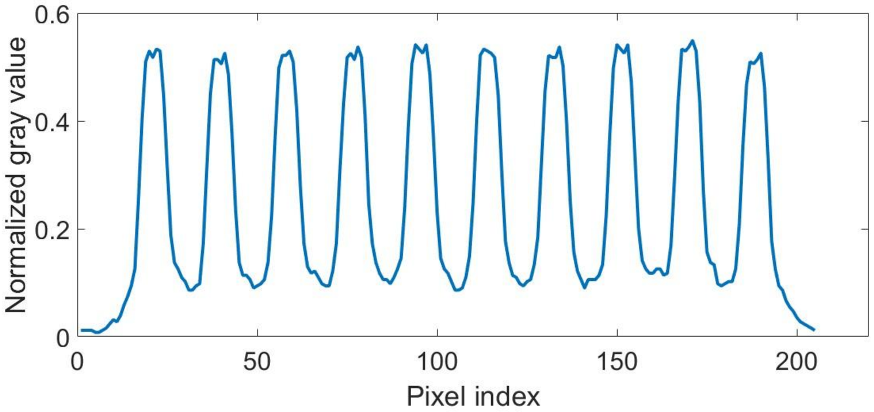
3. Trend analysis
- Spot size continuously shrinks with rising focusing voltage; beam uniformity slightly degrades at high focusing voltage but still meets application requirement.



Beam array snapshots captured under focusing voltage from 0 V to 2600



Dual-axis curve: Beamlet diameter (blue) & diameter uniformity (red) vs focusing voltage



Brightness distribution profile of the beamlet along the horizontal direction.

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Summary

- **Core Achievements:**

1. Fabricated high-precision MEMS aperture array and micro-arrayed Einzel lens (MAEL) for multi-beam splitting;
2. Developed a high precision assembly setup, actual lateral error <500 nm;
3. Realized a stable 10×10 multi-beam electron source based on ZrO/W Schottky cathode; sub-beam uniformity within 10% across full focusing range.

- **Existing Limitations:**

1. Single sub-beam current (~0.23 nA) needs further promotion for faster imaging;
2. Beam spot size still requires compression to sub-100 nm level (in the filed lens plane).

- **Future Work**

1. Optimize the collimator optics to boost angular current density;
2. Integrate multi-beam source into a prototype SEM for parallel imaging verification.

Thank you for your attention!

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Acknowledgements:
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