

**MeV Arc 2025**



**四川大学**  
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# Preliminary Results of Ion Implantation to Improve the Insulation of Non-arcing Metal Vacuum Gap in Vacuum Interrupter

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1

## **Background and Motivation**

- Undesired breakdown locations in vacuum interrupters
- Why use ion implantation?

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## **DC voltage withstand test, surface morphology, and surface performance analysis at 0.5mm gap**

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## **DC voltage withstand test, surface morphology, and surface performance analysis at 3-5mm gaps**

4

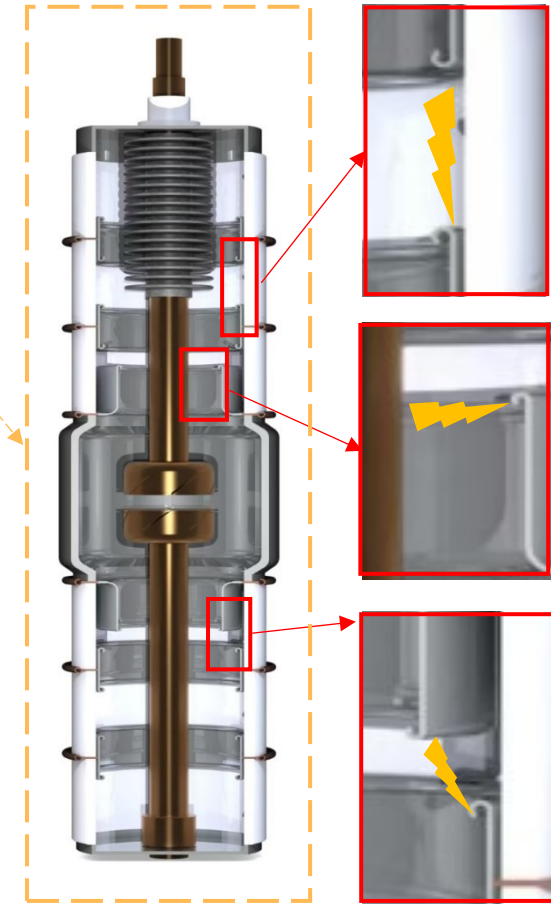
## **Conclusions**

- **Undesired breakdown locations in vacuum interrupters**

- The vacuum interrupter is the core of the vacuum circuit breaker, which undertakes most of the insulation properties of the circuit breaker.
- High-voltage, high-capacity vacuum interrupters adopt a multi-stage suspended shield structure.
- Breakdown can occur in unintended metal gaps, such as **between shields** or **between shields and conductive rods**.
- It is essential to enhance the withstand voltage performance of these gaps.



Vacuum breaker

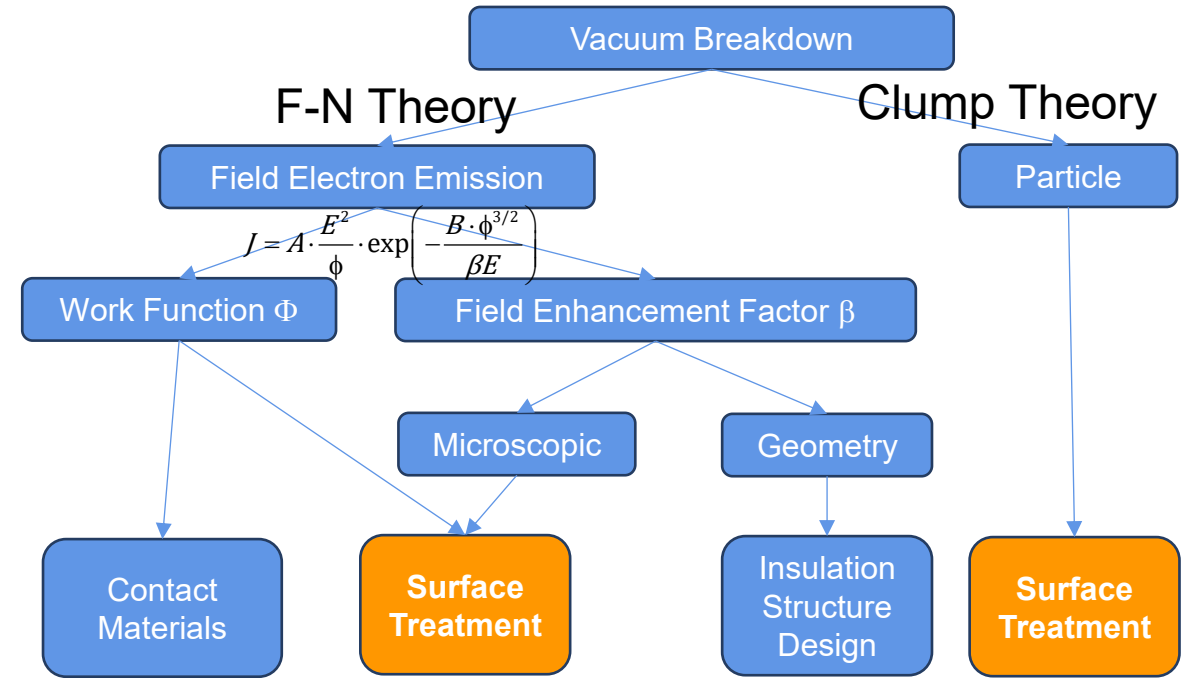


Vacuum interrupter

Undesired  
breakdown locations

- Why try ion implantation?
- Enhance vacuum gap insulation properties: **reducing field emission**、**suppressing particulate contamination**.
- The approaches : material、 structural optimization、 **surface treatment**.
- The commonly used surface treatment techniques in vacuum interrupter:
  - 1) Degreasing
  - 2) Acid cleaning
  - 3) Grinding
  - 4) Polishing
  - 5) Conditioning

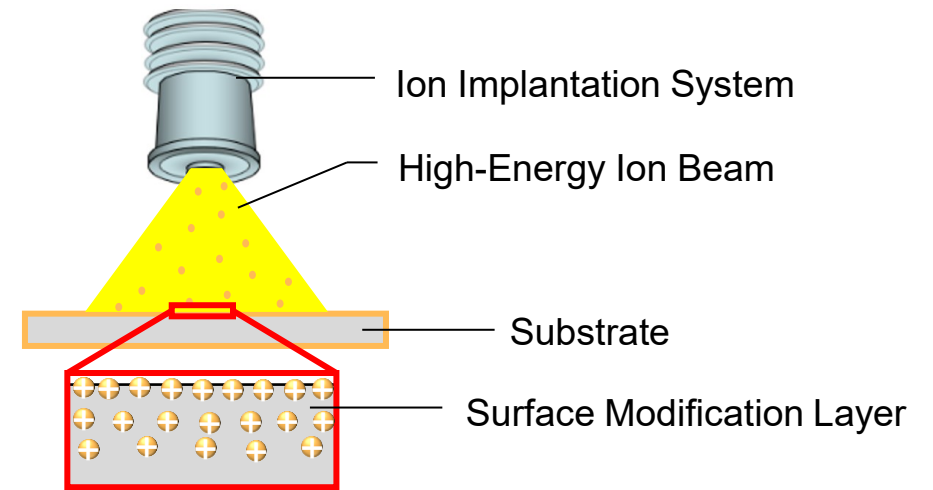
➔ suppress the microscopic enhancement factor but may damage the insulation of the surface
- **Other method to improve vacuum gap withstand voltage without conditioning?**



Breakdown traces after shields conditioning

- Why try ion implantation?

- Ion implantation technology involves bombarding and embedding high-speed ions into the substrate surface, creating a surface layer with unique physical, chemical, and mechanical properties.
- Proper ion implantation can enhance **the wear resistance, oxidation resistance, corrosion resistance**, fatigue resistance and high-temperature performance of metallic materials.
- Can ion implantation of **high-melting-point/ high hardness** metals on non-arcing surfaces enhance gap withstand voltage?

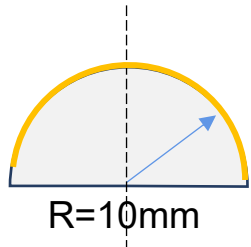


Ion implantation schematic

Metallic material	Melting point/°C	Hardness /HV	Work function
Mo	2623	250-300	4.36-4.95
Ta	3017	120-200	4.12-4.25

# EXPERIMENTAL SETUP

- Insulation test different gap: 0.5mm
- Preliminary verification under 0.5mm gap



SUS

SUS+Ta

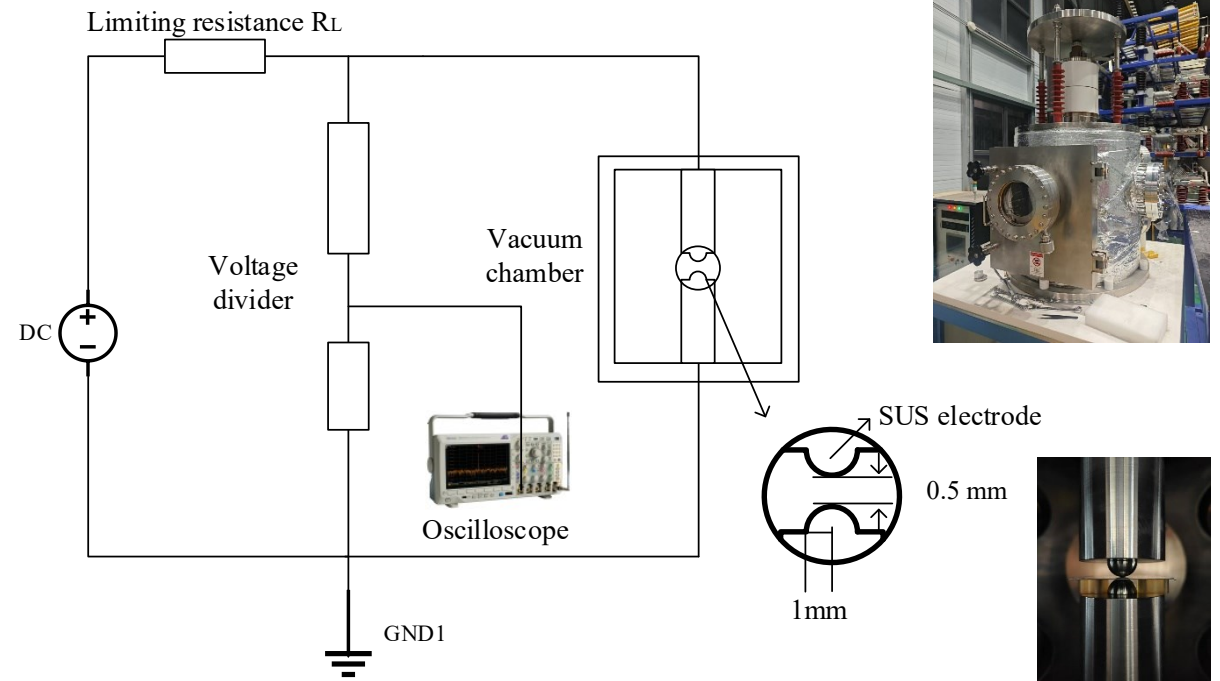
SUS+Mo

Ion implantation elements	Accelerating voltage/kV	Ion implantation dose/ions·cm <sup>-2</sup>
Mo	35	$3 \times 10^{17}$
Ta	35	$3 \times 10^{17}$



Ion implanter

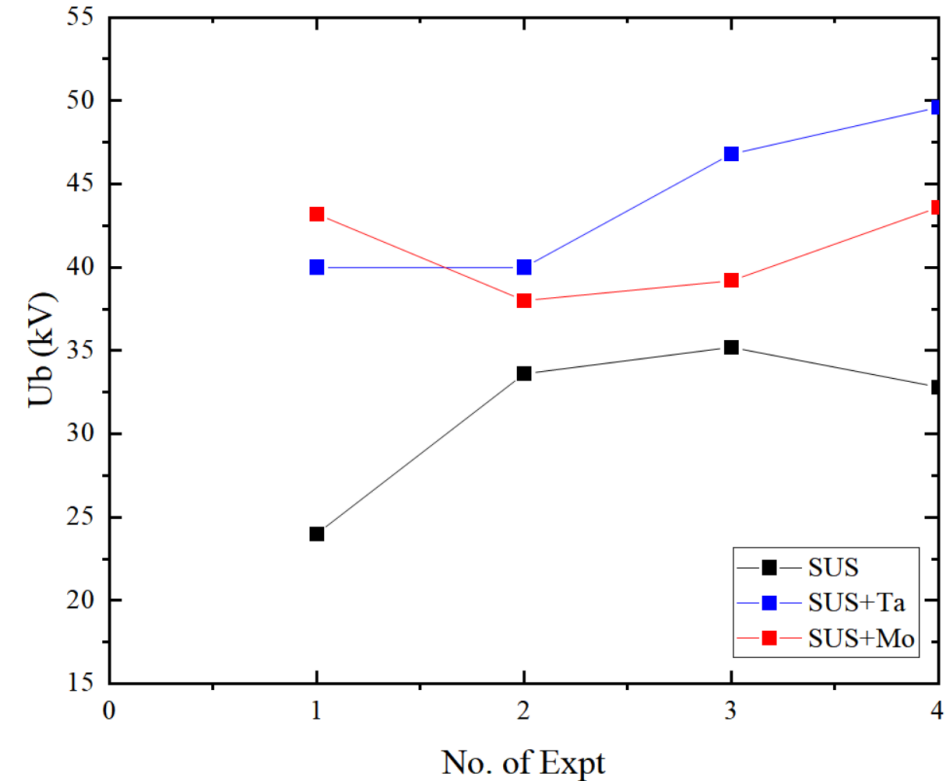
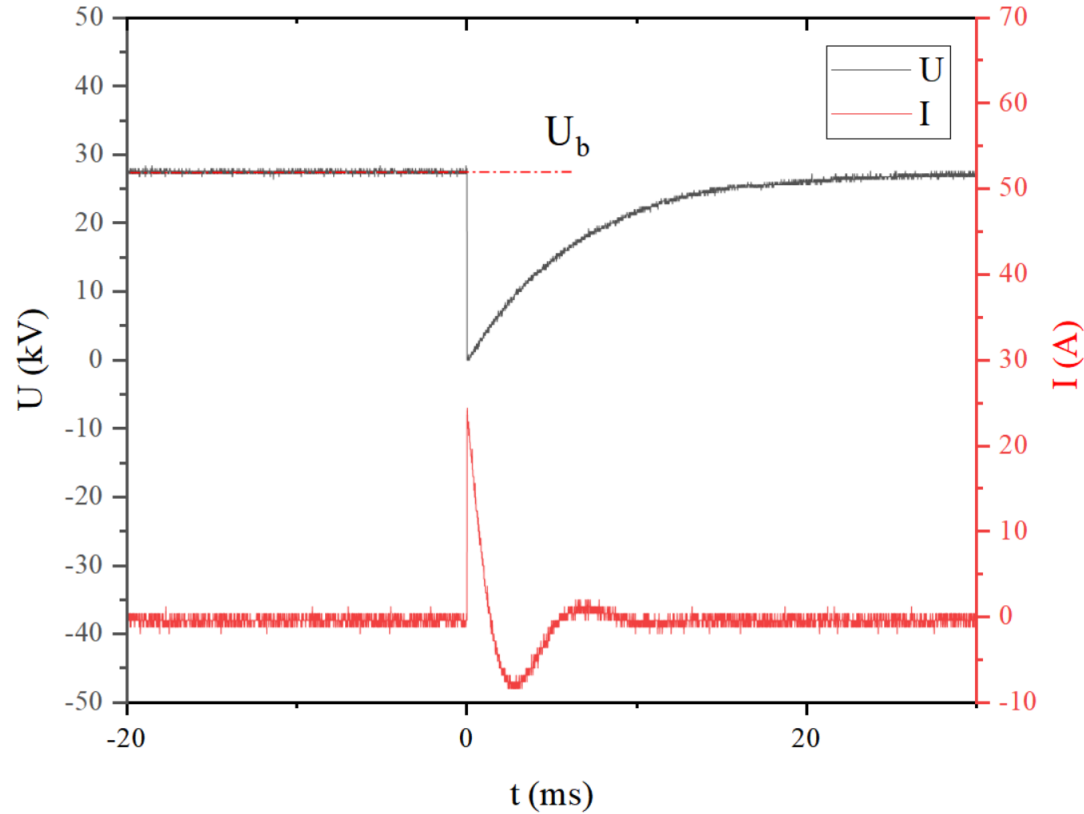
- Implantation Substrate: **Stainless Steel**
- consistent surface treatment
- Select appropriate parameters to ensure a better treatment effect on the electrode surface



Schematic diagram of the experimental setup

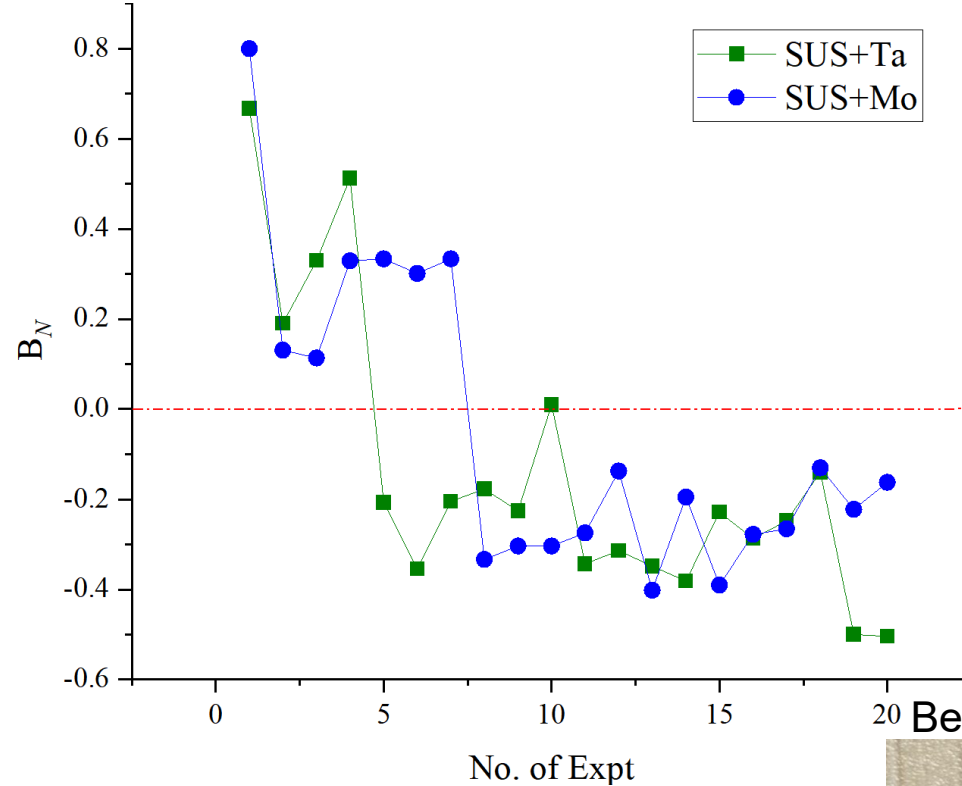
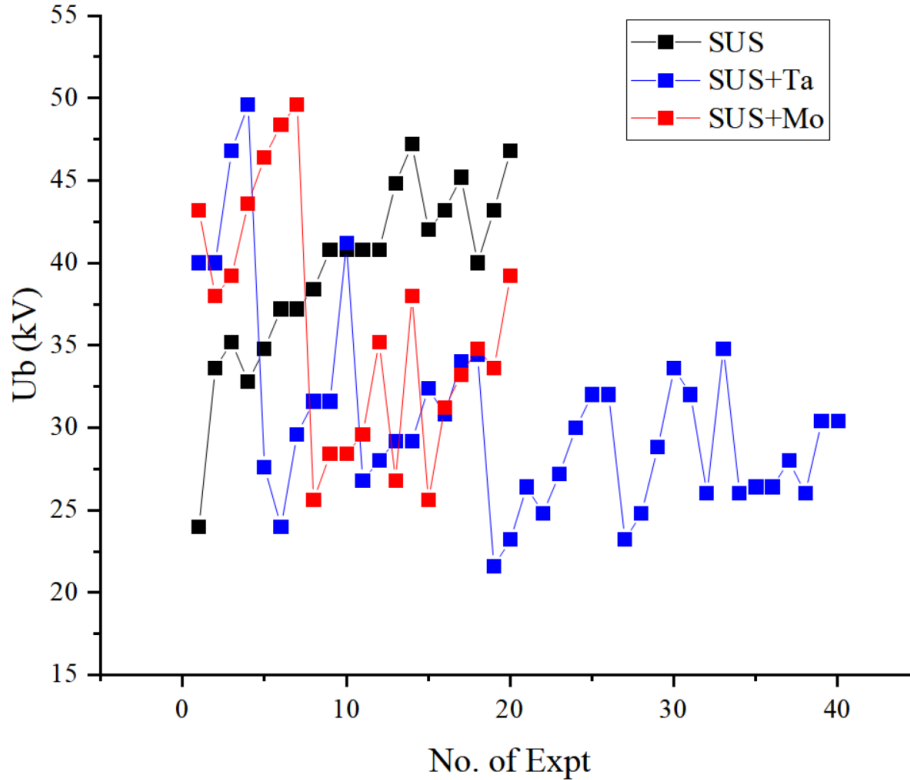
- Discharges occurred in demountable vacuum chamber
- A ball-ball electrode were installed with a 0.5mm gap
- The DC source provides 0-100kV high voltage with a rise rate of 1kV/s

- Insulation test gap: 0.5mm DC source



- Ion implantation effectively enhances the initial breakdown voltage
- The breakdown voltage and current is obtained by recording the waveform with an oscilloscope

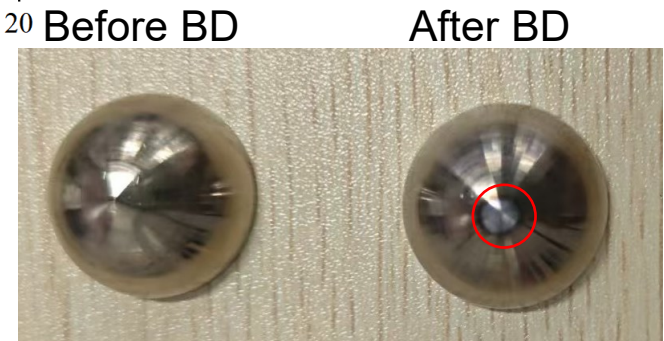
- Insulation test gap: 0.5mm DC source



$$B_N = \frac{U_{bi}^i - U_{bi}^{noi}}{U_{bi}^{noi}}$$

Parameter  $B_N$  reflects the significance of the increase in breakdown voltage

- The non-ion-implanted sample showed obvious conditioning effect.
- After a brief voltage rise, the breakdown voltage drops rapidly. The cause is presumed to be the destruction of the ion implantation layer.



- Insulation test gap: 0.5mm DC source

## Surface morphology-Ion implanted Mo

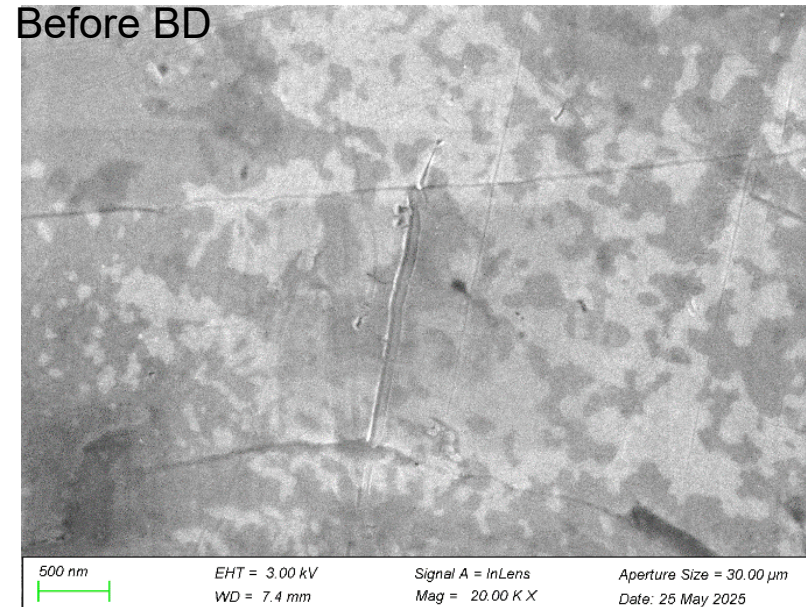
Scanning Electron Microscope(SEM) test



Analysis location

Before BD

After BD

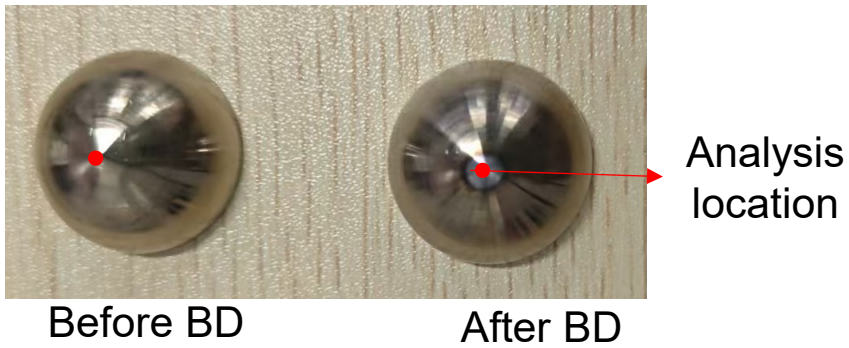


- Before breakdown, Uniform and fine nanostructures appears on the surface of the ion-implanted sample
- After breakdown, the surface becomes uniform due to arc ablation and loses its regional characteristics

- Insulation test gap: 0.5mm DC source

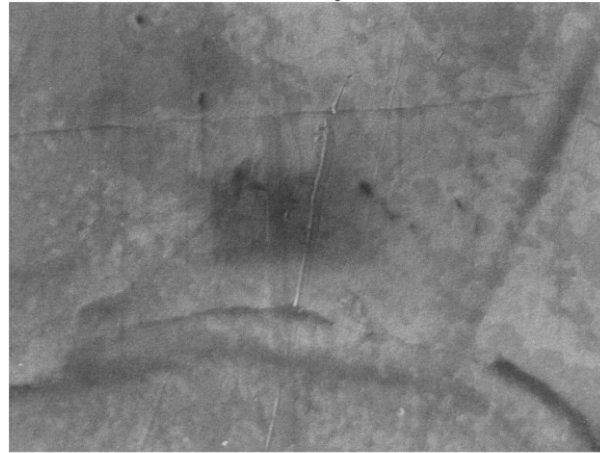
## Surface morphology-Ion implanted Mo

## Energy Dispersive Spectroscopy (EDS) test

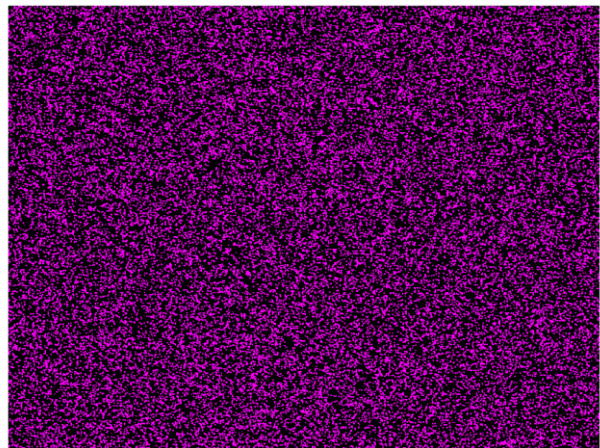


Before BD

Electron Image 1

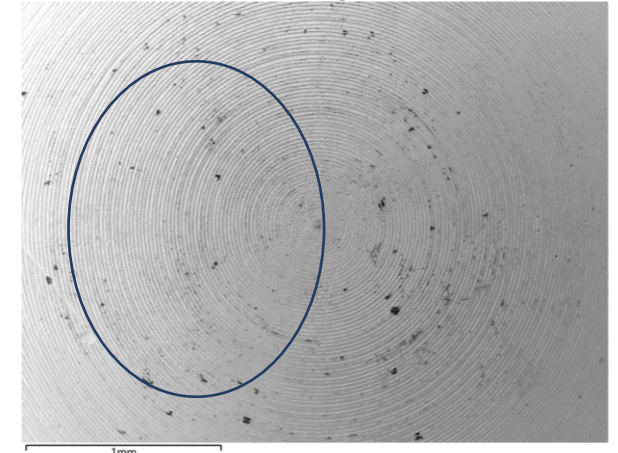


Mo L $\alpha$ 1

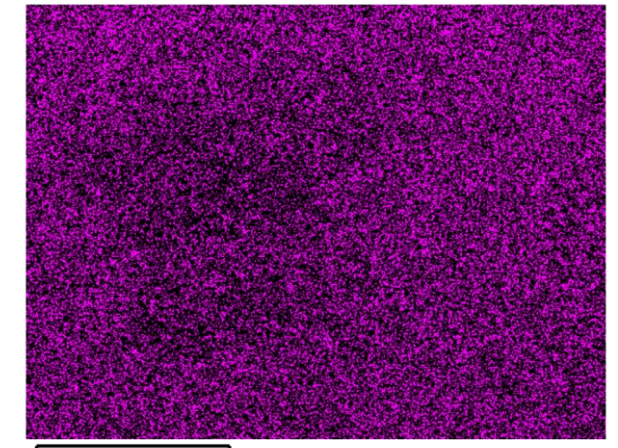


After BD

Electron Image 5



Mo L $\alpha$ 1

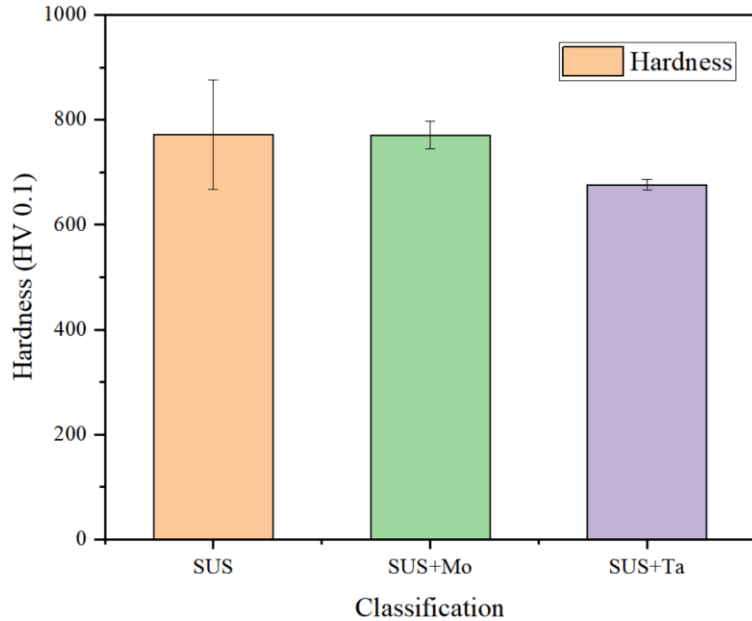


- Before breakdown, EDS can't detect elemental differences in different regions.
- After breakdown, the surface Mo elements are unevenly distributed.

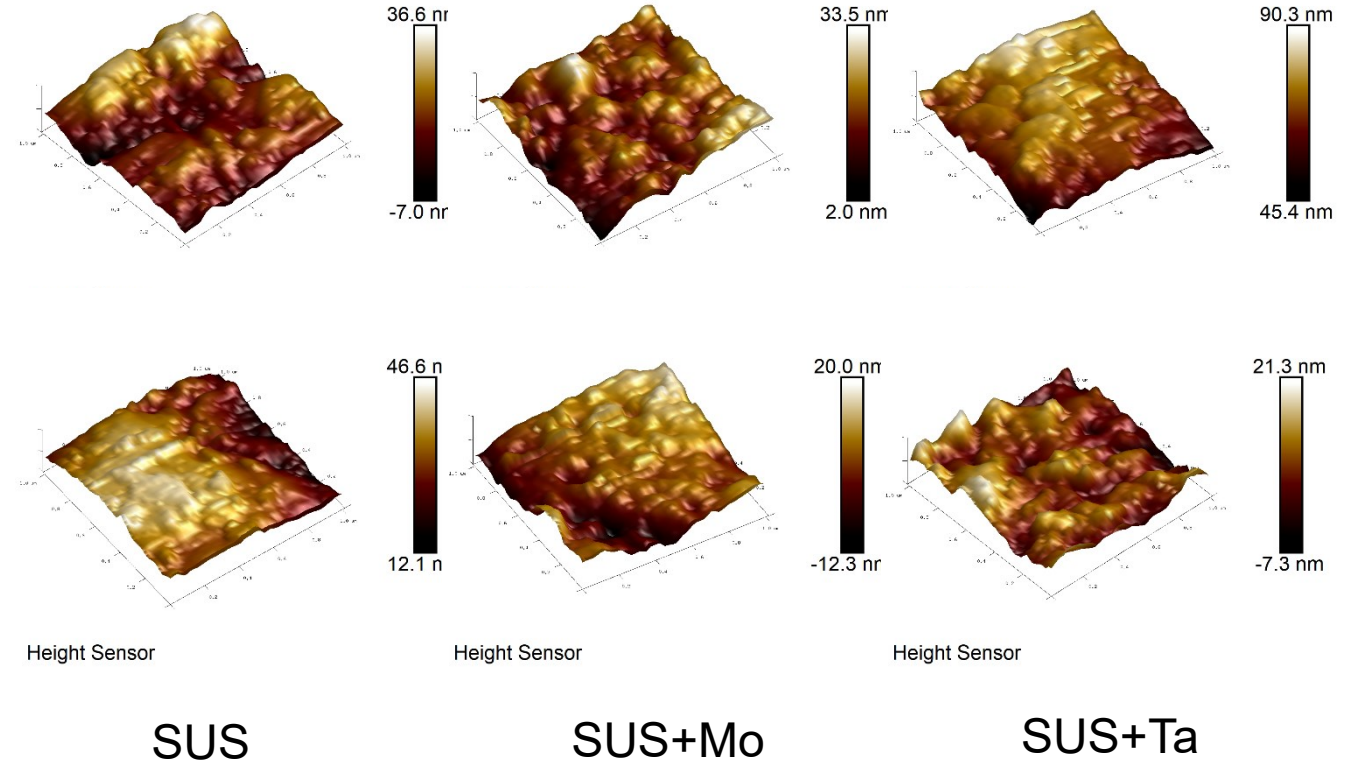
- Insulation test gap: 0.5mm DC

## Surface morphology-Ion implanted Mo

Microhardness tester      **Hardness**



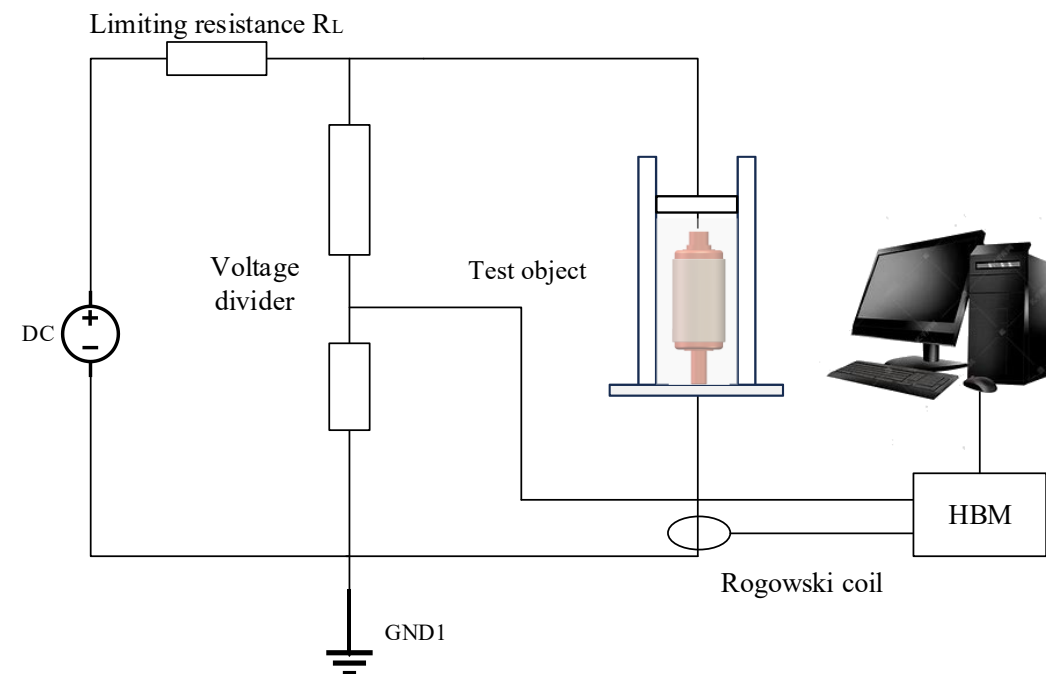
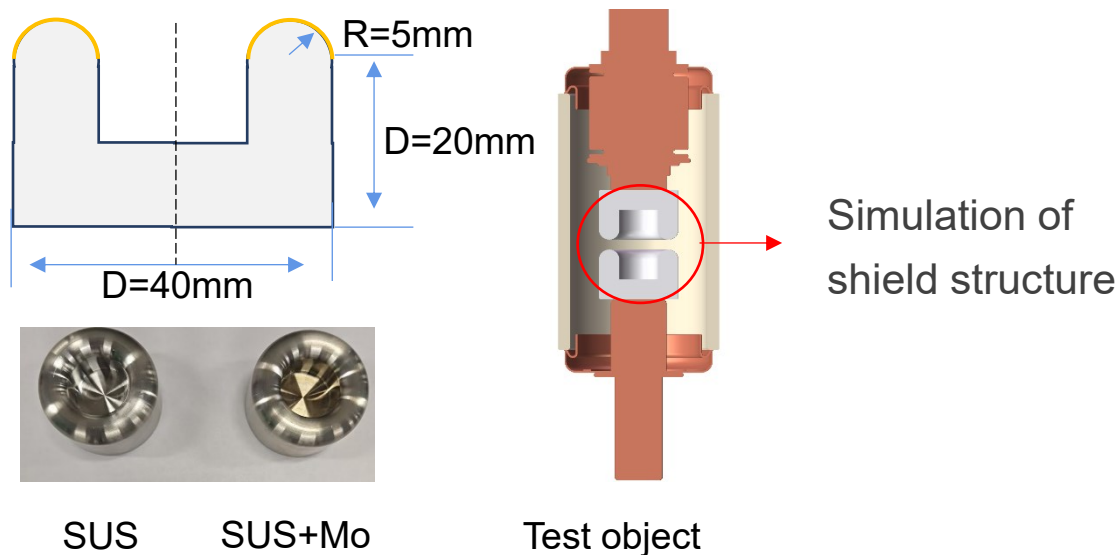
Atomic Force Microscope      **Surface roughness**



- Improved hardness uniformity after ion implantation
- The roughness of the sample itself is too large, and the effect of ion implantation on the roughness of the sample itself is not obvious

# EXPERIMENTAL SETUP

- Insulation test gap: 3mm/5mm
- Preliminary verification under 3/5mm gap

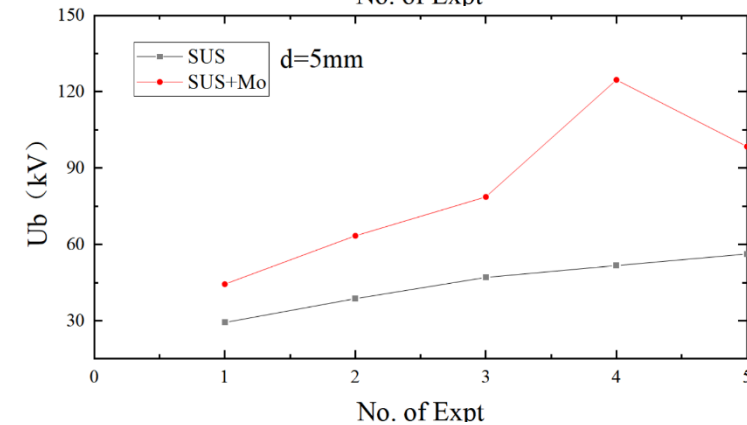
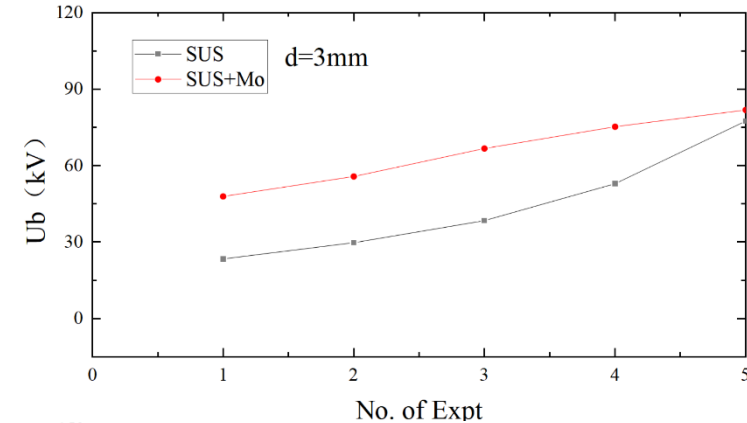
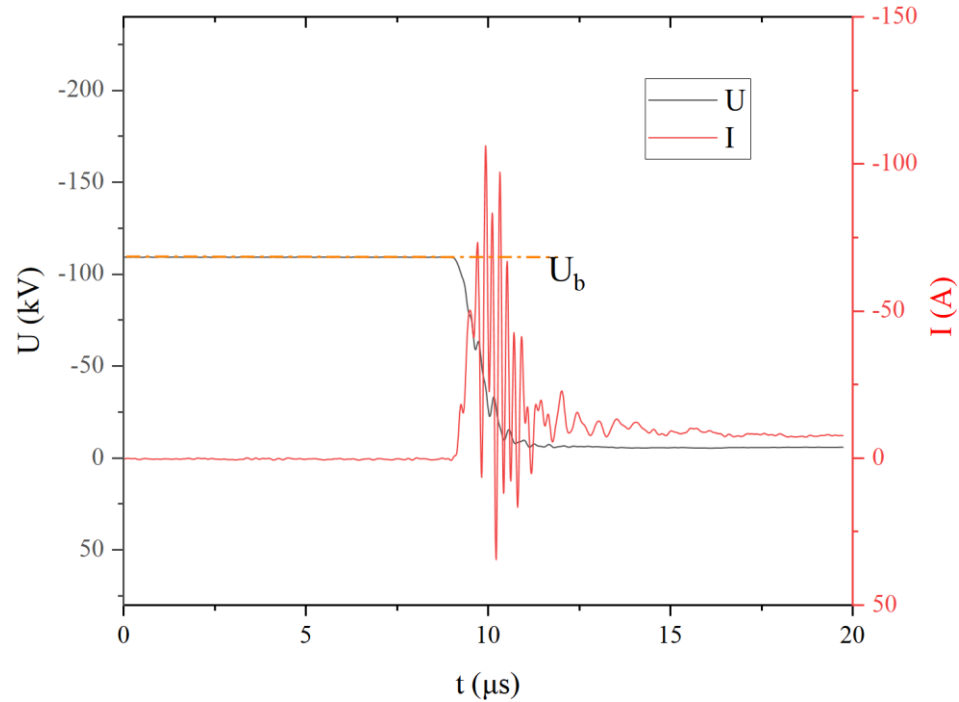
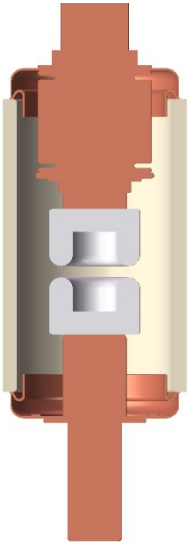


Schematic diagram of the experimental setup

- Discharges occurred in vacuum interrupters
- Assembly of ring-ring electrodes with 3mm/5mm gaps
- The DC source provides 0-500kV high voltage with a rise rate of 1kV/s

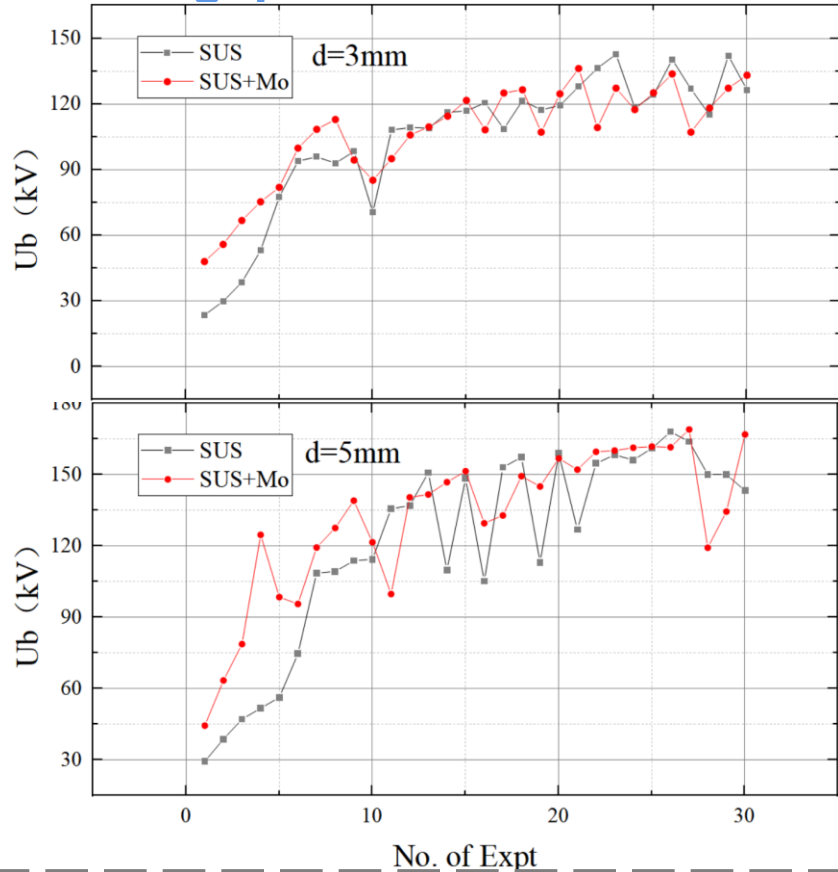
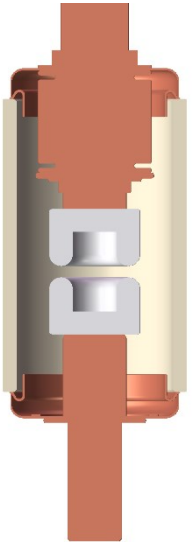
Ion implantation elements	Accelerating voltage/kV	Ion implantation dose/ions·cm <sup>-2</sup>
Mo	35	$3 \times 10^{17}$

- Insulation test gap: 3/5mm DC Ion implanted Mo

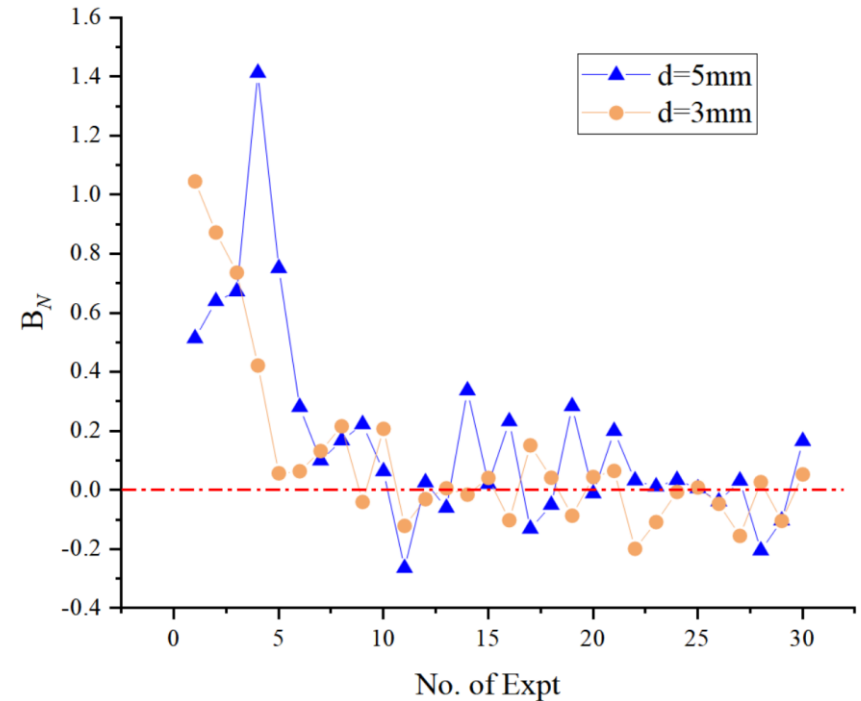


- Like small gaps, Ion implantation effectively enhances the initial breakdown voltage

• Insulation test gap: 3/5mm DC Ion implanted Mo



$$B_N = \frac{U_{bi}^i - U_{bi}^{noi}}{U_{bi}^{noi}}$$



- All sample showed obvious conditioning effect.
- Unlike small gaps, the breakdown voltage does not drop after the ion implantation layer is destroyed.
- Why? **It is speculated that first ion implantation introduced other elements.**

- Insulation test gap: 3/5mm DC Ion implanted Mo

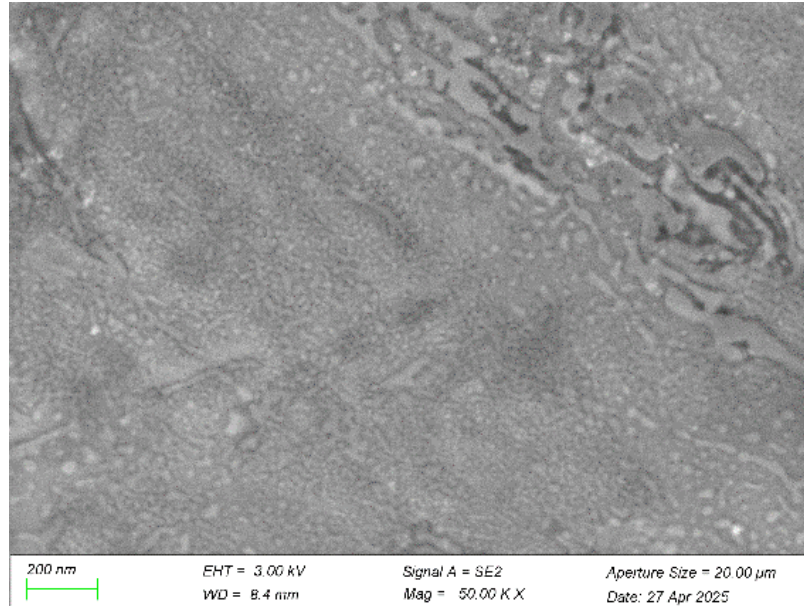
## Surface morphology

Scanning Electron Microscope(SEM) test

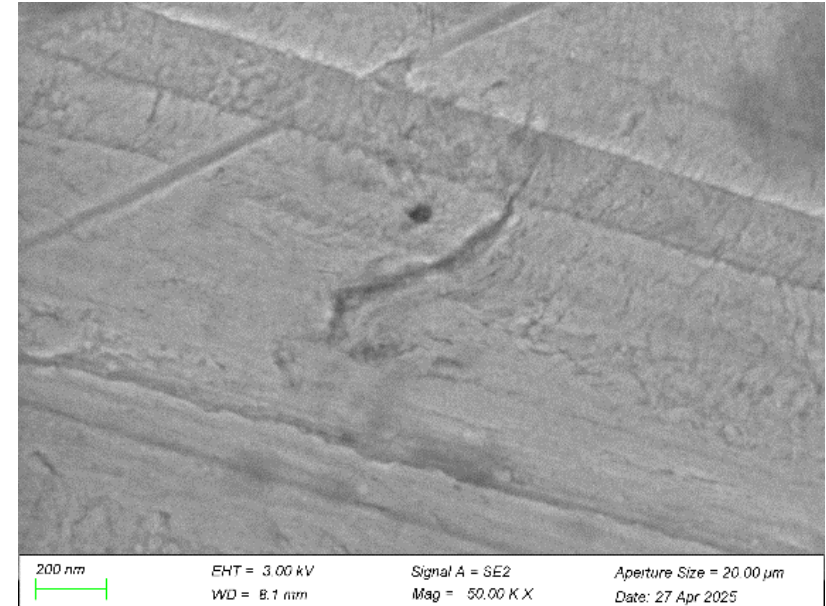


Ion Implantation

No Ion Implantation



Ion Implantation



No Ion Implantation

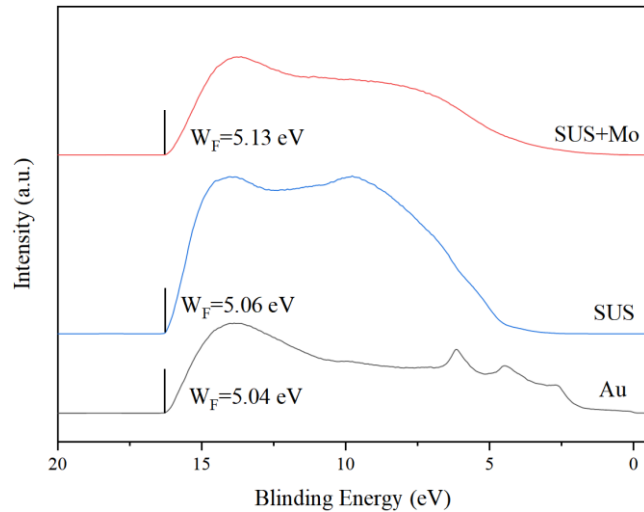
- Uniform and fine nanostructures appears on the surface of the ion-implanted sample

- Insulation test gap: 5mm lightning impulse voltage

## Surface characteristic parameters

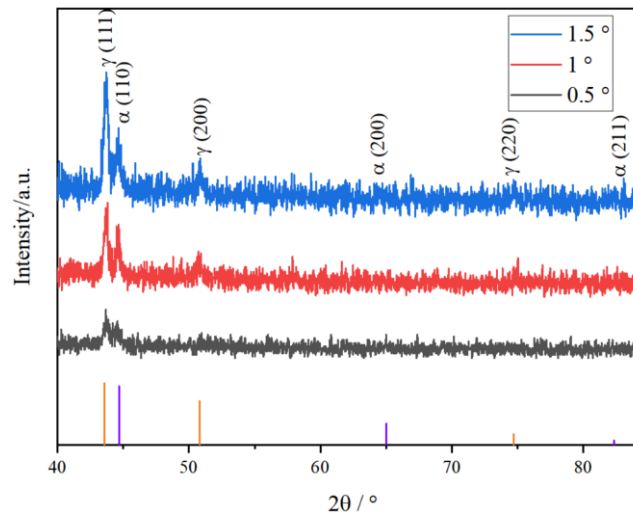
GIXRD test    Surface phase

UPS test    Work function

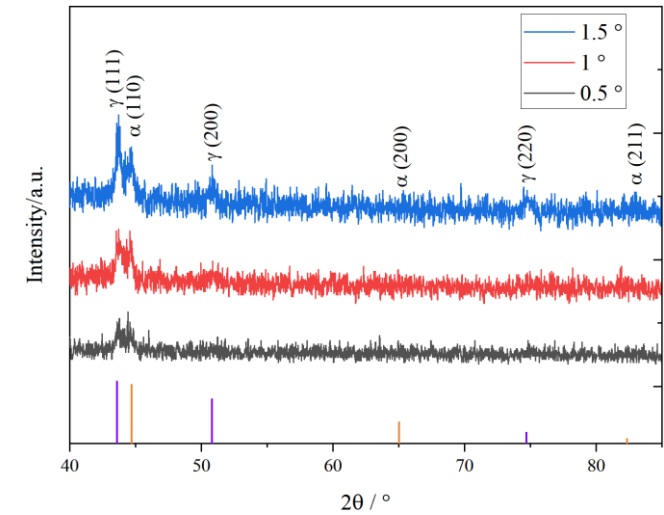


Element	Cr	Mo
WF /eV	4.5	4.6

No Ion Implantation



Ion Implantation



- Research indicates that after molybdenum ion implantation into stainless steel, molybdenum atoms extensively occupy the original chromium atomic sites on the steel surface.

Ding, L., Zhang, Hb., Wang, Rj. et al. Enhanced corrosion resistance and electrical conductivity of stainless steel bipolar plates by molybdenum ion implantation. J. Iron Steel Res. Int. (2024). <https://doi.org/10.1007/s42243-024-01296-1>

- Ion implantation is typically accompanied by damage to and modification of the surface crystalline structure.

- Under small gap conditions, Mo ion implantation on stainless steel electrode surfaces can increase the initial breakdown voltage of vacuum gaps.
- The reasons are as follows:
  - Ion implantation improves the uniformity of surface hardness on stainless steel by altering the phase composition of the electrode surface.
  - Ion implantation may also increase the surface metal work function by reconstructing the elemental composition of the surface.
- But:
  - Due to the extremely thin nature of the ion-implanted layer, it becomes completely ineffective after several breakdown events. Moreover, the introduction of non-metallic elements may further reduce the subsequent breakdown voltage.
- Next work plan:
  - Experiment with more types and more injection parameters
  - Try to apply it to the actual structure of vacuum interrupter

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Thank You for attention!