

# Application of Ion Beam Etching in the Micro-LED Process

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## Abstract

As an emerging display technology, GaN-based micron-scale light-emitting diodes (Micro-LEDs) possess broad application potential and have undergone rapid development in recent years. However, as device dimensions scale down, the fabrication yield of Micro-LEDs decreases significantly, primarily attributable to increased process complexity. This paper analyzes the issue of metal residue (commonly known as "metal fences") caused by metal etching during the Micro-LED manufacturing process. The effect of different etching angles on the removal efficiency of these metal residues was evaluated experimentally. The results indicate that the cleaning efficiency of metal residue per unit time is optimized when the ion beam etching angle is set to 140°.

## Keywords

Micro-LED; Ion Beam Etching (IBE); Metal Residue.

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## 1. Introduction

With the increasing adoption of wearable devices and their applications in fields such as Augmented Reality (AR) and virtual display, market demand for high-performance micro-displays is continuously rising. Micro-LEDs have demonstrated immense application potential in lighting and display sectors and have achieved significant progress in recent years. Traditional Liquid Crystal Display (LCD) and Organic Light-Emitting Diode (OLED) technologies are inferior to Micro-LEDs in terms of brightness, resolution, contrast ratio, energy consumption, operational lifetime, response speed, and stability.[1] Consequently, Micro-LED is widely regarded as a crucial direction for the development of next-generation display technology.

The chip size of traditional LEDs for lighting applications is typically larger than 300 μm, whereas Micro-LEDs are generally defined to be below 50 μm. Although Micro-LEDs possess numerous excellent properties, their manufacturing yield decreases markedly as the scales down. This phenomenon primarily stems from the increased surface-to-volume ratio associated with smaller device dimensions, which makes the sidewalls susceptible to metal splashing during the metal etching process. This splashed metal can form residual structures on the photoresist sidewalls (commonly known as "metal fences"), potentially leading to device short circuits and severely impacting production efficiency.

To mitigate the issue of metal residue from sidewall splashing generated during the etching process, this paper proposes the use of ion beam etching at tilted angles combined with a gas-liquid two-fluid cleaning process. The samples treated with different etching angles were characterized and analyzed using Scanning Electron Microscopy (SEM). The removal effectiveness of the ion beam etching on the metal fences was systematically evaluated, and the results validate the effectiveness of this strategy in improving Micro-LED production yield.

## 2. Study on the Mechanism of Ion Beam Etching Technology

This equipment employs an RF ion source. The vacuum system is comprised of a combination of a mechanical pump and a molecular pump. The sample stage is adjustable in tilt and rotation to allow the ion beam incidence angle to be set according to experimental requirements. During the process, helium gas is introduced to the backside of the sample stage to cool the wafer, thereby controlling the temperature rise induced by the ion beam and preventing overheating from adversely affecting the etch results. Key parameters such as ion energy can be adjusted within the process program to meet the requirements of different experimental conditions.

### 2.1 Structure and Operating Principle of the Ion Source

An ideal ion source system typically needs to meet the following requirements: an operating pressure below  $5 \times 10^{-7}$  mbar; compatibility with various process gases; etch uniformity better than 1% within a specified beam spot diameter range; continuously adjustable ion energy; the ability to generate efficient plasma suitable for high-beam-current operation; and the capability to form a contamination-free, collimated parallel ion beam. Depending on the method of ion generation, common ion sources mainly include radio frequency (RF) ion sources, electron cyclotron resonance (ECR) ion sources, and classical Kaufman ion sources. Generally, the basic structure of an ion source consists of three main parts: ion generation, ion extraction, and charge neutralization.

**Table 1.** Comparison of Three Types of Ion Sources

| Ion Generation Methods | 13.56 MHz RF (Radio Frequency) Excitation                 | 2.56 GHz Microwave Excitation                    | Hot Cathode Filament Electron Emission                                   |
|------------------------|-----------------------------------------------------------|--------------------------------------------------|--------------------------------------------------------------------------|
| Advantages             | Long lifetime, Low contamination, Electrodeless discharge | High ionization efficiency, Continuous operation | Simple operation, Wide parameter tuning range                            |
| Limitations            | High gas flow rate requirement                            | ECR operation requires a static magnetic field   | Frequent filament replacement, Limited range of compatible process gases |



**Fig. 1** Equipment External View (Mill 200 Etching System)

The RF ion source primarily consists of an RF power supply with its corresponding impedance matching network, a plasma discharge chamber, a multi-grid system for ion beam extraction, and a neutralizer for maintaining electrical neutrality.[2] Its structure is shown in Figure X: The RF power supply is responsible for providing the energy required to excite the plasma, during which the ion source acts as a variable load. As the impedance changes during the gas discharge process, the system

utilizes an RF matcher to achieve impedance matching, thereby effectively reducing reflected power and ensuring efficient energy transfer to the plasma.

The equipment used in this experiment was the Mill 200 etcher produced by scia system. In addition to its reactive ion beam etching (RIBE) capability, this equipment can also perform ion beam etching (IBE) and chemically assisted ion beam etching (CAIBE).[3]

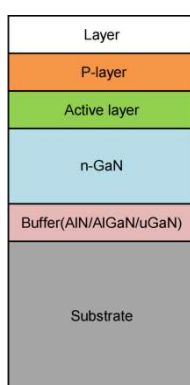
**Table 2.** Mill 200 Ion Source Parameters

| Ion Source               | Parameters                                                               |
|--------------------------|--------------------------------------------------------------------------|
| Filament                 | Filamentless design, compatible with process gases such as Ar, Xe        |
| Type                     | RF ion source                                                            |
| Ion Beam                 | Effective beam diameter $\geq 350$ mm (Note: unit verification required) |
| Grid Material            | Graphite                                                                 |
| Grid Structure           | Flat-plate structure                                                     |
| Ion Beam Energy          | Ion energy: 100–1800 eV; current density: up to 1 mA/cm <sup>2</sup>     |
| Ion Beam Power Supply    | Adjustable range: 0–2000 V, 1 A, 1200 W                                  |
| Accelerator Power Supply | 0~1000V, 400–1000 V, 400 mA, 400 W0mA, 400W                              |

### 3. Experiment

#### 3.1 Fabrication of Micro-LED Mesa Structures

This study utilized a blue LED epitaxial wafer based on a silicon substrate, which was prepared via heteroepitaxial growth using metal-organic chemical vapor deposition (MOCVD). The structure of the epitaxial wafer, from bottom to top, consists of: a silicon substrate; an approximately 1.5  $\mu\text{m}$  thick intentionally doped AlN/AlGaIn/GaN buffer layer; an approximately 1.8  $\mu\text{m}$  thick low-doped n-type GaN layer; an approximately 1  $\mu\text{m}$  thick highly doped n-type GaN layer; an approximately 0.55  $\mu\text{m}$  thick InGaIn/GaN multiple quantum well (MQWs) active region; and an approximately 0.15  $\mu\text{m}$  thick p-type GaN layer.



**Fig. 2** Structure of the Epitaxial Wafer

The pretreatment steps are as follows: First, the epitaxial wafer is cleaned using a semi-automatic organic cleaning machine and treated with an SPM solution on the surface. Subsequently, an ITO transparent conductive film is evaporated onto the p-type GaN layer.[4]Next, metal layers are evaporated onto both the epitaxial wafer and a low-resistivity silicon wafer. After defect inspection confirms no issues, the low-resistivity silicon wafer and the epitaxial wafer are bonded. Afterwards, the silicon substrate is removed post-bonding via wet etching until the buffer layer is exposed; the

buffer layer is then etched down to the n-type GaN layer using inductively coupled plasma (ICP) dry etching technology. After confirming the correct elemental composition ratio through scanning electron microscopy (SEM) energy dispersive spectroscopy analysis, the surface is treated with an SPM solution, and ITO and SiO<sub>2</sub> layers are sequentially evaporated onto the n-type GaN.

After verification, HMDS vapor treatment is applied to enhance surface adhesion, followed by spin-coating with 2 μm thick Model 220 photoresist. After pre-baking, pattern transfer is completed using a stepper lithography system, followed by post-exposure baking and development using a semi-automatic developer. The photoresist morphology is examined by SEM, and energy dispersive spectroscopy (EDS) is used to ensure no residual glue remains in the pixel gaps. Subsequently, ICP etching is employed to complete the etching of the SiO<sub>2</sub> hard mask and the GaN mesa. The etch depth is measured using a profilometer to ensure the etching reaches the target level. After confirming the pixel morphology via SEM, the SiO<sub>2</sub> hard mask is removed using BOE solution.

Following this, SiO<sub>2</sub> is deposited as a sidewall passivation layer via plasma-enhanced chemical vapor deposition (PECVD). HMDS vapor treatment is reapplied to improve adhesion, and 2 μm thick Model 220 photoresist is spin-coated again. After completing pre-baking, stepper lithography, post-exposure baking, and development processes, the photoresist morphology and any residual glue in the pixel gaps are inspected using SEM and EDS, respectively. Finally, the bottom metal layer is patterned using ion beam etching technology.

Through the above process steps, Micro-LED mesa structures with dimensions of approximately 3.5 μm were successfully fabricated. Ion beam etching technology was further employed to complete the patterning of the metal isolation structures. The surface morphology and structural characteristics of the resulting Micro-LED samples were characterized using scanning electron microscopy (SEM).[5]

#### 4. Study on the Ion Beam Etching Process for Metal Fences

Key Process Parameters of Ion Beam Etching:

The rationality and performance of etch process parameters are typically evaluated based on the following aspects: etch rate, etch selectivity, uniformity, repeatability, and pattern transfer fidelity. In practical process applications, etch rate and selectivity are particularly critical metrics of concern.

These parameters often exhibit certain interdependent relationships, which can be summarized as follows:

$$ER(E_i, J_b, \Phi) = -J_b / NY(E_i, \Phi) \cos \Phi \quad (1)$$

Where ER is the Etch Rate,  $E_i$  is the ion incident energy (eV),  $J_b$  is the ion beam current density (mA/cm<sup>2</sup>),  $\Phi$  is the ion beam incidence angle, N is the atomic density of the sample (atoms/cm<sup>3</sup>), and Y is the sputtering yield of the material.

Etching Experiment Procedures and Parameters:

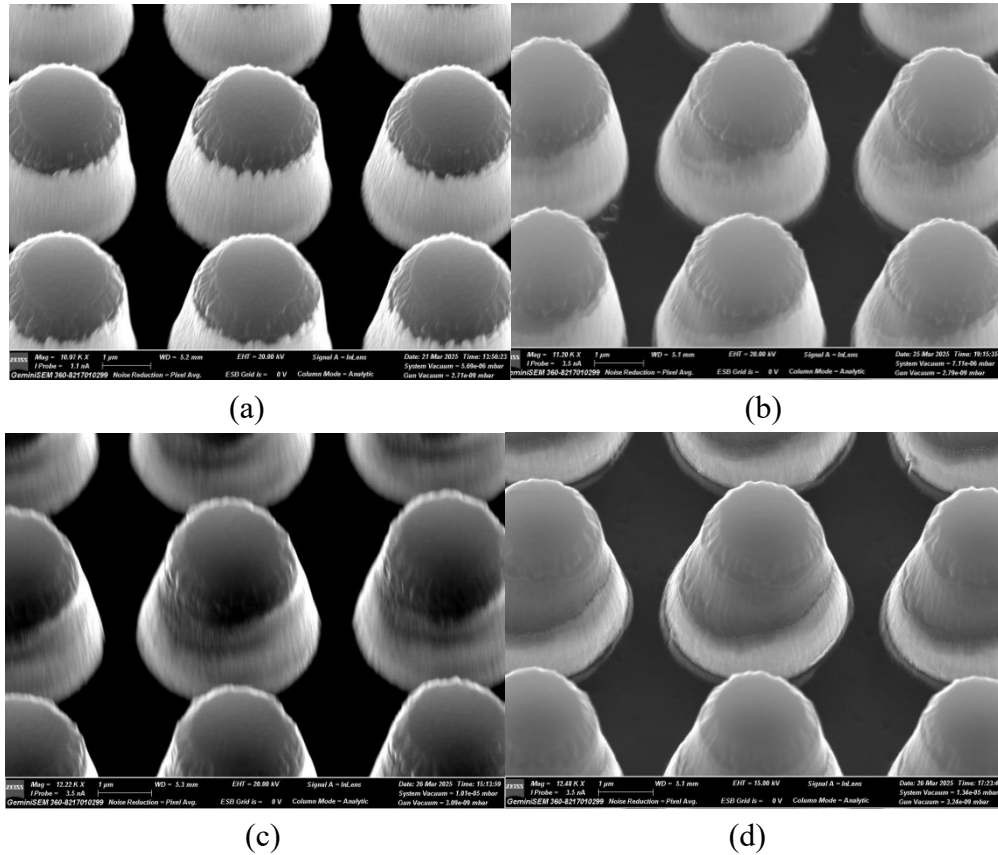
**Table 3.** Mill 200 Etching Parameters

| Gas & Flow Rate | Beam Current | Acceleration Voltage | Ion Energy |
|-----------------|--------------|----------------------|------------|
| Ar 35ccm        | 500mA        | 700V                 | 400eV      |

**Table 4.** Experimental Grouping

| Wafer No.                               | No.1       | No.2       | No.3       | No.4        |
|-----------------------------------------|------------|------------|------------|-------------|
| Etching Time & Ion Beam Incidence Angle | 90°, 5 min | 115°, 5min | 140°, 5min | 140°, 10min |

### SEM Images Post-Etching and Result Analysis:



**Fig. 3** SEM Images of Post-Etching Metal Fences on Wafers No. 1 to 4

**Table 5.** Fence Height after Ion Beam Etching at Different Angles

| Wafer No.            | No.1         | No.2         | No.3         | No.4         |
|----------------------|--------------|--------------|--------------|--------------|
| Average Fence Height | 1.72 $\mu$ m | 1.53 $\mu$ m | 1.35 $\mu$ m | 0.98 $\mu$ m |

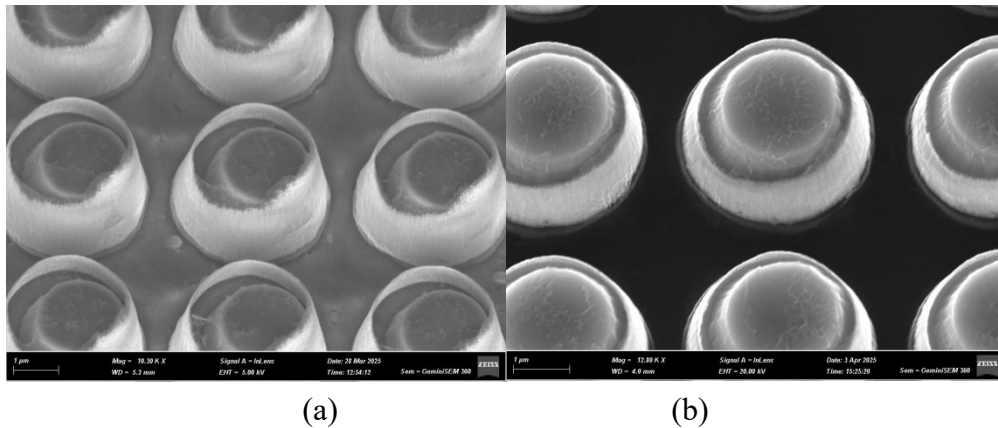
By adjusting the etching time and etching angle under different conditions, we successfully identified the optimal process parameters for enhancing metal fence removal and systematically investigated the specific effects of these parameters.

Results from Wafers No. 1 to 4 indicate that as the etching time at 140° increases, the fence height progressively decreases.

Overlay misalignment resulted in a more sloped photoresist profile on the left side. Experiments demonstrated that a more sloped photoresist is more prone to etching-through.

After photoresist removal, a gas-liquid two-fluid cleaning process was employed.

A comparison of the SEM images above indicates that the gas-liquid two-fluid cleaning can effectively reduce the height of the metal fences remaining after photoresist stripping by a certain extent. Therefore, performing the gas-liquid two-fluid cleaning after photoresist stripping is also an effective process step for removing metal fences.



**Fig. 4** (a) shows the SEM image after photoresist stripping but before the two-fluid cleaning; (b) shows the image after photoresist stripping and subsequent gas-liquid two-fluid cleaning.

## 5. Summary

This study employed tilted-angle ion beam etching combined with a gas-liquid two-fluid cleaning process to systematically analyze the influence of different ion beam incidence angles on metal residue structures. The post-etching morphology was characterized using scanning electron microscopy (SEM). Experimental results demonstrated that ion beam etching proved effective in removing metal fences, with the most significant removal effect observed at an etching angle of  $140^\circ$ . Furthermore, the combination of photoresist stripping followed by the gas-liquid two-fluid rinsing process could further eliminate residual metal structures, significantly enhancing surface quality. The process method described in this paper provides another viable technical option for improving the production yield of Micro-LED devices.

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