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Hidenori Mimura

*Research Institute of Electronics, Shizuoka University, Hamamatsu, Shizuoka 432-8011, Japan,  
mimura@rie.shizuoka.ac.jp*

Yoichiro Neo

*Research Institute of Electronics, Shizuoka University, Hamamatsu, Shizuoka 432-8011, Japan*

Toru Aoki

*Research Institute of Electronics, Shizuoka University, Hamamatsu, Shizuoka 432-8011, Japan*

Tomoya Yoshida

*National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8561, Japan*

Masayoshi Nagao

*National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8561, Japan*

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## Electron Emission Characteristics of Multi-gated Field Emitters

Hidenori Mimura<sup>1\*</sup>, Yoichiro Neo<sup>1</sup>, Toru Aoki<sup>1</sup>, Tomoya Yoshida<sup>2</sup>, and Masayoshi Nagao<sup>2</sup>

1. Research Institute of Electronics, Shizuoka University, Hamamatsu, Shizuoka 432-8011, Japan  
2. National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8561, Japan

\*-email: [mimura@rie.shizuoka.ac.jp](mailto:mimura@rie.shizuoka.ac.jp)

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### Abstract

We have developed a multi-gated field emitter (FE) such as a quadruple-gated FE with a three-stacked electrode lens and a quintuple-gated FE with a four-stacked electrode lens. Both the FEs can focus the electron beam. However, the quintuple-gated FE has a stronger electron convergence than the quadruple-gated FE, and a beam crossover is clearly observed for the quintuple-gated FE.

### Abstrak

**Karakteristik Emisi Elektron dari FE (Field Emitters = Pengemisi Lapangan) dengan Gerbang Multi.** Kami telah mengembangkan FE dengan gerbang multi seperti FE bergerbang empat kali lipat dengan lensa elektroda bertumpuk tiga dan FE bergerbang lima kali lipat dengan lensa elektroda bertumpuk empat. Kedua jenis FE ini dapat memfokuskan sinar elektron. Namun, FE bergerbang lima kali lipat mempunyai konvergensi elektron yang lebih kuat daripada FE bergerbang empat kali lipat, dan lintasan sinar secara jelas terlihat untuk FE bergerbang lima kali lipat.

*Keywords: beam crossover, electron beam, focusing*

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### 1. Introduction

A field emitter array (FEA) with a focusing electrode is an attractive device for applications, such as a scanning electron microscope and electron beam lithography and so on. As the FEAs with a focusing electrode, double-gated FEAs have been proposed. However, the double-gated FEA has a problem that the emission current decreases under the strong focusing conditions. This is due to the lowered field enhancement at the emitter tip caused by the low potential of a vicinal focusing electrode. [1] To solve such the problem, we have reported the other approach that uses the focusing electrode located below the extraction gate electrode in a volcano structure. [2,3] However, we observed that some electrons cannot penetrate the potential barrier formed by the focusing electrode potential under strong focusing conditions. These electrons go back to the extraction gate electrode. To overcome these problems simultaneously (field enhancement and potential barrier), an electrostatic lens using a multistacked-electrode should be integrated at the emitter tip, and at least three additional electrodes are necessary. The first electrode (near the emitter tip) is used to maintain the

potential at the emitter tip; therefore, a voltage higher than the extraction gate voltage is applied. The second electrode is used to focus the electron beam; therefore, a voltage lower than the extraction gate voltage is applied. The third electrode is used to inhibit the generation of a potential barrier on the electron trajectory; therefore, a voltage higher than the second electrode voltage is applied.

In this paper, we have developed a multi-gated field emitter (FE) with a four-stacked gate electrode, and a FE with a five-stacked gate electrode, that is, quadruple-gated FE with a three-stacked electrode lens and quintuple-gated FE with a four-stacked electrode lens.

### 2. Methods

**Fabrication of the multi-gated field emitters.** The fabrication process for the multi-gated FEs is schematically shown in Figure 1. (a) An emitter cone is formed from single crystalline Si by reactive ion etching (RIE) using a SiO<sub>2</sub> dot as an etching mask. The apex radius of the tip is 5-10 nm. (b) A SiO<sub>2</sub> insulating layer is deposited by plasma-enhanced chemical vapor

deposition (PE-CVD) using tetraethoxysilane (TEOS) gas followed by Nb deposition. (c) After the deposition of SiO<sub>2</sub> and Nb films, a photoresist is spin-coated on the Nb film. The thickness of the photoresist on top of the mountain structure becomes thinner than that on the flat surface. (d) Therefore, the Nb electrode at the tip is selectively etched by the following RIE step without precise lithography. The electrode height can be controlled by the etching time and is adjusted to be the same as that of the emitter tip. The first Nb electrode acts as an extraction gate electrode. (e) In the quadruple-gated FE, three additional electrodes, which form an electrostatic lens, are stacked by repeating the steps from (b) to (d) three times. In the quintuple-gated FE, four additional electrodes, which form an electrostatic lens, are stacked in the similar way. (f) Finally, the emitter tip is opened by the buffered hydrofluoric acid (BHF).

Figures 2 (a) and (b) show cross sectional SEM images of the quadruple-gated FE and quintuple-gated FE, respectively. In the both FEs, the first Nb electrode acts as an extraction gate electrode. In the quadruple-gated FE, the G1 and G2 among the three-stacked electrostatic lens are set at the same voltage. In the quintuple-gated FE, G1 and G4 among the four-stacked electrostatic lens are set at the same voltage. G2 and G3 (G2,3) are connected through a contact hole, and are set at the same voltage. Therefore, both the three-stacked and four-stacked electrostatic lenses form an eizel lens.

### 3. Results and Discussion

**Emission characteristics.** The electron emission from both the quadruple-gated FE and quintuple-gated FE were measured in a high-vacuum chamber at a pressure of  $1 \times 10^{-7}$  Pa. An anode phosphor screen biased at 1 kV was located 1 mm above the FE substrate. For the simple anode-current characteristics, the all potentials of the electrostatic lens were set equal to that of the extraction gate electrode. In the quadruple-gated FE, emission started at 20 V and reached 3  $\mu$ A at an extraction voltage of 60 V, while in the quintuple-gated FE, emission started at 30 V and reached 100 nA at an extraction voltage of 60 V. In the quintuple-gated FE, more electrons entered the gate electrodes in nonfocusing condition, because the lens size is larger than that of the quadruple-gated FE.

Figure 3 shows the beam spots measured from the anode phosphor screen images for the quadruple-gated FE and quintuple-gated FE. In the quadruple-gated FE, the voltages of G<sub>ex</sub>, G1 and G3 were fixed at 50, 100, and 100 V, respectively. The voltage of G2 was changed from 100 V (nonfocusing condition) to -20 V (focusing condition). In the quintuple-gated FE, the voltages of G<sub>ex</sub>, G1, and G4 were fixed at 50, 100, and 100 V, respectively. The voltage of G2,3 was changed

from 100 V (nonfocusing condition) to -10 (focusing condition). Figure 3 also shows the phosphor images at G<sub>2,3</sub> = 100, 10, and -10 V for the quintuple-gated FE. For the quadruple-gated FE, the beam spot monotonously decreases as the G2 voltage decreases from 100 to -30 V. On the other hand, for the quintuple-gated FE, the beam spot decreases as the G<sub>2,3</sub> voltage decreases from 100 to 10 V, but then the beam spot increases as the G<sub>2,3</sub> voltage go from 10 to -10 V. This indicates that a beam crossover (a beam focal point) is formed between the anode and the field emitter. Since the field emitter and anode are 1 mm apart and the crossover is formed immediately in front of the field emitter, the beam spot size shown in Figure 3 are not exact size, and real beam size of the crossover is expected less than 50 nm. The results in Figure 3 also show that the lens function for the quintuple-gated FE is stronger than that of the quadruple-gated FE.

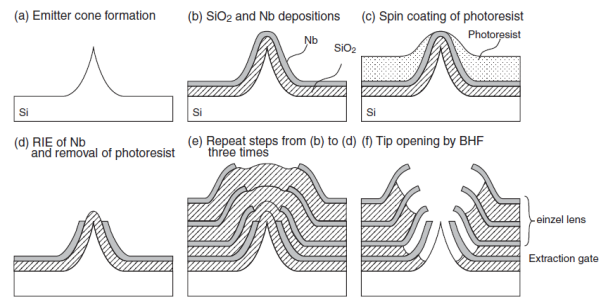


Figure 1. Fabrication Process for the Quadruple-gated FE with a Three-stacked Electrode Lens

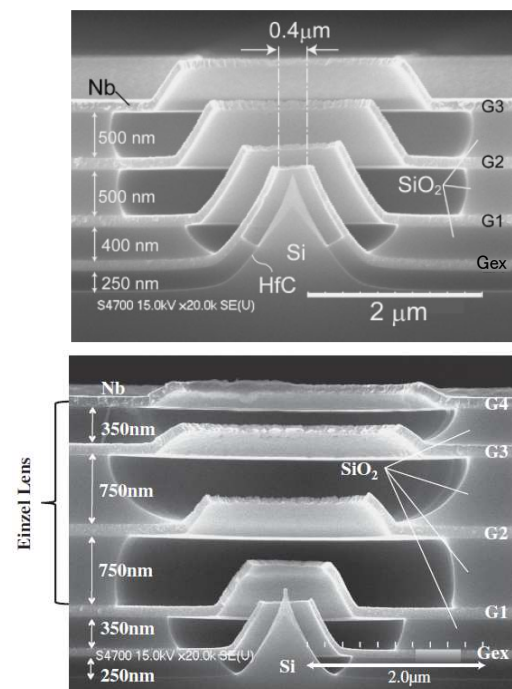
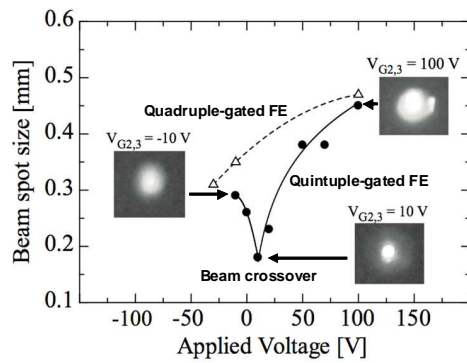


Figure 2. Cross-sectional SEM Images of the Quadruple-gated FE (a) and the Quintuple-gated FE (b)



**Figure 3. Beam Spots Measured from Phosphor Screen Images for the Quadruple-gated FE and the Quintuple-gated FE. Solid and Dashed Lines are the Least-square Estimations for the Quadruple-gated FE and the Quintuple-gated FE, Respectively**

#### 4. Conclusions

We have successfully fabricated a multi-gated FE such as quadruple-gated FE with a three-stacked electrode lens and a quintuple-gated FE with a four-stacked electrode lens. The fabrication process uses an etch-

back technique. In our method, gate hole opening is a self-aligned process; therefore, the axes of electrode holes are well aligned without precise lithography. Both the quadruple-gated FE and quintuple-gated FE can focus the electron beam. However, lens function for the quintuple-gated FE is stronger than that of the quadruple-gated FE, and a beam crossover is formed for the quintuple-gated FE. The multi-gated FE is a promising device for a micro-column for a scanning electron microscope and electron beam lithography.

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