Multi-gated Field Emitters for a Micro-column

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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.**

***Index Terms* – beam crossover, electron beam, focusing, micro-column, multi-gated field emitter**

I. 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.

II. FABRICTION OF THE MULTI-GATED FIELD EMITTERS

The fabrication process for the multi-gated FEs is schematically shown in Fig. 1. (a) An emitter cone is formed from single crystalline Si by reactive ion etching (RIE) using a SiO_2 dot as an etching mask. The apex radius of the tip is 5-10 nm. (b) A SiO_2 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_2 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.

Figure 3 shows the top-view micrograph of the quadruple-gated FE. The dotted line in the micrograph shows that the electrode holes from accurate concentric circles with the emitter tip as a center pole. This is due to the full self-aligned process. The alignment of electrode holes is very important for the electrostatic lens to avoid an aberration.

III. ELECTRON 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 x 10^{-7} Pa. Figures 4 (a) and (b) show extraction-gate-voltage (Gex) versus anode-current characteristics of the quadruple-gated FE and quintuple-gated FE, respectively. 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, as schematically shown in the insert of Figs. 4 (a) and (b). In the quadruple-gated FE, emission started at 20 V and reached 3 μA 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 5 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 Gex, 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 Gex, 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 5 also shows the phosphor images at G2,3 = 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 G2,3 voltage decreases from 100 to 10 V, but then the beam spot increases as the G2,3 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 Fig. 5 are not exact size, and real beam size of the crossover is expected less than 50 nm. The results in Fig. 5 also show that the lens function for the quintuple-gated FE is stronger than that of the quadruple-gated FE.

IV. CONCLUSION

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.

REFERENCES

[1] Y. Yamaoka, S. Kanemaru, and J. Itoh, Jpn. J. Appl. Phys. 35, pp.6626, 1996.

[2] Y. Neo, T. Soda, M. Takeda, M. Nagao, T. Yoshida, C. Yasumuro, S. Kanemaru, T. Sakai, K. Hagiwara, N. Saito, T. Aoki, and H. Mimura, Appl. Phys. Express 1, pp.053001, 2008.

[3] T. Soda, M. Nagao, C. Yasumuro, S. Kanemaru, T. Sakai, N. Saito, Y. Neo, T. Aoki, and H. Mimura, Jpn. J. Appl. Phys. 47, pp.5252, 2008.

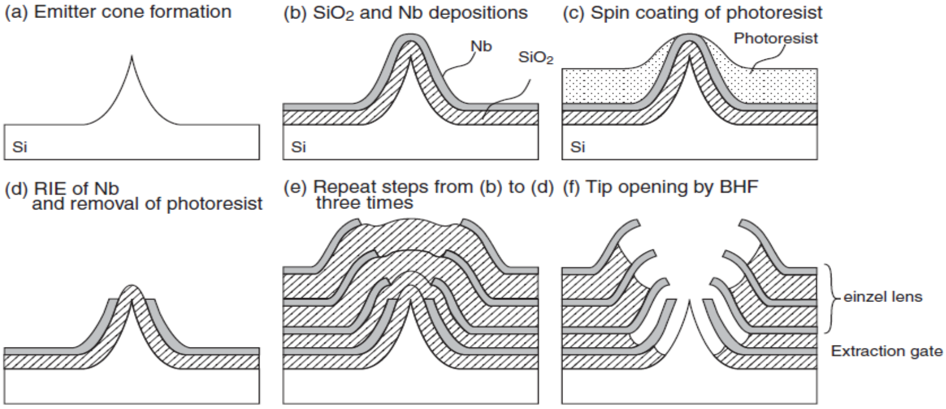


Fig. 1 Fabrication process for the quadruple-gated FE with a three-

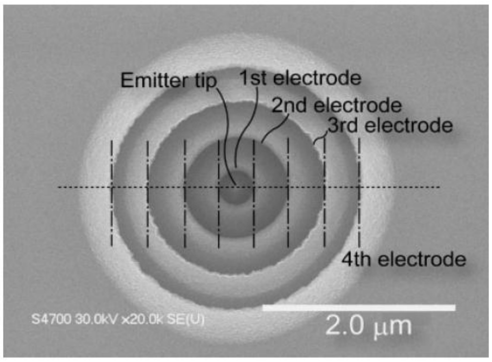
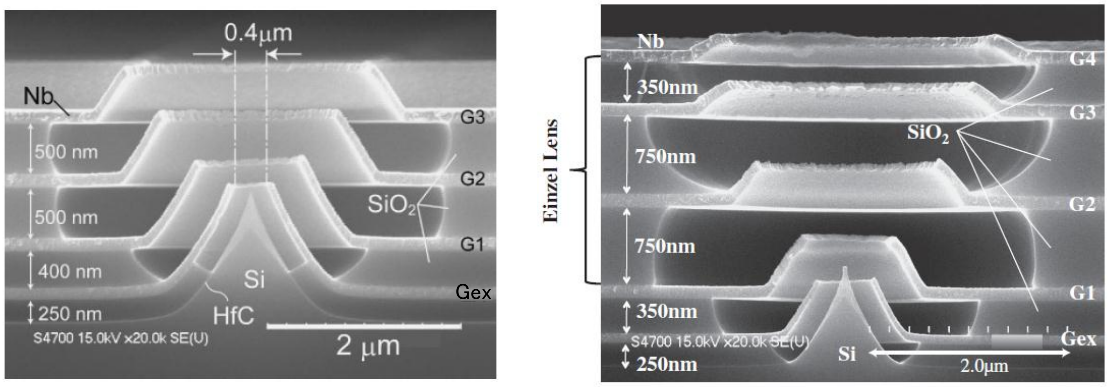
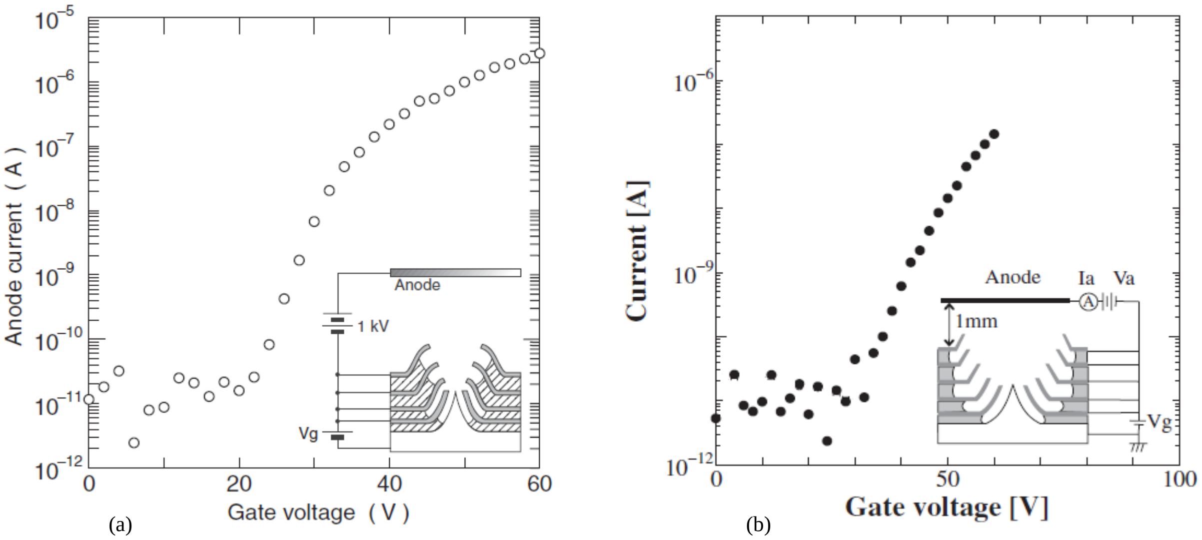


Fig. 2. Top-view SEM image of the quadruple-gated FE.



(a) (b)

Fig. 3 Cross-sectional SEM images of the quadruple-gated FE (a) and the quintuple-gated FE.



(a) (b)

Fig. 4 Emission characteristics of the quadruple-gated FE (a) and the quintuple-gated FE (b).

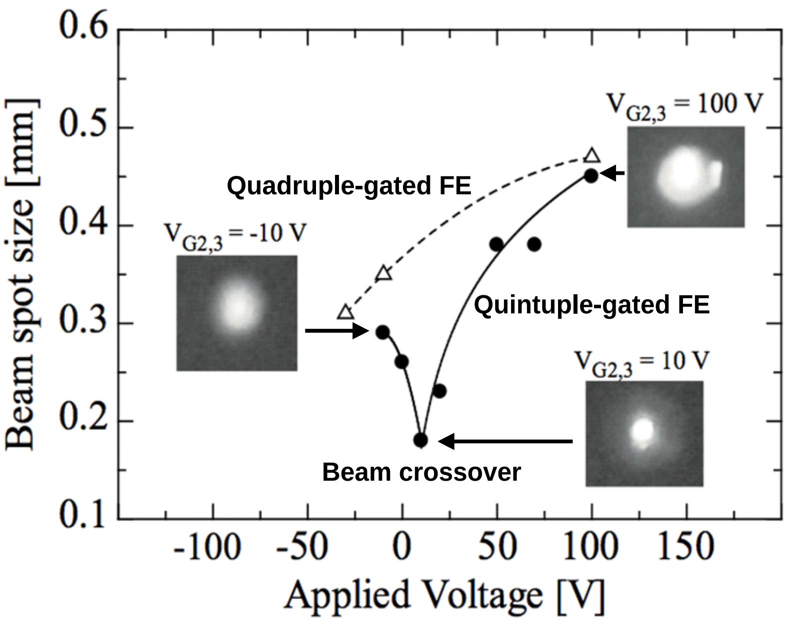


Fig. 5 Beam spots measured from phosphor screen images for the quadruple-gated FE (a) and the quintuple-gated FE (b). Solid and dashed lines are the least-square estimations for the quadruple-gated FE and the quintuple-gated FE, respectively.