Fabrication and Characteristics of Lateral Type Field Emitter Arrays

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Kyu-Man Choi, and Jung-Hee Lee

Abstract—**We have proposed and fabricated two lateral type field emission diodes, poly-Si emitter by utilizing the local oxidation of silicon (LOCOS) and GaN emitter using metal organic chemical vapor deposition (MOCVD) process. The fabricated poly-Si diode exhibited excellent electrical characteristics such as a very low turn-on voltage of 2 V and a high emission current of 300 μA/tip at the anode-to-cathode voltage of 25 V. These superior field emission characteristics was speculated as a result of strong surface modification inducing a quasi-negative electron affinity and the increase of emitting sites due to local sharp protrusions by an appropriate activation treatment. In respect, two kinds of procedures were proposed for the fabrication of the lateral type GaN emitter: a selective etching method with electron cyclotron resonance-reactive ion etching (ECR-RIE) or a simple selective growth by utilizing Si_3N_4 film as a masking layer. The fabricated device using the ECR-RIE exhibited electrical characteristics such as a turn-on voltage of 35 V for 7 μm gap and an emission current of ~ 580 nA/10tips at anode-to-cathode voltage of 100 V. These new field emission characteristics of GaN tips are believed to be due to a low electron affinity as well as the shorter inter-electrode distance. Compared to lateral type GaN field emission diode using ECR-RIE, re-grown GaN emitters shows sharper shape tips and shorter inter-electrode distance.**

Index Terms —**Field emission, lateral type, LOCOS, Poly-Si emitter, GaN emitter.**

I. INTRODUCTION

With the recent advances in vacuum microelectronics [1], the associated semiconductor field-emission arrays (FEAs) have recently become attractive candidates for relevant applications, such as in flat-panel displays, vacuum microelectronics, electron source, and high-power RF circuits [1-4]. Various materials, such as molybdenum [5], silicon [6], diamond-like carbon (DLC) [7], carbon nanotubes (CNTs) [8], and GaN[9-12] have been studied for field emitter tips maintaining lower turn-on voltage and much stable long-term operation even with higher emission current densities. Fabrication of silicon-based field emitters are promising in fact that reproducibility and uniformity can easily be obtained from the mature Si-based IC technology. Interest and research in GaN-based field-emission devices are also growing rapidly because of its inherent large bandgap, low electron affinity, excellent physical and chemical stability and conductivity controllability.

In addition to the vertical Spindt-type field-emission devices, lateral-type ones are also advantageous for high-speed operation and RF applications because of simple design and fabrication processes, easy control of electrode distances and better electrical characteristics, such as lower turn-on voltages and higher current

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densities [2,13-15]. In this work for a possible high power microwave application, we have fabricated two lateral type emitters of a poly-Si field emission diode by using the LOCOS process and a GaN field emission diode using metal organic chemical vapor deposition (MOCVD). The fabrication techniques employed in this work are very simple to implement and reproducible both in shaping the sharp electrode tips and controlling the inter-electrode gaps.

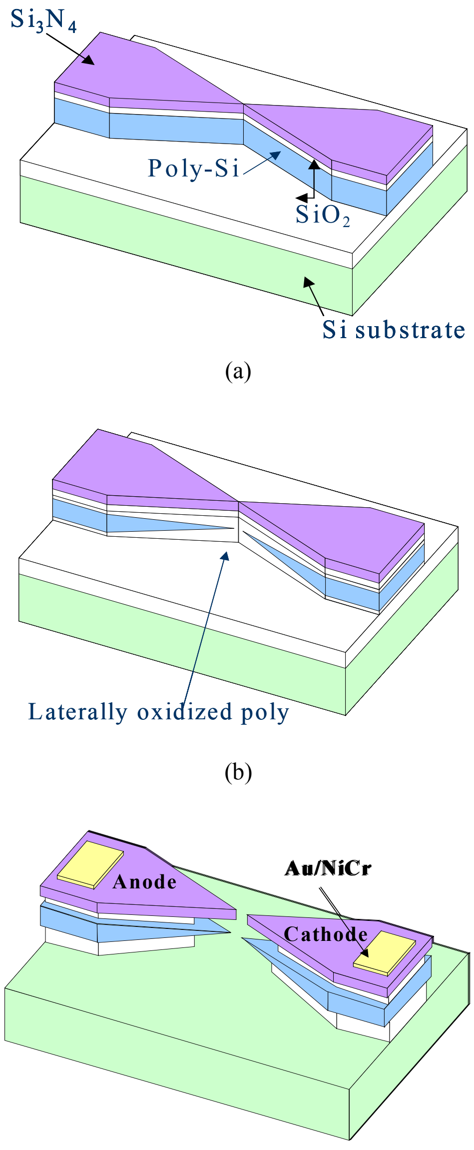
II. DEVICE FABRICATION

A. *A lateral type poly-Si field emission diode*

A schematic process flow diagram for the fabrication of the diode is shown in Fig. 1. Typical fabrication flow is as follows: i) A buried silicon dioxide layer of 6000 Å thickness was grown on a p-type (100) silicon substrate by using wet thermal oxidation at 1000 ^{o}C. ii) An n^{+}-doped polysilicon layer of 5000 Å was then deposited by low-pressure chemical vapor deposition (LPCVD). iii) After sequential deposition of 500 Å of silicon dioxide and 1600 Å of silicon nitride as an oxidation barrier, the top three layers of Si$_3$N$_4$/SiO$_2$/poly-Si were etched down selectively to the bottom oxide by reactive ion etching (RIE) with photolithographic definition of the electrodes. The original pattern of the polysilicon cathode tip was designed to overlap with those of anode by about 0.2 μm [Fig. 1(a)]. iv) Then, the polysilicon layer was laterally oxidized by the LOCOS process at 1100 ^{o}C in wet oxygen ambient for 60 min to control both the spacing between the electrodes and the sharpness of the tip ends of those electrodes. As a result of local the oxidation, the overlapped polysilicon layer was separated into two parts [Fig. 1(b)]. v) For metalization, the top Si$_3$N$_4$/SiO$_2$ layers were selectively etched, and an Au/NiCr contact was then made by thermal evaporation and subsequent annealing at 350 ^{o}C for 30 min in the nitrogen ambient. vi) Finally, all the oxides surrounding the polysilicon, the laterally formed LOCOS oxide, the deposited top oxide, and thermally grown bottom oxide, were etched out in buffered hydrofluoric acid (BHF) solution to isolate the sharpened cathode and andode tips [Fig. 1(c)].

B. *A lateral type GaN field emission diode*

The lateral type Si-doped GaN field emission emitters were fabricated from the GaN film on sapphire substrate grown by using metal-organic chemical vapor deposition (MOCVD) technique. In forming the pattern, two kinds of procedures were proposed: a selective etching method with electron cyclotron resonance-reactive ion etching (ECR-RIE) or a simple selective regrowth by utilizing Si$_3$N$_4$ film as a masking layer. The schematic views of the fabricated device were shown in Fig. 2.



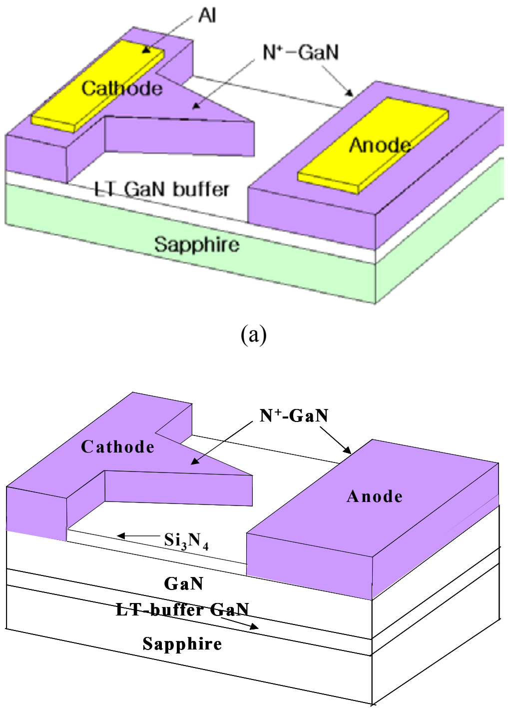
(a)

(b)

(c)

Fig. 1. Schematic process flow diagram for the fabrication of the diode: (a) electrode definition before LOCOS, (b) during the LOCOS process, (c) after metallization and oxide etching.

Si-doped GaN film was grown on a (0001) sapphire substrate at a temperature of 1020 ℃ by MOCVD. The

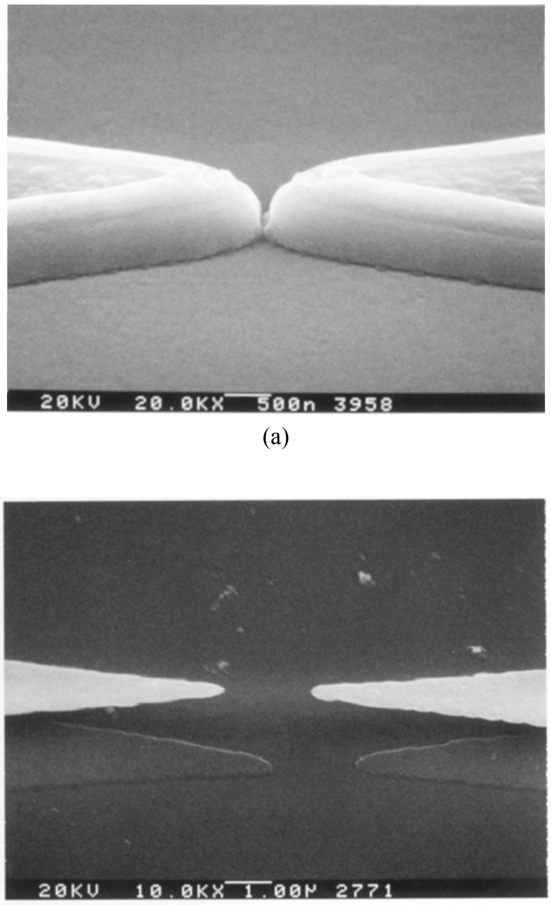


(a)

(b)

Fig. 2. Schematic views of the fabricated lateral type GaN field emitters: (a) fabricated device by ECR-RIE etching, (b) by selective regrowth of GaN layer.

respective Ga, N, and Si precursors were trimethylgallium (TMGa), ammonia (NH_3), and SiH_4. Prior to the epilayer growth, the wafers were cleaned by H_2 ambient at 1020℃, then a 34 nm-thick low temperature GaN buffer layer was grown at 550℃. During the growth, the chamber pressure was maintained at 300 torr. The thickness of n$^+$-GaN films was about 1.5 μm. For the electrode formation, the top two layers of n$^+$-GaN/LT-GaN were selectively etched down to the sapphire substrate using ECR-RIE. The Al contact was prepared by thermal evaporation of Al and subsequently annealed for 30 min. at 400 ^{o}C in nitrogen ambient. Since the GaN-based material has shown a high physical and chemical stability, the etching process was one of hard jobs during fabrication flow. The other type GaN-based field emitter was proposed as shown in Fig.2 (b). A Si_3N_4 of 2000 Å thickness as a masking layer was firstly deposited directly on the 1.5 μm-thickness GaN film by PECVD. Then, the Si_3N_4 layer was etched away selectively by BHF solution via photolithographic definition of the electrodes. Finally, the n$^+$-GaN layer was selectively re-grown on undoped GaN by MOCVD.



(a)

(b)

Fig. 3. SEM photographs of fabricated lateral field emission diode. (a) image after LOCOS, (b) image after BHF etching.

III. RESULTS AND DISCSSION

A. *A lateral type poly-Si field emission diode*

Fig. 3(a) shows scanning electron microscopy (SEM) photograph of the fabricated device after the LOCOS. The emission layer is n$^+$-polysilicon with a concentration of ~$8\times10^{20}/cm^3$, mobility of ~12 $cm^2/V\cdot s$ and sheet resistance of 15 Ω/□. The distance between the anode and the cathode was approximately 3 μm. Both anode and cathode tip can be sharpened by the LOCOS process and separated by the subsequent selective oxide etching process, as shown in Fig. 3(b). The substrate was electrically isolated from the tips by buried oxide. Prior to the electrical measurement, the samples were loaded into a vacuum chamber in a pressure of about 6×10^{-7} torr and heated at 200 ^{o}C for 3 h to eliminate water vapor or other residual contaminants near the electrodes. The measurements were performed with a semiconductor parameter analyzer (HP4145). Fig. 4 shows the diode current-voltage (I-V) characteristics between anode and cathode for single device. The applied DC voltage from power supply (HP4145) was first varied from 0 V to 200 V. The turn-on voltage was about 60 V and emission current of 200 nA at V_{AC} = 150 V. To obtain stable and large emission current, the high field DC shock activation was carefully carried out between anode and cathode [16].

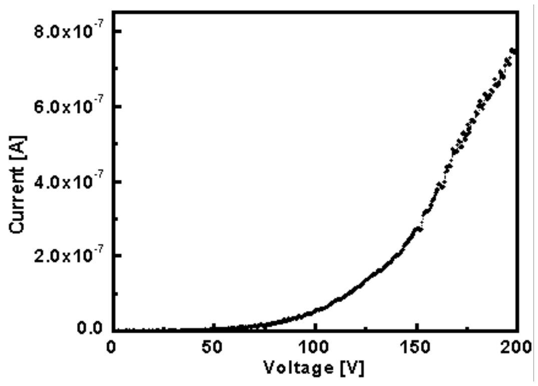


Fig. 4. Initial I-V characteristics of the poly-Si field emission diode before appropriate activation.

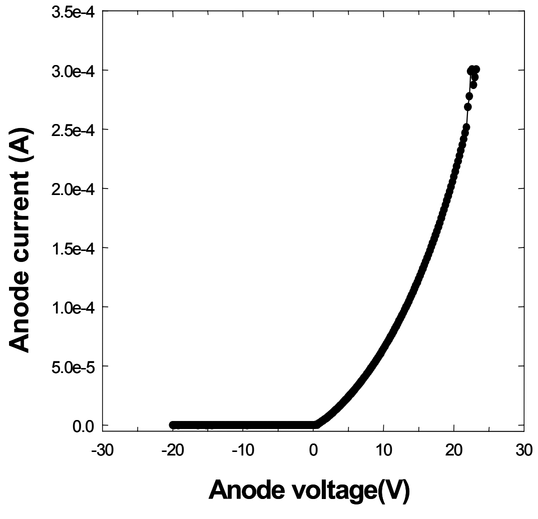
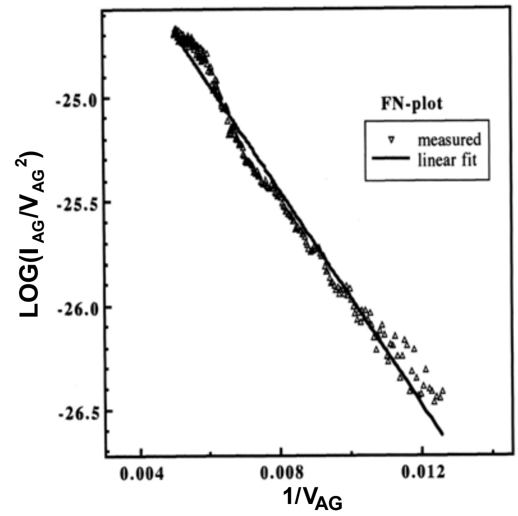


Fig. 5. I-V characteristics of the fabricated diode after appropriate activation.

Fig. 5 shows the diode I-V characteristics between anode and cathode after appropriated activation. Turn-on voltages were gradually decreased after appropriated activation and correspondingly the emission currents are rapidly increased. The turn-on voltage was reduced to 2 V and the emission current was increased to 300 μA at V_{AC} = 25 V after appropriate activation.



(a)

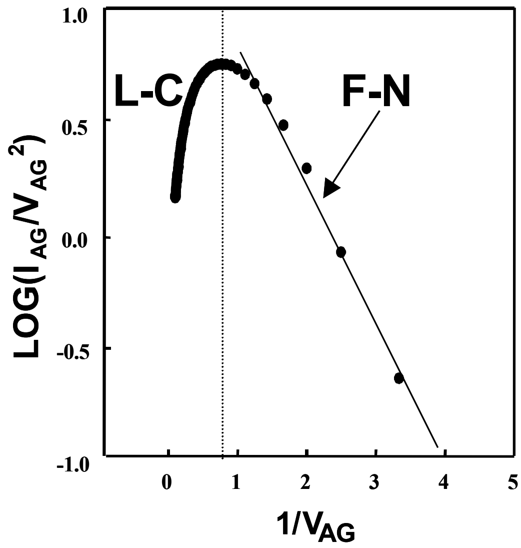


Fig. 6. Fowler-Nordeim plot of I-V curve between anode and cathode (a) before appropriate activation (b) after appropriate activation.

The basic field emission relationship between the emission current I in amperes and the applied voltage V in volts is obtained from the Fowler-Nordheim (FN) equation[11] given by

$$\log(I/V^2) = \log(a) + 0.434(-b/V) \tag{1}$$

where,

$$a \cong 1.5\times10^{-6}\frac{\alpha}{\varphi}\beta^{2}\exp(10.4/\varphi^{0.5})$$

$$b \cong 6.44\times10^{7}\frac{\varphi^{3/2}}{\beta},$$

α is emitting area in cm^2, φ is the work function in eV, and β is field enhancement factor in cm^{-1} which is dependent on the electrode configuration. Fig. 6(a) corresponds to a FN plot (converted from Fig. 4) for inactivated device. The linearity of the plot indicates that the current is originated from the field emission. From the slope and the y-axis intersection of FN plot, the field enhancement factor (β) were estimated about 3.6×10^{7} cm^{-1} and the effective emitting area (α) was about 3.9×10^{-18} cm^2, assuming poly-Si work function of 4.1 eV. Fig. 6(b) shows the FN plot (converted from Fig. 5) of the appropriate activated device. Normal FN plot with a negative slope was observed below anode voltage of 0.8 V, but the emission behavior was suddenly changed with large positive slope at anode voltages larger than 0.8 V.

From the approximated field conversion factor (β) suggested by F. M. Charbonnier *et al.* [17,18] and assuming tip structures were kept same before and after activation process, a useful equation can be derived as,

$$\frac{\Phi_2}{\Phi_1} = \left(\frac{S_2}{S_1}\right)^{\frac{2}{3}}\left(\frac{r_2}{r_1}\right)^{\frac{4}{9}} \qquad (2)$$

where $\Phi_{1,2}$ is the effective work function, $S_{1,2}$ is the slope of FN curve, and $r_{1,2}$ is the tip radius. 1 and 2 stand for inactivated and activated cathode tip, respectively. In this calculation, assuming $r_1=r_2$, the effective work function of the activated cathode tip was calculated to be 0.5 eV. This is believed to be due to a strong surface modification that can induce a quasi-zero electron affinity at tip surface as well as locally sharp atomic scale protrusions appeared on the surface of the tip resulting in an increase of emission site density and the field enhancement effect [14]. When the emission current was small, the FN plot was almost linear. As the emission current increases, the magnitude of slop becomes gradually and eventually becomes positive. This is due to the screening effect caused by large space charge, which is thought limit the emission current from the tip-end at an increased field. The large space charge effect can be suggested to be responsible for this observation changing the well-known FN relation to the typical Langumuir-Child (LC) equation [17], which saturates the increasing rate of the emission current from the tip-end [18].

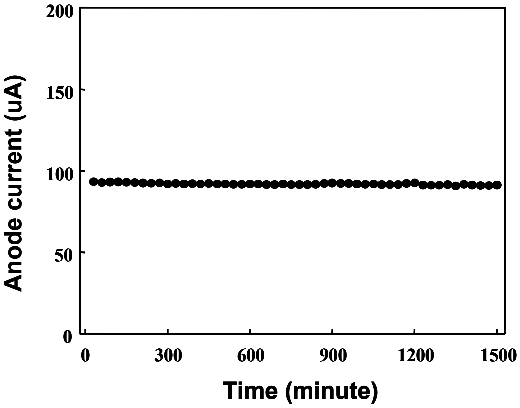


Fig. 7. Time variation of the field emission current.

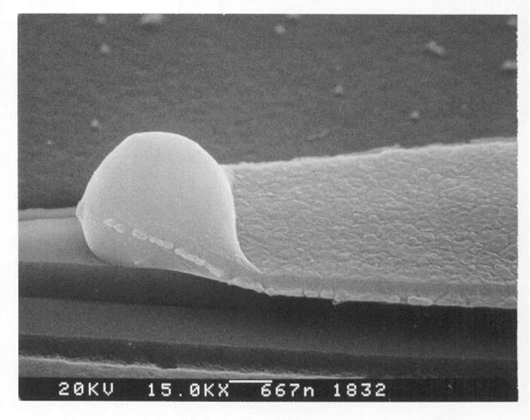


Fig. 8. SEM photographs of cathode tip after high field DC shock activation.

Fig. 7 shows the long-term stability of the field emission current between anodes and gates after appropriate activation. Under the bias condition of V_{AG} = 13 V, it shows a stable emission current of 97 μA with only ±1.5 % fluctuations over 25 h.

During this activation, however, significant electron overheating by Nottingham effect and Joule-heating.

might occur and hence frequently totally destroy the whole devices [18-20]. Fig. 8 shows SEM photographs of tip shape after high field DC shock activation, which is illustrating that a cathode tip can be catastrophically melted. Therefore, one should be very careful for the activation treatment.

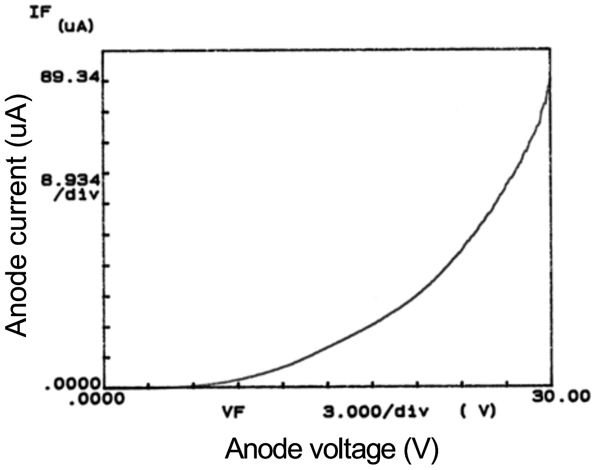


Fig. 9. I-V characteristics measured under high vacuum after 2 hr. in atmosphere.

Fig. 9 shows the diode I-V characteristics between anode and cathode measured again under about 6×10^{-7} torr after 2 hr. in atmosphere. The turn-on voltage was increased 10 V and the emission current was decreased 70 μA at V_{AC} = 25 V due to oxidation of poly-Si surface. To maintain a high emission current, therefore, it is need to develop surface treatment avoiding surface oxidation for microwave device application.

B. *Lateral type GaN field emission diodes*

Fig. 10 shows a SEM photograph of fabricated lateral type GaN diode using the ECR-RIE. The concentration of n^+-GaN layer is abut ~5×10^{18}/cm^3. Thedistance between anode and cathode is about 7 μm. This gap is lager 3 times than the original deigned pattern due to difficulty of GaN-etching. Fig. 11 shows the current-voltage (I-V) characteristics between the anode and cathode using the ECR-RIE. The turn-on voltage was as low as 35 V and the emission current was ～580 nA/10tips at anode-to-cathode voltage of 100 V.

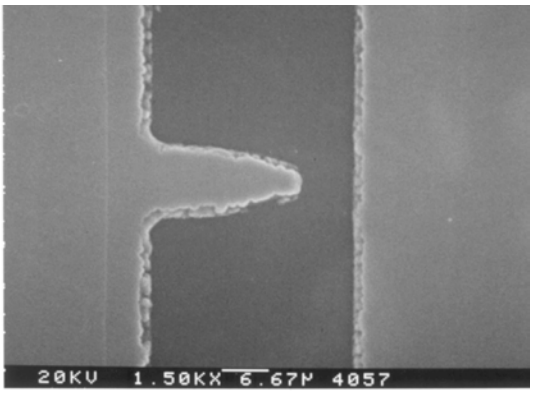


Fig. 10. SEM photograph of fabricated device using the ECR-RIE.

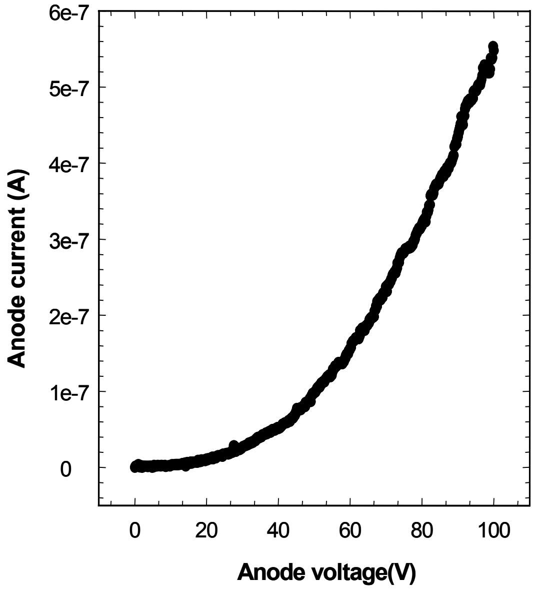


Fig. 11. I-V characteristic between anode and cathode using the ECR-RIE.

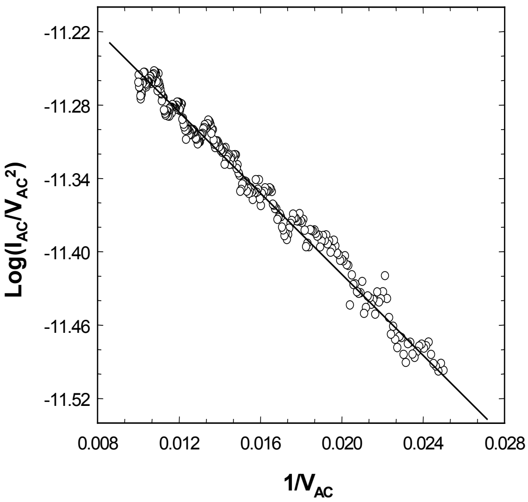
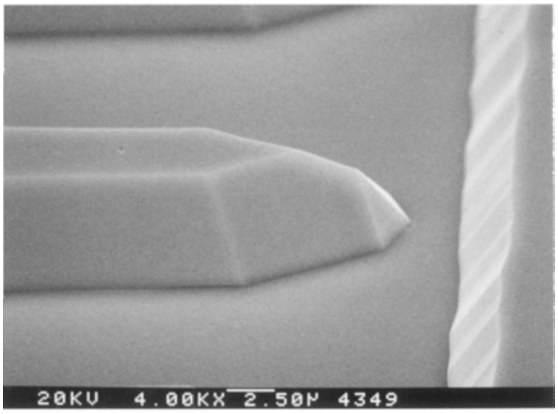


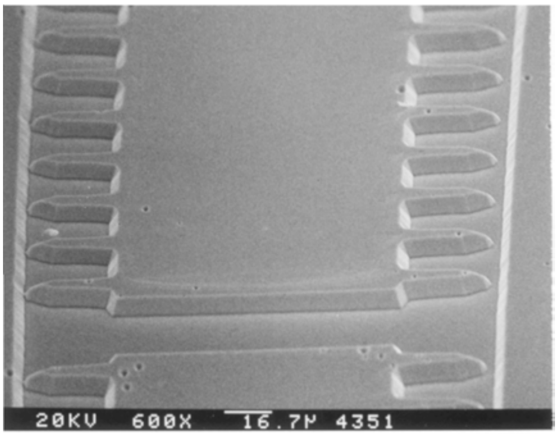
Fig. 12. Fowler-Nordeim plot of I-V curve shown in Fig. 10.

Fig. 12 shows the FN plot converted from I-V characteristics of the diode. The good linearity of FN plot indicates that the current is evidently from the field emission phenomena. These superior field emission characteristics are believed to be due to a low electron affinity as well as the shorter inter-electrode distance. Fig. 13 shows SEM photographs of selective re-grown

n^+-GaN emitters on undoped GaN by utilizing Si_3N_4 film as a masking layer. Compared to lateral type GaN field emission diode using ECR-RIE, re-grown GaN emitters shows sharper shape tips and shorter inter-electrode distances. Detailed emission behaviors are under investigation by introducing a new field emission model with a consideration of statistically distributed tip radiuses.



(a)



(b)

Fig. 13. SEM photographs of re-grown GaN emitters using Si_3N_4 mask (a) sing emitter, (b) emitter arrays.

Ⅳ CONCLUSION

We have fabricated two lateral type field emission diodes by utilizing LOCOS and lateral type GaN field emission diode using MOCVD process. The fabricated poly-Si diode exhibited excellent electrical characteristics such as a very low turn-on voltage of 2 V and a high emission current of 300 ㎂/tip at the anode-to-cathode voltage of 25 V. These field emission characteristics was speculated as a result of strong surface modification inducing a quasi-negative electron affinity and the increase of emitting sites dueto local sharp protrusions by an appropriate activation treatment. In the other method of lateral type GaN emitter, two kinds of procedures were proposed: a selective etching method with ECR-RIE or a simple selective growth by utilizing Si_3N_4 film as masking layer. The fabricated device using the ECR-RIE exhibited electrical characteristics such as a turn-on voltage of 35 V and an emission current of ~ 580 nA/10tips at anode-to-cathode voltage of 100 V. These superior field emission characteristics are believed to be due to a low electron affinity as well as the shorter inter-electrode distance. Compared to lateral type GaN field emission diode using ECR-RIE, re-grown GaN emitters shows sharper shape tips and shorter inter-electrode distances.

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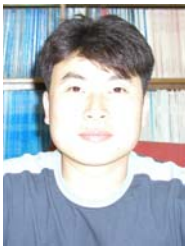

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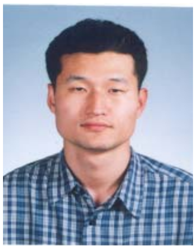

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