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Effect of the Hybrid Etching Methods on the Field Emission Characteristics of Mo-Tip Field Emitter Arrays

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Changes of the electron emission properties of the field emitter arrays (FEAs) were studied with the variations of oxide etching methods for defining the gate hole. In this study, we introduced a new hybrid etching process, which combines wet and dry etchings for gate hole formation and two kinds of Spindt-type Mo-tip FEAs having different structures of gate insulator were fabricated on heavily doped n-type Si wafer: FEAs with a dry-type gate-insulator by dry etching (dry-type FEAs) and FEAs with a hybrid-type gate-insulator by hybrid etching (hybrid-type FEAs). We found that the field emitter formed by the hybrid-type method revealed less gate leakage current than that of the dry-type FEAs, in which the gate insulator edge lies at the same line with the edge of gate metal. Numerical simulation results agree well with the experimentally observed results. Furthermore, the emission properties for the hybrid-type FEAs were found to be more stable over the operating time than those of the dry-type FEAs. Therefore, we suggest that the FEAs formed by the hybrid etching method may be suitable for a high-performance field emission display.

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Field emission display (FED) is a promising flat panel display (FPD), which provides a superior brightness, wide viewing angle, variety of colors, fast response time, and wide range of operating temperatures. Though some prototypes of FEDs are realized,[1,2] until now the success in its manufacturing depends on the fabrication technologies for uniform and stable field emitter arrays (FEAs), spacers with a high aspect ratio, and a low voltage phosphor.

Most research on FEAs was focused on lowering the threshold voltage and increasing the emission current.[3,4] However, to improve the operating stability of FED, making FEAs with less gate leakage current is one of the most important issues. It is well known that the stability of FEAs depends on the geometrical shape both of the field emitter and the gate insulator.[5-9] Some simulation results[6] suggest that an emission current increases with the edge slope of the insulator, and the maximum electric field is obtained when the insulator edge lies at the same level with the gate edge. In the case that a vertical shape of gate insulator can be formed by dry etching, which has higher electric field on the tip apex and the gate insulator, so, the dry-type FEAs in which the insulator edge lies at the same level with the gate edge can have higher emission current and higher gate leakage currents. In this case, to decrease the gate leakage current of dry-type FEAs while the emission current increases, several processes with different etching steps have been used.[10,11]

This work begins by considering that the etched shape of gate insulator can be one of the most important parameters for improving the emission stability of the FEAs. Based on this assumption, we carried out a new etching process for Mo-FEAs called a hybrid etching method to optimize the shape of the gate insulator. Electron emission currents were measured for the two kinds of FEAs corresponding to each etching method and the electric field distribution on the tip apex and gate insulator were simulated for the two kinds of single triode using a simulation tool of SNU-FEAT [6] which is discussed.

Experimental

As a first step, the electric field on the apex of a tip and a gate insulator for an emitter were simulated by using an SNU-FEAT program.[6] This program is based on finite element method (FEM) analysis, and includes the routines of automatic mesh generation and device analysis. Next, two kinds of Spindt-type Mo-tip FEAs were fabricated on a heavily doped n-type silicon wafer, FEAs with a dry-type gate-insulator by dry etching, and FEAs with a hybrid-type gate-insulator by hybrid etching. The fabrication process for all FEAs in this work is fundamentally the same as that reported by Spindt *et al*.[12] Thermal oxide of 1.1 and 0.25 μm thick sputtered Cr layers were deposited sequentially on heavily doped n-type Si wafer, and after the defining of 1.5 μm diam holes by photolithography, the gate metal layer was etched by reactive ion etching (RIE) with a mixture of 50% O_2 and 50% Cl_2 at the rf power of 150 W. Then the gate insulator was opened by two kinds of etching methods, dry etching by RIE with a mixture of 33.3% Ar and 66.7% CHF_3 at the rf power of 200 W (dry-type FEAs) and hybrid etching which combines wet and dry etchings sequentially (hybrid-type FEAs). Figure 1 shows the details of our hybrid etching process. First, SiO_2 was etched by dipping in buffered oxide etch for 5 min after patterning the gate metal. This specimen was then exposed to plasma for dry etching the remnant SiO_2. Then, an Al sacrificial layer was deposited by electron beam evaporation and during the deposition, the substrate was rotated and tilted about an axis perpendicular to its surface. Mo was evaporated onto the specimen with normal incidence, and the size of the gate hole decreases with increasing the thickness of evaporated Mo layer due to the condensation of Mo on its periphery. Finally, the Mo layer on the gate metal was dissolved by an Al etching solution. After a drying process to clean up the FEAs from the Al etching solution, the samples were then mounted in a high vacuum chamber to measure current-voltage (*I-V*) characteristics. The two kinds of FEAs were processed together under the same conditions, except for the gate hole formation, in order to make a comparison.

Results and Discussion

Theoretical simulation.—Simulation had been carried out for the geometrical parameters such as apex radius, tip height, vertical position of tip, tip angle, and gate hole diameter. In these simulation results, we can see that the emission current increases with increasing the edge slope of the insulator, and the maximum electric field can be obtained when the insulator edge lies at the same line with the gate edge.[6] Figure 2 shows the simulation results for an electric field of the two kinds of emitters. Especially, the simulation was conducted to obtain the etched shape of a gate insulator. The thicknesses of the gate electrode, the gate insulator, and the tip height were fixed at 0.25, 1.1, and 1.4 μm, respectively. The other input parameters were selected based on the estimation from scanning electron microscopy (SEM) image of the emitter. Gate and anode voltages were fixed at 100 and 300 V, respectively, and the equidistant electric field lines were drawn at 1 MV/cm. In Fig. 2, we can see the maximum electric field on the gate insulator above the etched line of gate insulator, and the distribution of electric field is changed by the etched shape of a gate insulator. From the results, we could understand that the

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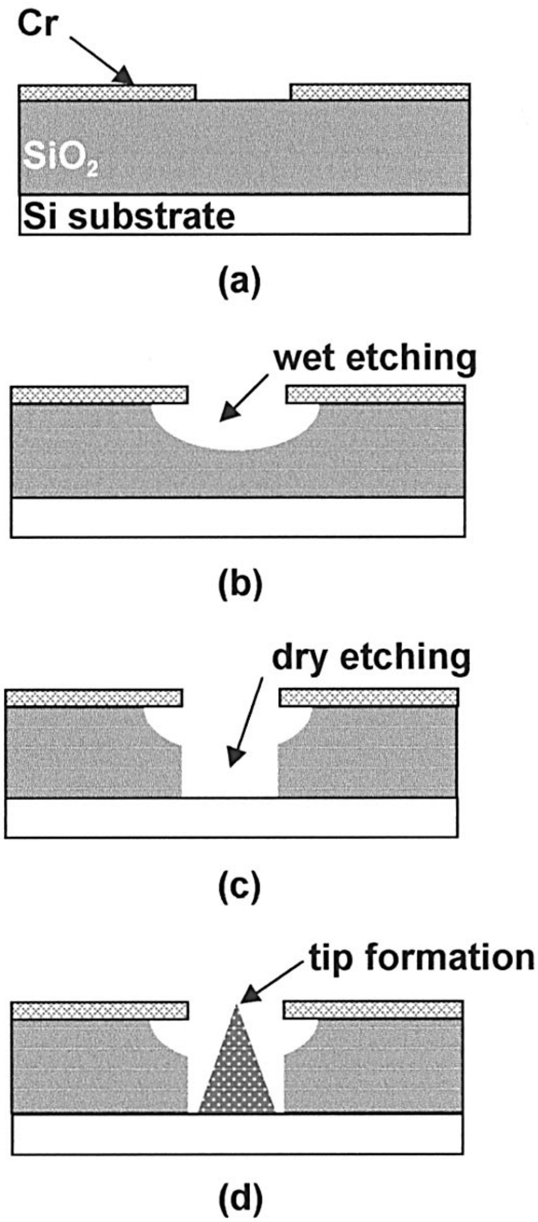

Figure 1. The fabrication procedure of hybrid-type FEAs: (a) gate metal etching; (b) wet etching of gate insulator; (c) dry etching of gate insulator; (d) formation of Mo tip.

etched shape of the gate insulator clearly affects the electric field on both the tip and the gate insulator. Figure 3 shows the simulation results for the maximum electric field on a tip and gate insulator. In this figure we can see that the electric field on tip and gate insulator in the hybrid-type emitter are smaller than those in the dry-type emitter, but there is a difference in the amount of reduction in the electric field on the tip and gate insulator. In the case of the hybrid-type emitter, the reduction of the electric field on a gate insulator is 9.3% while that of electric field on a tip is 0.7%. Thus, it means that the distribution of the electric field on the tip apex and gate insulator has a strong dependence on the etched shape of the gate insulator. Through the obtained observations, we understand that the etched shape of the gate insulator is one of the most important parameters. It is a noticeable fact that there is a difference of reduction rate in electric field on tip and gate insulator by adopting a new etching method (hybrid etching method).

Experimental results.—First, we investigated the change of breakdown electric field of gate insulator with the process flow

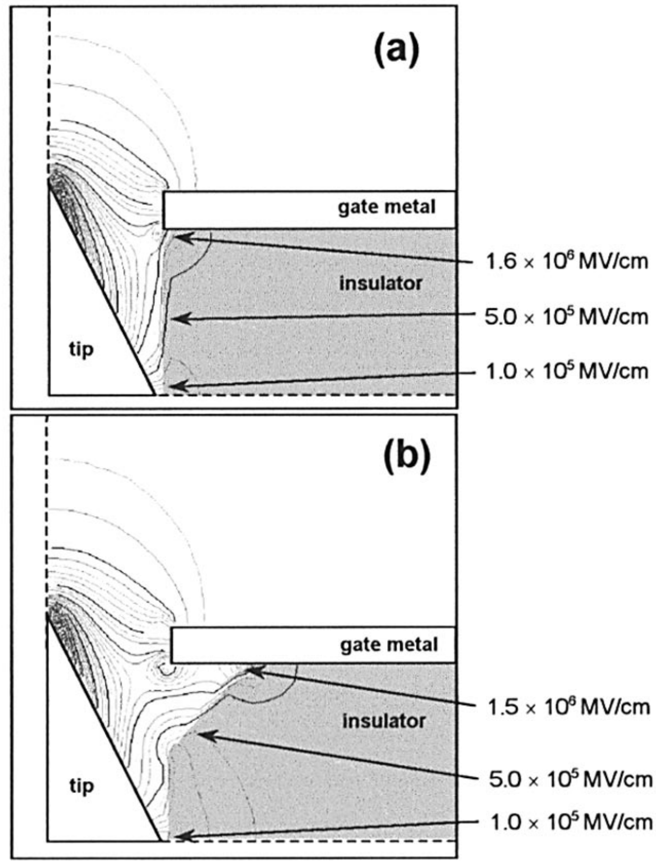

Figure 2. Simulation results of electric field in a triode field emitter with (a) a dry-type and (b) a hybrid-type gate-insulator openings.

before the tip formation process (Fig. 4). The gap between the ground and the biased electrode was about 1.1 μm in thickness (oxide thickness) and the contact area to measure the breakdown electric field was set to 2.0×10^{-3} cm^2. In the figure, we can see that the breakdown electric field was slightly decreased after the Cr etching process. It means that the Cr etching process for patterning the gate hole did not affect the properties of the gate insulator. Also, the breakdown electric field abruptly decreased after the oxide etching process and also that of the gate insulator was changed with the variation of etching methods, and the hybrid-type gate insulator has

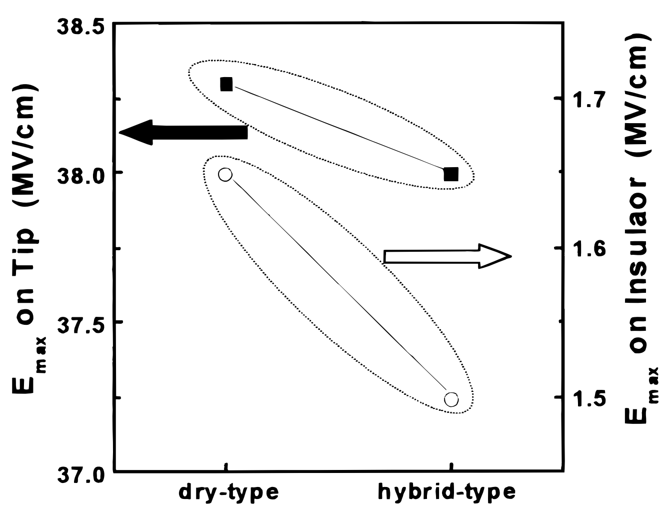

Figure 3. Comparison of the maximum electric fields on an apex of tip and on a gate insulator of (a) a dry-type emitter and (b) a hybrid-type emitter.

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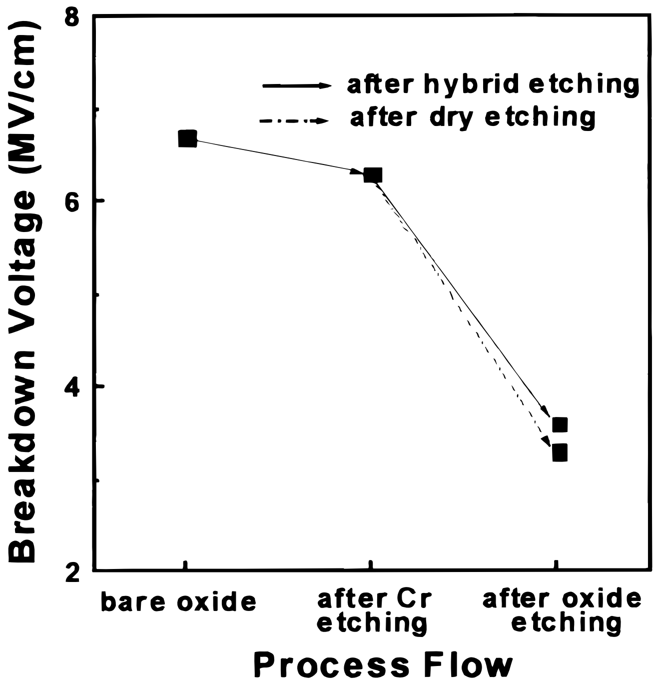
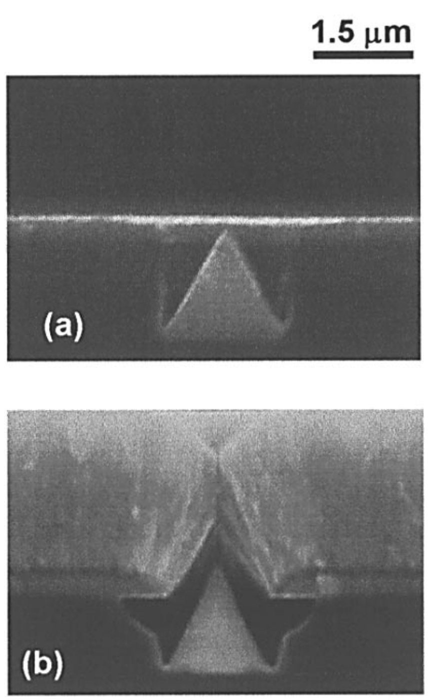


Figure 4. Changes in the breakdown voltage upon process flow.

the higher breakdown electric field than that of dry-type insulator. These results can be explained by the abrupt decrease in the breakdown electric field after oxide etching as being due to the impose the high electric field at the gate insulator edge. Also, we can consider that the difference of breakdown electric field as a function of etched shape of gate insulator resulting from the fact that the applied electric field on the etched shape of the gate insulator edge has a different distribution.

Figure 5 shows the cross-sectional views of the two kinds of FEAs. Figure 5b is a typical scanning electron microscope micrograph (SEM) of the hybrid-type emitter before the lift-off process. In



Figue 5. The typical SEMs of (a) a dry-type and (b) a hybrid-type emitters.

this figure, we can see that Mo-tip field emitter was well defined within the hole by decreasing the size of the hole with increasing the thickness of evaporated Mo layer. Here, the emitter height, gate hole diameter, and thickness of the insulating layer in two kinds of FEAs were 1.4, 1.5, and 1.1 μm, respectively. The observed profiles indicate that the maximum electric field decreased and the change of electric field distribution on gate insulator easily occurred, because the upper part of dry-type gate insulator where the maximum electric field is applied on the gate insulator was overetched by the wet etching.

Figure 6a shows the current-voltage characteristics for the FEA consisting of 900 emitters. An anode plate was placed at 700 μm above the gate and was biased +300 V. A ZnO thick film on an indium tin oxide (ITO) glass was used as an anode electrode for the measurements. Both the anode and gate leakage currents were measured as a function of gate-to-cathode bias voltage in a vacuum of 4×10^{-8} Torr using a Keithley source and measurement unit of 237. During the measurements, the device was in a common emitter configuration having the emitter grounded, so, that the anode was at a positive voltage and the gate was driven positive to turn the device on. The turn-on voltages of the dry-type and hybrid-type FEAs are 46 and 49 V, respectively. When the gate was biased at +100 V, the anode currents for the dry-type and hybrid-type FEAs were 119.84 and 107.67 μA, and the gate leakage currents for the two samples were 76.5 and 16.7 μA, respectively. Note that the gate leakage current of the hybrid-type FEAs showed a lower value than that of dry-type FEAs while the anode current of the hybrid-type FEAs has almost the same value compared to that of dry-type FEAs. From this result we could understand that dry-type FEAs have both the highest anode current and gate current because of highest electric field on tip and gate insulator. By overetching the upper part of dry-type gate insulator, the maximum electric field on the gate insulator is decreased compared to dry-type FEAs and the maximum electric field on the tip is not decreased. This means that the hybrid-type FEAs may be suitable for the reduction of the gate leakage current without reduction of the anode current. These results agree well with the previous results mentioned in Fig. 2.

Figure 6b shows the Fowler-Nordheim (F-N) plots for the current-voltage characteristics. From the linearity in this plot, it is clear that the current originated from the field electron emission under the high field. Generally, the emission current density (*J*) of FEAs is described by the F-N equation

$$J = \frac{AE^2}{\phi t^2(y)} \exp\left[-B\frac{\phi^{3/2}}{E}v(y)\right] \qquad [1]$$

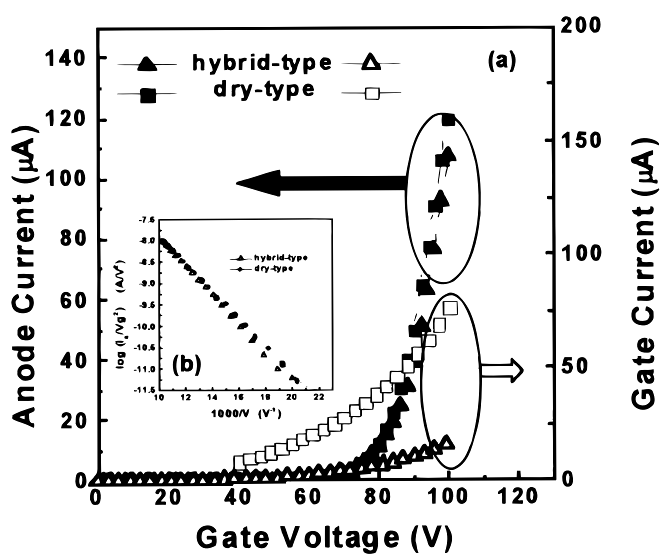


Figure 6. Current-voltage (a) characteristics and (b) F-N plot for the two kinds of FEAs.

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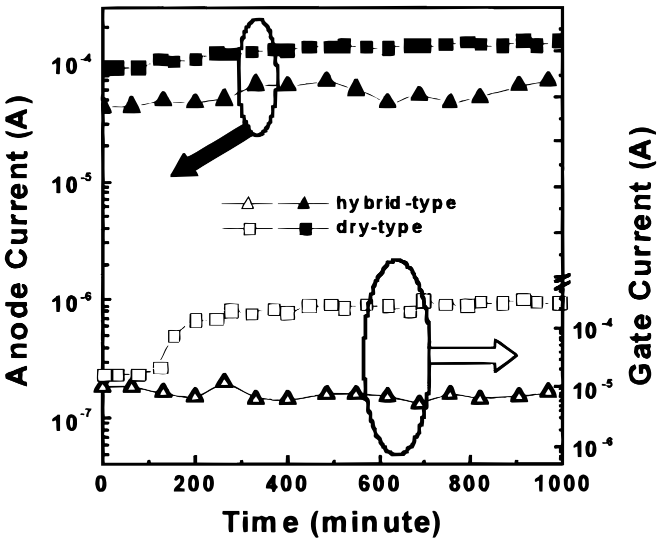

Figure 7. Time-dependence of anode current and gate current for the two kinds of FEAs.

where E is the electric field (V/cm), ϕ is the work function of the emitter material (eV), A and B are the parameters of 1.54×10^{-6} and 6.87×10^{-7}, respectively, $v(y)$ and $t^2(y)$ are the Nordheim elliptic function, and y is the Schottky lowering of the work function barrier expressed in Eq. 2

$$y = 3.79 \times 10^{-4} \frac{\sqrt{E}}{\phi} \qquad [2]$$

The electric field at the tip due to an applied voltage is typically given by

$$E = \beta V \qquad [3]$$

where β is one of the most critical geometric factors and V is applied voltage.[13]

In this F-N equation, we can roughly calculate the field conversion factor (β) from the slope of this plot. If the work function of molybdenum is 4.5 eV, the calculated field conversion factor (β) for dry-type and hybrid-type FEAs is 3.95×10^5 and 3.86×10^5 cm^{-1}, respectively. Thus, we can understand that the emission property of hybrid-type FEAs is the same as that of dry-type FEAs, and this result support previous results.

Another important factor, the long-term stability for the improved properties of hybrid-type FEAs, *i.e.*, higher electric field on tip and lower electric field on the hybrid-type gate insulator, should be evaluated with respect to device application. Especially, the stability and the behavior of gate leakage current in FEA gives practical information on the field emitter. Thus, we investigated the stability for two kinds of the FEAs. Figure 7 shows the time-dependence of the anode current and the gate current of the two kinds of FEAs. The measurement was done for 1,000 min, and the anode and gate were biased at +300 and +100 V, respectively. Though the test is a very accelerated stress condition for the FEA, the results show that both the anode and gate current of two kinds of FEA were stable over time. In the case of dry-type FEA, the anode current was stable with the operating time but the gate current abruptly increased after the elapse of 2 h. In the case of the hybrid-type FEA, anode current and gate current were stable enough to operate as an electron source. Therefore, we can conclude that hybrid-type FEA has more stable properties than the dry-type FEA through the optimized etched shape of gate insulator.

Conclusions

In this work, the etched shape of the gate insulator was optimized to enhance both the emission current and to reduce the gate leakage current by the hybrid etching method to form the gate hole without increasing the packing density or over-coating the tips. The emission characteristics of the Mo FEAs were studied using a variation of etching method for the gate holes and the greatest enhancement in the electron emission property was achieved by changing the etched shape of the gate insulator. The hybrid-type FEAs using wet and dry etchings have almost the same field conversion factor (β) and less gate leakage current than that of dry-type FEAs which the gate insulator edge lies at the same line with the gate edge. Also, the electric field distribution on the tip apex and gate insulator was estimated for a single triode using a simulation tool. Simulation results agree well with experimental results for the emission currents observed.

Furthermore, the hybrid-type FEAs have long-term stability with the improved properties, *i.e.*, a higher electric field on the tip and a lower electric field on the hybrid-type gate insulator.

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