Journal of Ceramic Processing Research. Vol. 8, No. 4, pp. 261~265 (2007)

J O U R N A L O F
Ceramic Processing Research

Synthesis of ZnO nanorods and their application to hybrid plasma display panels for reduction of discharge voltages

Sang-Hoon Yoon, Heesun Yang* and Yong-Seog Kim
Department of Materials Science and Engineering, Hongik University, Seoul 121-791, Korea

An array of ZnO nanorods was grown by thermally evaporating Zn metal in the presence of oxygen molecules on various Au-deposited substrates (PbO/glass, SiO_2/PbO/glass, and Al_2O_3/PbO/glass), and incorporated onto the front panel of plasma display panels (PDPs), forming a hybrid PDP. In an effort to obtain reasonable transmittance of visible light through the front panel of a PDP, the areal density of ZnO nanorods was controlled by patterning the Au seed layer on the substrate in a cubic array of circles by a conventional lift-off process. The resulting transmittance varied from 40-50%, depending on the area fraction of ZnO nanorods. The discharge voltage, luminance, and efficiency of ZnO nanorod-based hybrid PDP were characterized, indicating that the use of ZnO nanorods may provide an effective way of reducing discharge voltages of PDP.

Key words: ZnO nanorods, plasma display panel, hybrid, transmittance, areal density, discharge voltage.

Introduction

Owing to the great potential of ZnO in applications including light-emitting diodes, UV lasers, solar cells, photodetectors, and gas sensors, nanometre-sized ZnO crystals have been one of the most intensively studied nanomaterials [1-4]. One-dimensionally grown ZnO nanocrystals (nanowires, nanorods, nanotubes, and nanowhiskers) are of substantial interest due to their unique properties such as a highly polarized photoluminescence [5], a lower lasing threshold [6], and field emission characteristics [7-9]. An array of ZnO nanorods or nanowires, which are aligned parallel or perpendicular on the substrate with a specific pattern, is of particular importance for the development of novel applications.

The characteristics of plasma display panels (PDPs) including luminance efficiency, discharge voltage, and addressing delay need to be further improved in order to compete with other types of flat panel displays. The reduction of discharge voltage, in particular, is very important since the luminance of PDP increases with a decrease in sustaining voltage. In addition, a reduction in discharge voltage is beneficial in cutting the cost of electronic and electrical parts and the materials used in a device. The discharge voltage is mainly determined by the coefficient of secondary electron emission of the MgO protective layer on the dielectric layer of the front glass plate. A great deal of research efforts has been directed to increase the coefficient of secondary electron emission by patterning [10], changing the preferred orientation [11], and alloying the MgO layer [12-15]. However, these studies had only led to limited improvements in the coefficient of secondary electron emission and subsequently in the discharge voltage.

In an attempt to increase the secondary electron emission coefficient of MgO, our research group proposed a concept of a hybrid PDP [16]. Carbon nanotubes (CNTs) have been demonstrated as a promising material for field emitters due to their high mechanical stability, high aspect ratio, and high conductivity [9, 17]. In our previous hybrid PDP, CNTs planted on the surface of the transparent dielectric layer acted as field electron emitters under the electric field of the PDP, leading to an apparent increase in the coefficient of secondary electron emission from the MgO protective layer. This study demonstrated that the discharge voltage could be reduced considerably and the luminance be increased dramatically with this type of hybrid PDP. The use of CNTs on the surface of the dielectric layer, however, was limited by agglomeration and oxidation of CNTs during the processing [16].

In addition to CNTs, one-dimensionally grown gallium nitride (GaN) and ZnO as field emitters were also investigated because of their negative electron affinity, high mechanical strength, and chemical stability [9]. In this study, a hybrid PDP was developed with arrayed ZnO nanorods which are grown by thermal evaporation on the surface of the transparent dielectric layer of the front plate. ZnO nanorods were formed rather uniformly and are inherently more stable compared with CNTs. In addition, ZnO nanorods are more resistant to plasma etching during plasma discharges, causing less outgassing during the device operation.

*Corresponding author:
Tel : +82-320-3039
Fax: +82-333-0127
E-mail: hyang@hongik.ac.kr

Experimental Procedure

A 3-5 nm thick metal film of gold (Au) on a ~20 μm thick dielectric layer (PbO)-coated glass substrate was deposited using a plasma sputtering process. The Au seed layer acts as a catalyst for ZnO nanorod growth. Then, ZnO nanorods were grown by thermally evaporating Zn metal under an oxygen atmosphere. A current of 20 A was applied for Zn evaporation and 10 sccm of oxygen was flowed into the chamber. The substrate temperature was kept at 250-300 °C during the growth. For the purpose of controlling the transmittance of visible light through the panel, the Au seed layer was patterned in a cubic array of circles (by a conventional lift-off process), onto which ZnO nanorod growth is predefined. Six different patterns with different circle diameters and inter-circle distances were formed (specified in Table 1). After the growth of ZnO nanorods on the patterned area, the sample was coated with a 100 nm thick MgO protective layer using an e-beam evaporation process. The front plate with the ZnO nanorods was sealed with a rear plate and filled with a Ne-Xe (4%) discharge gas at a gas pressure of 400 Torr (or 5.33×10^4 Pa). The discharge voltages of the panels were measured, and the luminance and luminance efficiency of the panels were evaluated as well. In order to grow longer ZnO nanorods, an additional layer such as 10 nm thick SiO_2 or Al_2O_3 was sputter-deposited on the dielectric layer and used for ZnO nanorod growth. Another hybrid panel with an array of ZnO nanorods grown on the Au/Al_2O_3 seed layer was fabricated and evaluated accordingly. The morphologies and microstructural features of ZnO nanorods grown on different substrates were investigated by field emission scanning electron microscopy (FESEM). A schematic diagram of the fabricated hybrid panel with the structure of a surface-discharge type of AC plasma display is shown in Fig. 1.

Table 1. Geometry of Au seed layer patterns in a cubic array of circles formed on the dielectric layer

Pattern features \ Pattern number	1	2	3	4	5	6
Circle diameter (μm)	20	20	10	10	5	5
Circle Pitch (μm)	40	80	20	40	10	20
Area fraction (%)	21.4	5.9	20.2	5.3	19.6	5.1

Results and Discussion

Figure 2(a) shows an SEM image of ZnO nanorods grown directly on the surface of Au/glass substrate without a dielectric layer. As seen from the micrograph, the diameter and the length of nanorods were approximately ~150 nm and ~1 μm, respectively. When the glass surface was coated with a transparent dielectric layer (Fig. 2(b)), ZnO nanorods were grown more randomly with a broader size distribution. Also in this case the areal density of the nanorods was decreased significantly.

By incorporating ZnO nanorods on the front plate of PDP, the areal density of the nanorods is crucial since it affects the transmittance of visible light through the front glass. When the density of nanorods is too high, the transmittance of visible light becomes negligible, reducing light transmittance through the front glass from the discharge cells. It was, in fact, difficult to

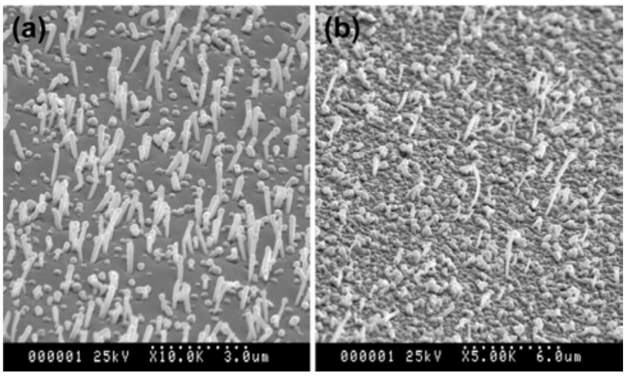

Fig. 2. Comparison of SEM images of Au seed layer-catalyzed ZnO nanorods grown on (a) glass substrate and (b) transparent dielectric layer-coated glass substrate. The scale bars in (a) and (b) are 3.0 and 6.0 μm, respectively.

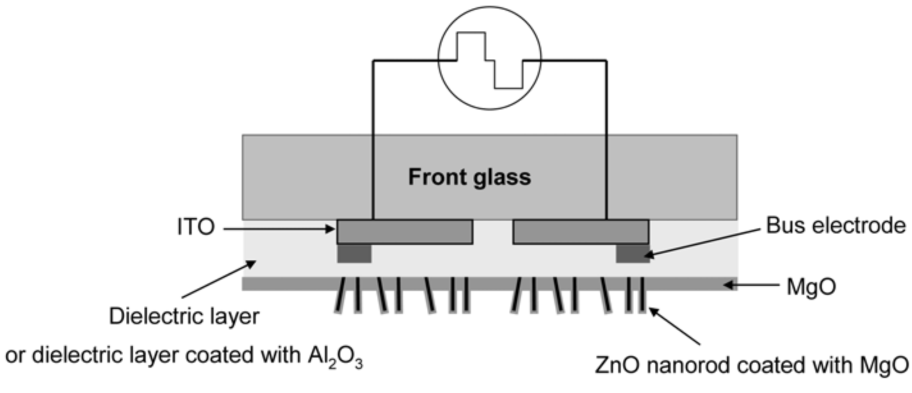

Fig. 1. Schematic diagram of the fabricated hybrid panel structure.

Table 2. Variations of discharge voltage as a function of sustaining frequency of hybrid PDPs with an array of ZnO nanorods grown on the front panel with pattern 6

	first cell-on	last cell-on	first cell-off	last cell-off
50 kHz	188	225	145	127
40 kHz	187	224	140	123
30 kHz	189	238	145	123
20 kHz	188	226	149	125
10 kHz	189	225	146	125

obtain a reasonable transmittance when the ZnO nanorods were grown uniformly on the whole surface of the dielectric layer. If the density of nanorods is too low, on the other hand, the emission of electrons from the nanorods would become negligible. In this study, therefore, a patterned Au seed layer was used for predefined ZnO nanorod growth. Here, six different patterns were formed, and the dimensions of each pattern are listed in Table 1. The transmittance of the front plate varied from 40 to 50%, depending on the area fraction of ZnO nanorods.

Table 2 shows the static discharge voltages measured at various sustaining frequencies with the hybrid PDP with pattern 6. The first cell-on and the last cell-on voltages were around 187-189 and 224-238 V, respectively. The first cell-on (firing minimum) voltages were decreased approximately by ~20 V compared with those of conventional PDPs. The first cell-off and the last cell-off voltages were in a range of 140-149 and 123-127 V, respectively. The last cell-off (sustaining minimum) voltages were decreased by ~10 V with the hybrid PDP with ZnO nanorods, compared with those of conventional PDPs. It is worth noting that with some hybrid panels, the first cell-on voltage was measured to be 105 V and the last cell-off voltage to be 93 V, demonstrating the possibility of a dramatic reduction in discharge voltages by the use of ZnO nanorods.

The luminance and luminance efficiency of the hybrid PDP were measured (Fig. 3). As seen from the Fig. 3(a), the luminance increased with the sustaining voltage as in conventional PDPs. In general, the luminance and luminance efficiency (Fig. 3(b)) for the panels with a smaller area fraction of the Au seed layer (patterns 2, 4, and 6) were slightly higher versus those with a larger area fraction. The discharge voltages, however, were not affected significantly by the variation of the area fraction of the ZnO pattern arrays, indicating the transmittance of visible light through the front panel directly determines the luminance and luminance efficiency.

ZnO nanorods grown on the dielectric layer surface were somewhat irregular in shape and length compared with those formed on the glass substrate. In this study, therefore, an additional layer of either 10 nm thick SiO_2 or Al_2O_3 was deposited onto the dielectric layer by a sputter process, followed by the Au seed layer coating with pattern 6. Figure 4(a) and (b) show SEM images

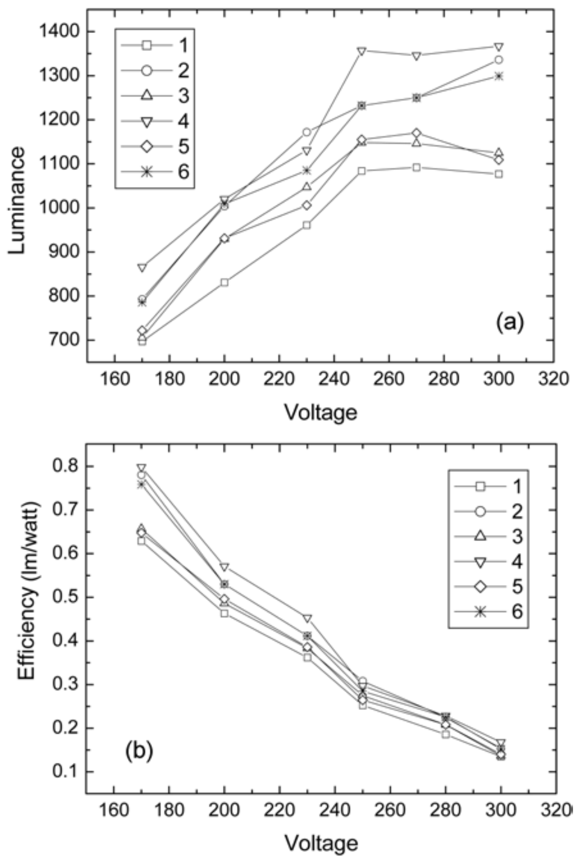

Fig. 3. Comparison of (a) luminance and (b) luminance efficiency of hybrid PDP as a function of sustaining voltage with different patterns (see table 1) of arrayed ZnO nanorods.

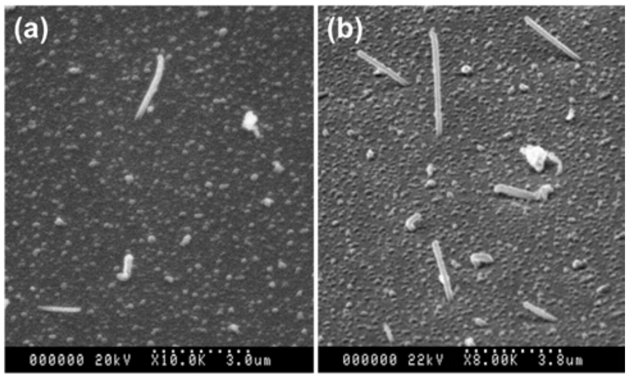

Fig. 4. SEM images of ZnO nanorods grown on (a) Au/SiO_2 and (b) Au/Al_2O_3 seed layers. The scale bars in (a) and (b) are 3.0 and 3.8 μm, respectively.

of ZnO nanorods grown on Au/SiO_2 and Au/Al_2O_3 seed layers, respectively. As seen from the figure, the nanorods grew rather significantly up to ~4 μm long. ZnO nanorods grown on the Au/Al_2O_3 seed layer (Fig. 4(b)) were more or less uniform in diameter and length. In addition, the areal density of the nanorods was higher with the Au/Al_2O_3 seed layer. An MgO protective layer was e-beam evaporated on the arrayed ZnO nanorods grown on Au/Al_2O_3 seed layer for the panel fabrication.

The discharge characteristics of the conventional

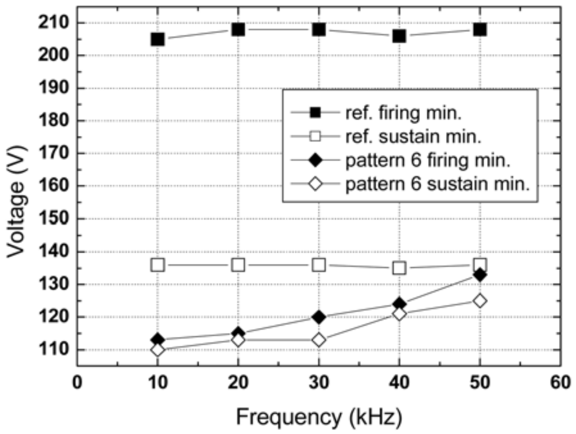

Fig. 5. Discharge characteristics of the conventional (reference) and the hybrid panel with pattern 6-based ZnO nanorods grown on a Au/Al_2O_3 seed layer as a function of the sustaining voltage frequency.

(reference) and hybrid panel above (pattern 6 used) were evaluated by measuring the static firing minimum (first cell-on) and sustaining minimum (last cell-off) voltages as a function of the sustaining voltage frequency (Fig. 5). With the presence of ZnO nanorods, the firing minimum and sustaining minimum voltages were decreased from 205-210 to 113-133 V and from 135-136 V to 110-125 V, respectively, indicating that more reduction in discharge voltages were observed in the hybrid panel with longer ZnO nanorods compared with that with shorter nanorods. It is believed that the significant reduction of the discharge voltage results from the field emission of electrons from the tip of ZnO nanorods induced by the electric field of PDP. It could be also speculated that longer ZnO nanorods (i.e., ones grown on the Au/Al_2O_3 seed layer) could exhibit more efficient field emission because a higher field enhancement (amplification) factor (β) can be realized from one-dimensional nanostructures with longer lengths and smaller diameters [17]. The luminance efficiency

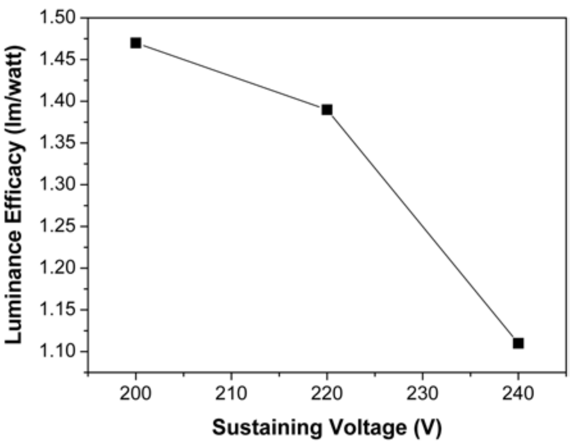

Fig. 6. Luminance efficiency of the hybrid panel with pattern 6-based ZnO nanorods grown on Au/Al_2O_3 seed layer as a function of the sustaining voltage.

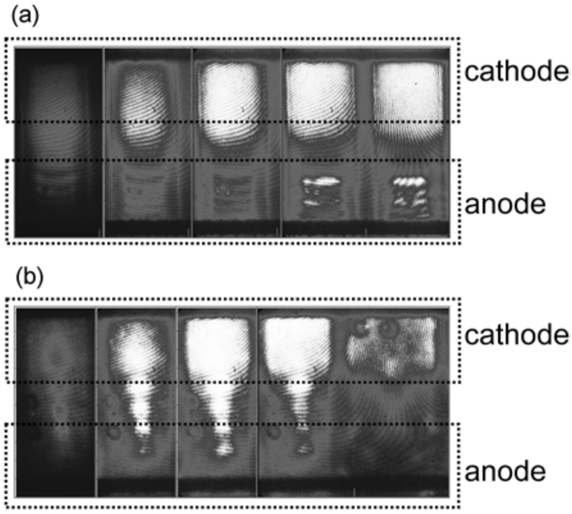

Fig. 7. Comparison of ICCD images of (a) reference panel and (b) hybrid panel. Both panels were operated under a discharge voltage of 240 V with a frequency of 30 kHz.

of the panel with pattern 6-based ZnO nanorods grown on Au/Al_2O_3 was evaluated at different sustaining voltages as shown in Fig. 6. The efficiency varied from 1.1 to 1.5 lm/watt. In order to investigate such a high luminance efficacy of the hybrid PDP, intensified charge coupled device (ICCD) images were taken from the discharge cells and compared with those from conventional PDP as shown in Fig. 7. With the conventional PDP prepared in our laboratory, a typical diffuse negative glow was generated on the surface of the cathode and striations on the surface of the anode. Interestingly enough, a quite different gas discharge behavior was monitored in the hybrid panel. A gas discharge with a stronger intensity and a different type of discharge mode were observed with the hybrid panel compared with the conventional one, which might be responsible for the high luminance efficiency, and more investigation on this distinct discharge phenomenon is under way.

Conclusions

ZnO nanorods were successfully grown on the dielectric layer of the front glass of a display panel by a thermal evaporation process. Hybrid PDPs were fabricated using front panels with arrayed ZnO nanorods. The transmittance of the front panel was manipulated by changing the area fraction of grown ZnO nanorods. The static firing minimum (first cell-on) and sustaining minimum (last cell-off) voltages of hybrid PDPs were compared with those of a conventional PDP, which was affected by the morphology of ZnO nanorods. It was concluded that the presence of arrayed ZnO nanorods in the hybrid PDPs contributes to a significant reduction of discharge voltages and that longer ZnO nanorods are more effective in reducing discharge voltages presumably due to enhanced field electron emission. It is expected that better controlled nanorod arrays, consisting of ZnO nanorods with smaller diameters and longer lengths, would lead to even more reduction of discharge voltages, and further study of this is under way.

Acknowledgment

Authors would like to acknowledge NRL research program of the Korean government for financial assistance for this study.

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