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# Stable zinc oxide field emitter-based backlight unit for liquid crystal display

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**Abstract:** A zinc oxide (ZnO) field emitter-based backlight unit for liquid crystal display with a gated structure is fabricated by screen-printing processes. The measured anode field emission current density reaches 0.62 mA/cm$^2$ when the applied gate voltage is 570 V. Part of the anode current is contributed by the secondary electron emission which is excited from the MgO layer inside the gate apertures on the gate plate. The average emission current density and luminance are 0.47 mA/cm$^2$ and 1 250 cd/m$^2$, respectively, with a fluctuation of about 10% during the 1 000 min measurement. By a finite element method calculation, the gated structure shows a good electron beam focusing property. The driving performance of the backlight unit is characterized by SPICE simulation tools and measured by the oscilloscope. Stable field emission, line-by-line scanning and fast response characteristics of the backlight unit indicate its promising application in the liquid crystal displays.

**Key words:** field emission; zinc oxide; backlight unit; response time

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Field emission display (FED) has been considered as an encouraging display device for its remarkable features: thin thickness, high contrast ratio, high luminance efficiency and distortion free images[1-3]. Recently, the zinc oxide (ZnO) nanostructures with excellent field emission properties have also been intensively studied[4-5]. The ZnO field emitter-based FED which combines these two kinds of technologies has been successfully fabricated by the screen-printing method[6] and direct growth[7]. Particularly, the screen-printing method makes it possible to manufacture the large-sized FED with very low cost. Various kinds of structures have been proposed since the invention of the FED. The triode structure, which is usually called the normal gate structure[8], has its emitters between the gate and cathode plates. It has higher brightness than the diode structure and better electron beam focusing performance than the under-gate structure[9]. Researchers have also devoted lots of efforts to synthesize high efficient field emitters such as carbon nanotubes (CNT)[10] and CNT/ZnO hybrid nanostructures[11-12].

Except for its image display applications, the FED can also be utilized as a light source[13]. It is well known that the cold cathode fluorescent lamp (CCFL) and light emitting diode (LED) are the most common backlight units (BLUs) for the liquid crystal display (LCD), but they suffer from several disadvantages. The diffuser and prism sheet are necessary components no matter whether we take the CCFL or the LED as the BLU for the LCD. Another disadvantage is that the conventional BLU illuminates the whole display area even in the dark image area. So it is not easy to realize a high contrast ratio because of the small amount of light leaks through the liquid crystal layer. Moreover, the motion blur[14] is also a critical issue for the LCDs without a scanning BLU. However, the line-by-line scanning, fast response FED light source can easily overcome the above disadvantages. Lee et al.[15] developed a carbon nanotube field emitter BLU with a new component of CNT paste which can effectively reduce the residue and improve the field emission property. Jang et al.[16] reported that bright white light was generated from the CNT field emission BLU by mixing two kinds of phosphors systems (ZnS/AgCl and YAG/Ce).

In this paper, a ZnO BLU with the gated structure is successfully fabricated by the screen-printing method. A layer of the MgO thin film, which is used for stimulating the secondary electron emission (SEE)[17], is prepared in the inner side of the gated structure by electron beam evaporation. The electron beam focusing property of the gated structure is examined by finite element method calculation. Moreover, the driving performance of the BLU is characterized by SPICE simulation tools[18] and measured by the oscilloscope. Stable field emission, line-by-line scanning and fast response characteristics of the ZnO field emitter-based BLU indicate its promising application in the LCDs.

## 1 Experimental Section

We fabricated the proposed gated structure in the ZnO

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BLU with erosive acid solution. The prepared solution was mixed with sulfuric acid ( $H_2SO_4$, 98% ) and hydrofluoric acid ( HF, 40% ) to adjust its pH value to 1.0. Fig. 1 shows the schematic diagram of the fabrication processes of the gate plate. A piece of glass of 0.4 mm thickness is utilized as the substrate ( see Fig. 1( a) ). Photoresist ( PR) of 30 μm thickness is spin-coated on both sides of the glass ( see Fig. 1( b) ). Then two pieces of mask which define the apertures array are aligned and covered on both sides of the glass. After that, the PR film in the holes of the mask is etched by UV light ( see Fig. 1( c) ). After cleaning with deionized ( DI) water in the ultrasonic cleaner, the substrate is immersed in the prepared solution for 2 h. Eventually, the substrate is washed with DI water again and dried at room temperature ( see Fig. 1( d) ).

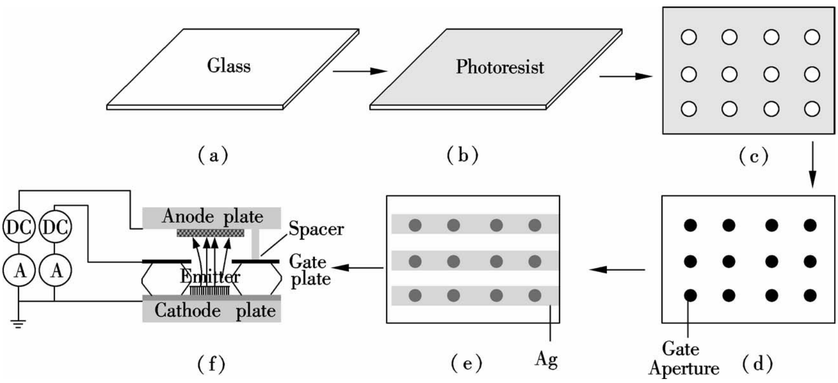


**Fig. 1** Schematic of the ZnO BLU fabrication process

The fabrication of the ZnO nanostructures is similar to our previous report[6]. Organic solvent and binder are mixed with prepared ZnO nanostructures to make the paste. The ZnO BLU is configured as a triode structure which is composed of anode, cathode and gate plates. Ag paste, which is used as electrodes, is screen-printed on the gate ( see Fig. 1( e) ) and cathode plates. Then the ZnO paste is screen-printed on the Ag electrodes of the cathode plate. A piece of ITO glass with the phosphor layer is used as the anode plate. The gate plate and the anode plate are separated by 2 mm high ceramic spacers which are mechanically robust and electrically resistive. The surface of the spacers is carefully polished to maintain an equal height so that the spacer structure provides a uniform support. Additionally, a layer of the MgO film is prepared in the inner side of the apertures by electron beam evaporation.

The morphology of the prepared ZnO nanostructures and the gate plate are examined by the scanning electron microscope ( SEM). The field emission measurement is carried out in a vacuum chamber with a vacuum level of $2.67 \times 10^{-4}$ Pa at room temperature and the measurement configuration is shown in Fig. 1( f). The field emission current is recorded with an IV meter ( Keithley 2440) by varying the gate voltage. The response time of the ZnO BLU is calculated by SPICE simulation tools based on an equivalent circuit model. In order to verify the simulation results, the response time is also measured by an oscilloscope.

## 2 Results and Discussion

Fig. 2( a) shows the SEM image of the prepared ZnO nanostructure which is randomly oriented and shows multi-pod-like morphology. Fig. 2( b) illustrates the SEM image of a single gate aperture. The cone-shaped aperture has an external diameter of about 300 μm at the surface of the glass. Due to different etching speeds, the diameter of the aperture gradually decreases to about 200 μm inside the glass. The gate apertures array, which keeps a distance of 400 μm between the adjacent apertures, is shown in Fig. 2( c).

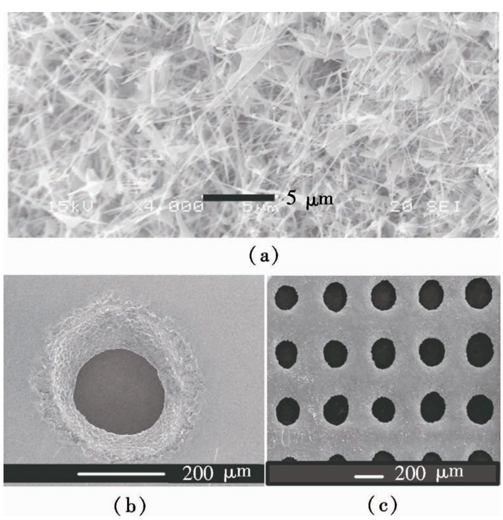


**Fig. 2** SEM images. ( a) Prepared ZnO nanostructures; ( b) Single gate aperture; ( c) Gate apertures array

Fig. 3( a) shows the measured anode field emission current density as a function of voltage applied on the gate electrode. The anode current density reaches 0.1 mA/$cm^2$ when the gate voltage is 375 V, and the current density keeps increasing quickly until it reaches 0.62 mA/$cm^2$ with a gate voltage of 570 V. Part of the anode current is contributed by the SEE. The MgO film at the electron entrance of the aperture is a kind of representative SEE material. It exhibits a high SEE yield ratio which normally ranges from 2 to 22[19]. After a primary electron emitted from ZnO nanostructures, it penetrates into the MgO layer, and then it transfers its energy to a bound electron, which leads to release of another one or more electrons. The released electrons hop on the surface of the MgO thin film and are accelerated toward the anode as the secondary electrons. A uniform field emission image is shown in the inset of Fig. 3(a). The relatively stable performance of the BLU is supposed to be related with the inherent chemical stability and the structure rigidity of ZnO[20]. Fig. 3(b) shows the field emission and luminance stability by plotting the emission current density and the luminance as a function of time, respectively. The applied gate voltage is 500 V and the anode voltage is 3 200 V. No obvious degradation of the current density and luminance is observed during the 1 000 min measurement and their fluctuations are about 10%. The average emission current density and luminance are 0.47 $mA/cm^2$ and 1 250 $cd/m^2$, respectively.

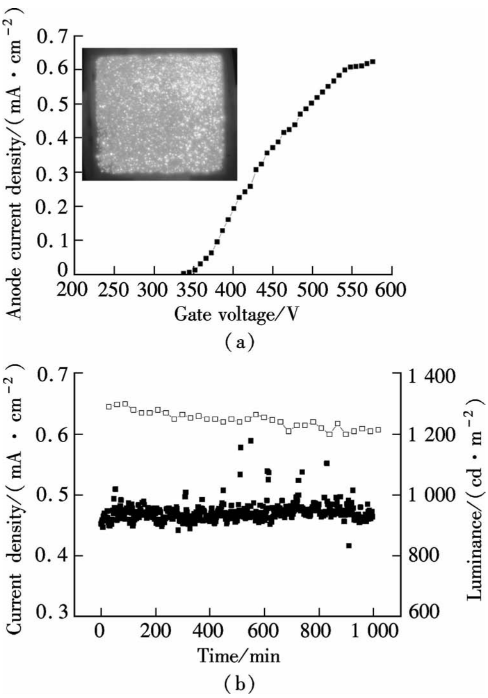


**Fig. 3** Field emission performance of ZnO field emitter based backlight unit. (a) Anode field emission current density as a function of gate voltage; (b) Current density and luminance as a function of time recorded for 1 000 min

In order to address the electron beam focusing characteristics of the gated structure, a finite element method is utilized to calculate the electrostatic potential distribution and the electron beam trajectories. Because of the axial symmetric structure of the gated structure, the electrostatic field distribution can be represented in a two-dimensional cylindrical coordinate system. The Laplace equation in the cylindrical coordinates can be expressed as

$$\nabla^2 V = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) + \frac{\partial^2 V}{\partial z^2} \tag{1}$$

where $V$ represents the electric potential; $r$ is the radial coordinate; and $z$ is the axial coordinate. In this simulation, cathode and anode electrodes are electrically biased by 0 and 700 V, respectively. An anode plate is located 0.55 mm away from the cathode plate in order to reduce the size of the simulated device. The typical distance between the cathode and the anode in FED is approximately 2.5 mm. In this model, the anode potential is accordingly adjusted to keep the anode field as close to the real situation. Figs. 4(a) and (b) demonstrate the simulated electrostatic potential distribution and electron beam trajectories, respectively. The electron beam plot demonstrates a good focusing characteristic which guarantees the luminance uniformity and field emission stability of the device.

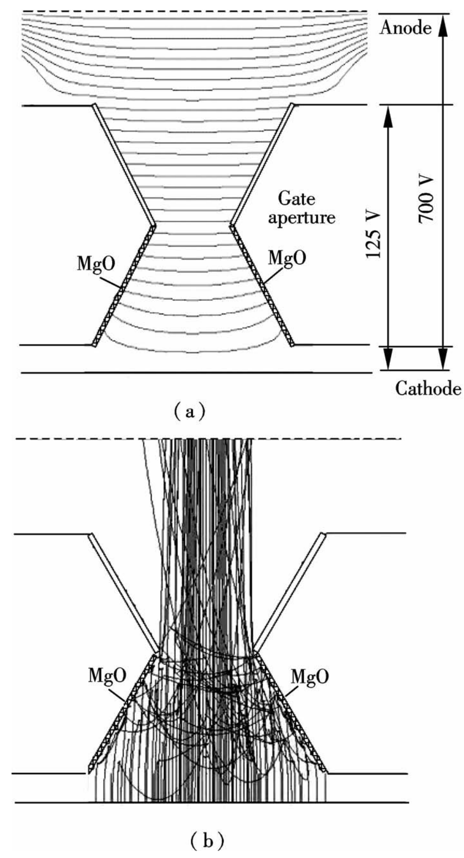


**Fig. 4** Electron beam focusing characteristics of the gated structure. (a) Simulated electrostatic potential distribution; (b) Simulated electron beam trajectories

Local dimming[21] is one of the solutions to solve the low contrast ratio and motion blur problems for the LCDs. The brightness of the ZnO BLU can be modulated by varying the pulse width of the driving signal. An 8 bit digital input signal can present 256 levels of grayscales. Therefore, the local dimming can be achieved by applying a scanning signal on the gate electrodes of the ZnO BLU with low grayscales. The response time of the driving signal determines the lowest grayscale and the maximum row scanning frequency. Fig. 5(a) shows a simplified equivalent circuit model of two adjacent rows in the ZnO BLU. $R_1$ includes the gate electrode resistance of Row A and the resistance in the external driving circuit component. $R_2$ and $C_1$ are the resistance and capacitance between the gate and the cathode in Row A, respectively. Other parasitic capacitances such as the anode to cathode capacitance and the anode to gate capacitance are so small that they can be ignored[22]. The capacitance $C_3$ between the adjacent rows is also taken into account, because it usually causes transmission effects between the adjacent rows. Therefore, while the applied driving signal keeps changing, the capacitances charge and discharge successively. Simulation parameters of the circuit model are extracted from the physical and electrical properties of the fabricated BLU. The response time defined here refers to the time required for the signal varying from 450 to 50 V (90% to 10% of the applied voltage). So, the simulated response time shown in Fig. 5(b) is approximately 27.7 ns with an input of 500 V, 14.3 kHz voltage source. In order to verify the circuit model, the same voltage source is also applied on the gate electrodes in the ZNO BLU. The gate electrode driving signal waveform observed from an oscilloscope is illustrated in Fig. 5(b). The measured response time is 38.2 ns which is greater than the simulated result. It is suspected that the difference between the simulated and measured results is caused by the inaccurate parameter determination in the circuit model. The measured resistance of the ZnO can be affected by the measurement

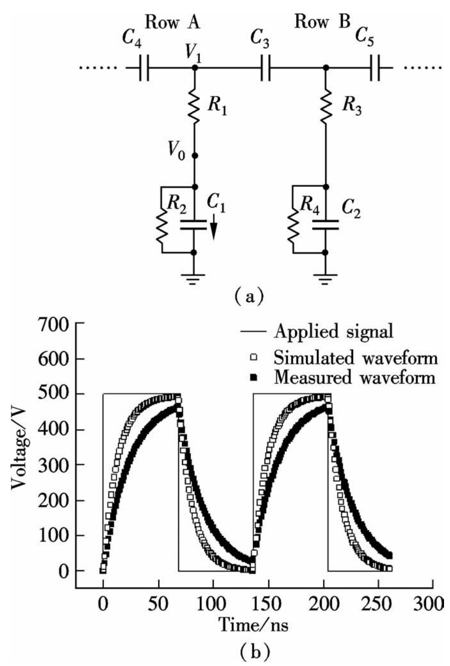


**Fig. 5** Simulation of the driving performance of ZnO field emitter-based backlight unit. (a) Simplified equivalent circuit model of two adjacent rows; (b) Simulated and measured waveform of the gate electrode with applied signal

configuration[23-24]. Besides, for the simplicity of the simulation, the leakage current caused by the parasitic parameters is not taken into consideration. Actually, the leakage current will consume part of the driving current and this will lead to longer response time. But this result still shows that the pixel capacitance and resistance in the device is well controlled and the ZnO BLU is suitable for its applications in current LCDs.

## 3 Conclusion

We manage to fabricate the gated structures for a ZnO BLU with a piece of glass. The measured anode field emission current density reaches 0.62 mA/cm$^2$ when the applied gate voltage is 570 V. The average emission current density and luminance are 0.47 mA/cm$^2$ and 1 250 cd/m$^2$, respectively, with a fluctuation of about 10% during the measurement. Part of the anode current is contributed by the secondary electron emission which is excited from the MgO layer inside the gate apertures in the gate plate. The gated structure also shows a good electron beam focusing property which is examined by finite element method calculation. The driving performance of the backlight unit is characterized by SPICE simulation tools and also measured by the oscilloscope. Good field emission, line-by-line scanning and fast response characteristics of the ZnO BLU indicate its encouraging application in the LCDs.

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# 一种基于稳定的氧化锌场致发射体的液晶显示器背光源

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**摘要：**利用丝网印刷的方法制备了一种基于氧化锌发射体的三极结构场致发射背光源器件. 当栅极电压达到 570 V 时，阳极场发射电流密度达到 0.62 mA/cm$^2$，部分阳极电流的产生是由于在栅极孔洞内侧的氧化镁受到电子激发产生了二次电子发射. 在 1 000 min 的测试过程中，平均场发射电流密度和器件亮度分别为 0.47 mA/cm$^2$和 1 250 cd/m$^2$，波动小于 10%. 有限元模拟计算的结果表明，栅极结构具有良好的电子束聚焦性能. 利用 SPICE 仿真模拟和示波器测量的方法考察了该背光源的驱动性能. 稳定的场发射性能、逐行扫描的特性和高响应速度预示了基于该三极结构的场致发射器件在液晶显示器的中具有良好的应用前景.

**关键词：**场致电子发射；氧化锌；背光源；响应时间

**中图分类号：**TN873