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The controllable performances of triode device were intensively investigated and the results for more than 70 hours continuous emission. Besides, based on the optimized T-ZnO, we developed metal cells. ZnO (T-ZnO) nanostructure has attracted considerable attention. In this letter, we firstly grew T-ZnO nanostructures by simple efficient, and uniform lighting. Through the in-situ comparatively studying the performance of the triode structure light source, we demonstrated that the optimum performance could be obtained by controlling the grid voltage working at the saturation region.

Experimental section
Preparation of T-ZnO nanostructure materials
T-ZnO nanostructures were synthesized by simple controllable vapour phase oxidation method using low vacuum horizontal tube furnace. In the process of material preparation, the ceramic plate held with high purity zinc powder (purity: 99.99%) was pre-placed into quartz tube and the flow rates of Ar and O2 were adjusted to 200 sccm and 10 sccm, respectively. Before heating up, the chamber was pumped to the pressure of 500, 200, 100 and...
20 Pa, respectively. Then, the temperature was increased at a rate of 100 °C min⁻¹ and kept at 950 °C for 60 min. By changing the chamber pressure so as to adjust the partial pressure of Zn vapour, we obtained different T-ZnO nanostructures with chamber pressure at 500, 200, 100 and 20 Pa, corresponding to sample A, B, C and D, respectively. The effect of the chamber pressure on the morphology of T-ZnO nanostructures could be investigated.

Fabrication of triode structure field emission device

The Ag strip electrodes were used as cathodic electrodes of triode structure. At first, we obtained periodic hole-shaped array cathodic electrodes by fabricating hole-shaped insulator layer on Ag electrodes in terms of thick film screen-printing process and high temperature sintering. Then, T-ZnO nanostructures were dispersed in deionized water by ultrasonic and formed T-ZnO suspension of 0.05 wt%. Using the method of electrostatic spraying, the T-ZnO suspension was transferred to hole-shaped Ag electrodes and dried at 100 °C for 30 min. In the spraying process, hole-shaped metal grid was used as a mask to ensure that T-ZnO nanostructures were only sprayed in the holes. After finishing the preparation of T-ZnO field emission cathode, it was combined with hole-shaped metal grid and fluorescent screen to assemble triode structure device. The metal grid was directly placed on the insulator layer while the fluorescent screen kept a space of 500 μm from metal grid.

Characterization and measurement

The morphology and structure of T-ZnO nanostructures were characterized by scanning electron microscopy (SEM, Hitachi S-4800) and X-ray diffraction (XRD, Bruker D8). The field emission property of sample A, B, C and D was investigated by current density-electric field (J-E) characteristic which was measured under the conditions of 9 x 10⁻⁵ Pa vacuum pressure, 3 mm x 3 mm effective field emission area and 200 μm distance between cathode and anode. The field enhancement factors (β) of four samples were calculated by Fowler-Nordheim (FN) equation. All of the electrical properties, including J-E and electron emission stability (J-T) were characterized by Agilent testing system. In addition, the parameters and morphology of hole-shaped dielectric layer in triode structure were characterized by step profiler (Vecco Dekatk150).

Results and discussion

Fig. 1 shows a typical XRD pattern of the synthesized T-ZnO nanostructure and its macro morphology which looks like white cotton. The positions of the XRD peaks corresponding to (100), (002), (101), (102), (110) and (103) planes are well consistent with those of the hexagonal wurtzite-structured ZnO (Joint Committee for Powder Diffraction Standards (JCPDS): Card No. 36-1451). Its lattice constants are calculated to be 0.3248 and 0.5205 nm for a- and c-axis, respectively, using the Bragg diffraction equation and lattice constant formula of hexagonal system described as follows:

\[
\frac{1}{d_{(hkl)}^2} = \frac{4 \cdot (h^2 + k^2 + hk)}{3a^2} + \frac{t^2}{c^2}
\]  

(2)

Where \((hkl)\) is on behalf of Miller indices, \(d_{(hkl)}\) is the interplanar spacing, \(\theta_{(hkl)}\) is the angle between the incident X-ray and \((hkl)\) crystal face and \(\lambda (\approx 0.15406 \text{ nm})\) is the wavelength of X-ray.

![Fig. 1 The typical XRD pattern of the as-grown T-ZnO nanostructure. The inset shows its macro morphology under 500 times microscopy which looks like cotton.](image)

The T-ZnO nanostructures with different morphologies are synthesized by adjusting the chamber pressure at 500, 200, 100 and 20 Pa, as shown in Fig. 2(a)-(d). The morphologies of T-ZnO nanostructures change along with the variation of chamber pressure which mainly lies in the adjustment of the Zn partial pressure. As per the laws of vacuum, in a certain temperature, lower the chamber pressure, higher is the evaporation rate of Zn, thus resulting into higher partial pressure of Zn vapour. On the contrary, higher chamber pressure results in lower partial pressure of Zn vapour. Under high chamber pressure, compared with the low Zn partial pressure, the supply of O₂ is adequate, therefore, the needles of T-ZnO grow enough or even excessively that appear butterfly-shaped T-ZnO nanostructure, as shown in Fig. 2(a). With the chamber pressure decreasing, the Zn partial pressure increases. In this process, the supply of O₂ undergoes the transition from sufficiency to moderation firstly which results in good orientated growth of whisker and obtains T-ZnO nanostructures with uniform morphology and high purity, as shown in Fig. 2(b) and (c). When the chamber pressure further decreasing, the partial pressure of O₂ is relatively insufficient and cannot meet the need of the whisker growth, the result leads to the bad orientated growth of whisker and generate ZnO particles in the product, as shown in Fig. 2(d). In other words, the T-ZnO nanostructures with uniform morphology can be fabricated at proper Zn partial pressure by well controlling the chamber pressure. In addition, as the partial pressure of Zn vapour increases, the lateral growth of needles of T-ZnO nanostructure gradually becomes remarkable so that the needles grow thickly. The lateral growth will affect the curvature radius of needles of T-ZnO nanostructure as to its field enhancement factor.
The field emission properties of Sample A, B, C and D are demonstrated in Fig. 3(a) and (b). As shown in Fig. 3(a), different J-E curves are presented. The turn-on electric field (E_TO) is conventionally defined as the electric field at the field emission current density of 10 μA cm⁻². Therefore, we get the E_TO of four samples at 3.5 V μm⁻¹, 2.75 V μm⁻¹, 3.9 V μm⁻¹ and 7.4 V μm⁻¹, corresponding to sample A, B, C and D, respectively. Moreover, the field emission characteristics can be evaluated by the FN model. According to typical FN theory, the field emission current density J can be described as the equation of electric field E:

\[
J = \frac{A \beta^2 E^2}{\Phi} \exp \left( -\frac{B \Phi^{3/2}}{\beta E} \right)
\]

or

\[
\ln \left( \frac{J}{E^2} \right) = \ln \left( \frac{A \beta^2}{\Phi} \right) - \frac{B \Phi^{3/2}}{\beta E}
\]

where A and B are constants with the value of 1.56 × 10⁻¹⁰ A V⁻² eV and 6.83 × 10⁴ V eV⁻¹/₂ μm⁻¹, respectively. Φ is the work function of the material which is 5.3 eV for ZnO. β is the field enhancement factor related to the aspect ratio and curvature radius of needles of T-ZnO nanostructures. By plotting ln(J/E²) versus 1/E, we obtain FN plots of four samples, as shown in Fig. 3(b). The observed FN plots exhibit deviation from linearity at high field region which can be ascribed to the semiconducting nature of T-ZnO involved in the characteristic of the energy band structure and voltage-to-barrier-field conversion factor. From the slope of FN plots, the field enhancement factors of four samples (designated as β_A, β_B, β_C and β_D) are estimated to be 2812, 3410, 2431 and 905, respectively. Sample B presents a higher field enhancement factor due to the advantage of its geometry fabricated at proper Zn partial pressure. Besides, the field emission stability of sample B is also confirmed by J-T measurement, as illustrated in Fig. 3(c). The measurement is carried out at 1100 V for more than 70 h. Its current density undergoes a slight decrease at first, and then turns to stabilization as time going on. In a word, sample B exhibits excellent characteristics such as uniform morphology and size, low turn-on electric field, large field enhancement factor and good stability which are better than the reported properties of other-shaped ZnO nanostructures and beneficial to use as field emitter.

We fabricate a field emission planar light source based on metal grid triode structure using the T-ZnO nanostructure of sample B as the field emitter. The structural schematic diagram of triode device is shown in Fig. 4(a). The preparation of physical device has been introduced in the experimental section above in

**Fig. 2** SEM images of T-ZnO nanostructures under different chamber pressures: (a) 500 Pa, (b) 200 Pa, (c) 100 Pa, and (d) 20 Pa, respectively.

**Fig. 3** Field emission properties of Sample A, B, C and D: (a) the J-E curves, (b) corresponding FN plots and (c) the J-T curve of Sample B.
detail. Herein, as illustrated in Fig. 4(b), the 500 times microscopy image of hole-shaped insulator layer is presented. The dimension of insulator hole is 600 μm for bottom diameter with a period of 1 mm and the layer thickness is about 12 μm, as measured by step profiler in Fig. 4(d). Fig. 4(c) exhibits the SEM image of hole-shaped Ag electrode in local area. As can be seen, T-ZnO nanostructures with 2-μm-long needles are distributed on the surface of Ag electrode uniformly and uprightly. In addition, the used metal grid has hole-shaped arrays with 600-μm-diameter, 1-mm-period and 100-μm-thickness, as shown in Fig. 4(e).

Fig. 4 (a) The structural schematic diagram of triode device; (b) image of hole-shaped insulator layer under 500 times microscopy; (c) the SEM image of T-ZnO nanostructures located at the surface of hole-shaped Ag electrode; (d) the dimension of insulator hole; (e) hole-shaped metal grid used in triode structure.

The performance of triode structure device is investigated by current-voltage (I-V) under the condition of 9 x 10⁻⁵ Pa vacuum pressure. The electrical connection in triode structure is shown in the inset of Fig. 5. Fixing the voltage of anode fluorescent screen (Vₐ) at 3300 V, we obtain the relationships of anode current (Iₐ) versus grid voltage (V₂) and cathode current (Iₖ) versus V₂ by adjusting the V₂ from 0 V to 200 V, as shown in Fig. 5. With the increase of V₂, the Iₖ increases while the Iₐ undergoes the process of increasing at first, and then tending to saturation. We define four points labelled as a, b, c and d (pointed by green arrows) on Iₐ versus V₂ curve, corresponding to V₂ = 0 V, 100 V, 150 V and 200 V, respectively, and record their field emission images in Fig. 6(a)-(d) for in-situ comparative study. As can be seen from Fig. 6, V₂ = 0 V which means that the triode device behaves as the diode structure, the uniformity of luminance is poor. When applying 100 V to V₂, the modulating electric field formed by V₂ (about 8.33 V μm⁻¹) slightly improves the uniformity of luminance, as shown in Fig. 6(b). In Fig. 6(c), when V₂ is further increased to 150 V, the modulation effect of V₂ is obvious that the device emerges large-scale uniform luminance with brightness of 7200 cd m⁻². At this point, Iₐ and Iₖ increase dramatically. With the further increase of V₂ to 200 V, corresponding to the modulating electric field of 16.67 V μm⁻², though the luminous intensity still has a certain level enhancement with brightness reaching up to 8000 cd m⁻² in Fig. 6(d), comparing with Fig. 6(c), Iₖ tends to saturation. However, Iₖ keeps on increasing in this process. That is to say, the modulation effect of grid voltage to anode current has a limit under a specific anode voltage.

Fig. 5 The relationships of anode current (Iₐ) versus grid voltage (V₂), cathode current (Iₖ) versus V₂ and grid current (I₉) versus V₂ when fixing anode voltage (Vₐ) at 3300 V. The inset is the electrical connection in triode structure.

The main reason for the saturation of Iₐ lies in that: with the increase of V₂, the electric field at the tips of T-ZnO nanostructures is enhanced gradually so that more and more electrons will obtain sufficient energy to overcome the barrier of T-ZnO and emit into vacuum to form free electrons. These free electrons move directionally under the accelerating field formed by Vₐ and generate cathode current Iₖ. The Iₖ can be described as Iₖ = I₉ + Iₐ. When V₂ is relatively small, the ability of metal grid to attract electrons is weak, so the difference between Iₐ and Iₖ is not obvious. With the further increase of V₂, when it reaches a certain value (such as 150 V in this paper), although the Iₖ largely increases, the ability of metal grid to attract electrons is also enhanced, which weakens the focussing of electron trajectories and captures more and more electrons. Therefore, the I₉ substantially increases to restrain the increase of Iₐ. It results in the saturation of Iₐ. On the other hand, the weak focussing of electron trajectories leads to relative large electron beam spots...
which stimulate the anode fluorescent screen and improve the uniformity of luminance.

![Image](image-url)

**Fig. 6** The field emission images at $V_A = 3300$ V and (a) $V_G = 0$ V, (b) $V_G = 100$ V, (c) $V_G = 150$ V and (d) $V_G = 200$ V.

**Conclusions**

Through adjusting the partial pressure of Zn vapour in the total pressure of quartz chamber, the excellent characteristics of T-ZnO nanostructure materials were synthesized by simple vapor phase oxidation method without any catalysts or additives. The optimized T-ZnO nanomaterials presented low turn-on electric field of 2.75 V μm$^{-1}$, large field enhancement factor of 3104 and excellent field emission stability for more than 70 h continuous emission, in addition to the uniform morphology and size. Based on the optimized T-ZnO, we developed metal grid mask-assisted water-based electrostatic spraying technology, and fabricated large-scale, pollution-free, hole-shaped arrays T-ZnO nanostructure cathodes. A triode structure field emission planar light source was assembled using T-ZnO nanostructure cathode, hole-shaped metal grid and fluorescent screen. Through the in-situ comparatively studying the performance of the triode structure light source, we demonstrated that the optimum performance could be obtained by controlling the grid voltage working at the saturation region. As the experimental results shown, the triode structure light source uniformly illuminated with luminous intensity as high as 8000 cd m$^{-2}$ under the conditions of 200 V grid voltage and 3300 V anode voltage. It is believed that the research in this paper will benefit the development of novel, high performance planar light source based on T-ZnO nanomaterials.

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**Notes and references**