

## Electron emission from discontinuous gold-carbon compound film on etched porous aluminum oxide

Zengmei Wang,<sup>a)</sup> Dejie Li, Baolun Yao, and Jian Wang

Department of Electronic Engineering, Tsinghua University, Beijing 100084, People's Republic of China

(Received 21 April 2006; accepted 19 July 2006; published online 29 August 2006)

An electron emitter composed of discontinuous gold-carbon compound conducting film on etched porous aluminum oxide (PAO) layer is proposed in this letter. The PAO layer is located between two  $30\ \mu\text{m}$  spaced cathode and grid electrode, and is etched in diluted phosphoric acid to introduce roughness on the soda lime glass surface and enhance discontinuity of the conducting film. Electron emission with good uniformity and stability is reproducibly obtained. The electron emission efficiency is higher than 2% at an anode voltage of 3 kV. © 2006 American Institute of Physics. [DOI: 10.1063/1.2340018]

Electron emission from discontinuous conducting films has already been studied for about four decades.<sup>1</sup> Most work was focused on metal or semiconductor films several nanometers thick<sup>1,2</sup> directly deposited on a smooth surface. Effect of low-work-function overlayer (e.g., barium oxide) on the conduction and emission characteristics was also investigated.<sup>1,3</sup> Nevertheless, no significant improvement had been reported until Yamamoto *et al.*<sup>4</sup> and Oguchi *et al.*<sup>5</sup> recently achieved in their surface conduction electron emitter wherein a palladium oxide discontinuous film was used. However, to obtain stable and uniform electron emission with high current density, highly complicated and time-consuming chemical vapor deposition process including the so-called formation and activation process<sup>4</sup> were involved. In this letter, we proposed and demonstrated an emitter with compound discontinuous conducting film on etched porous aluminum oxide (PAO) layer. Time-consuming process becomes unnecessary and electron emission is instantly obtained after the forming process. The PAO layer etched in diluted phosphoric acid introduces a roughness of several hundred nanometers on a smooth glass surface, and the discontinuity of the conducting film deposited on the etched PAO layer is enhanced. Porous anodizing of aluminum is a kind of simple and mature electrochemical process. The cell size of the PAO is proportional to the anodizing voltage,<sup>6-8</sup> so it is easy to control the transverse and longitudinal magnitudes of roughness by changing anodizing voltage and etching time.

A schematic of the emitter structure and related experimental setup is shown in Fig. 1(a). The emitter has a coplanar structure, and the discontinuous conducting film is located between two  $30\ \mu\text{m}$  spaced cathode and grid electrode. As the islands in the conducting film cannot be completely isolated, there exist conducting paths between them. The forming process takes place in a narrow zone as roughly shown by a winding gray curve in Fig. 1(b) when a grid voltage ( $V_g < 100\ \text{V}$ ) is applied to provide a large current flowing through the film, by which some of the conducting paths are burnt away. After that, the electric field between the isolated islands parallel to the surface in this zone (generally speaking  $> 10^6\ \text{V/cm}$ ) makes tunnel effect and field emission take place, and electrons are transferred at the discon-

tinuous thin film surface. While the major part of the transferred electrons forms the conduction current [ $I_c$  in Fig. 1(a)], a minor part of those electrons escapes from the surface under the action of anode voltage ( $V_a$ ) and corresponds to the emission current ( $I_e$ ).

In our experiment,  $I_c$  and  $I_e$  were measured at room temperature in a vacuum chamber with a base pressure of about  $10^{-4}\ \text{Pa}$ . A glass plate with transparent indium tin oxide electrode and phosphor was used simultaneously as an anode to collect electrons and a display screen to observe the uniformity of electron emission. Distance between the anode and the emission surface was  $\sim 2\ \text{mm}$  and  $V_a$  was kept at 3 kV.

The detailed fabrication process of the proposed structure is as follows. First, a  $\sim 500\ \text{nm}$  thick aluminum film was deposited on a piece of smooth soda lime glass by electron beam evaporation. Then, thorough porous anodizing of the film was carried out in 5% (mass ratio) phosphoric acid<sup>7</sup> agitated by nitrogen flow to avoid surface discharge and assure uniformity of oxidation. During the anodizing process,

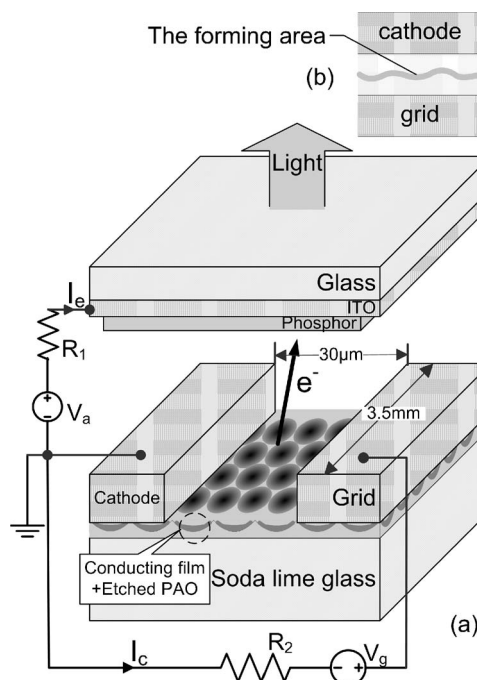


FIG. 1. (Color online) Schematic of (a) the emitter structure and the experimental setup and (b) the forming area.

<sup>a)</sup>Electronic mail: wangzm02@mails.tsinghua.edu.cn

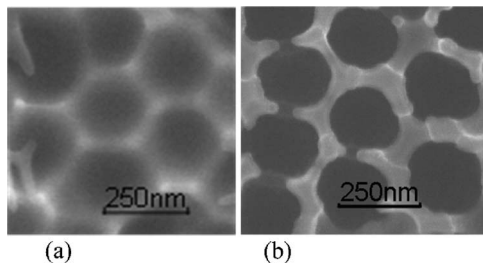


FIG. 2. (Color online) Typical SEM image of (a) fully etched and (b) less-etched porous  $\text{Al}_2\text{O}_3$ .

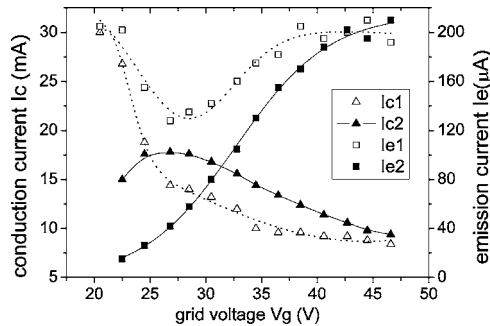


FIG. 3. (Color online) Conduction current ( $I_{c1}$ ,  $I_{c2}$ ) and emission current ( $I_{e1}$ ,  $I_{e2}$ ) as a function of  $V_g$  after the forming process: dashed lines (subscript 1) and solid lines (subscript 2) (see text). 2 min is used to stabilize the currents for each  $V_g$ . The grid width is  $\sim 3.5$  mm.

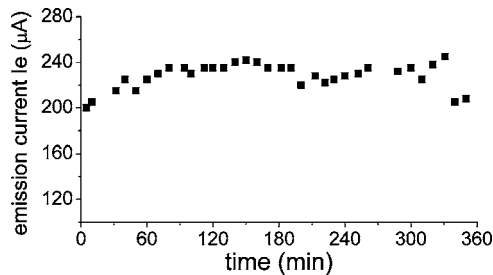


FIG. 4. (Color online) Fluctuation of  $I_e$  with time.  $V_g$  and  $V_a$  are kept at 46.6 V and 3 kV, respectively, and the distance between the anode and the emission surface is about 2 mm.

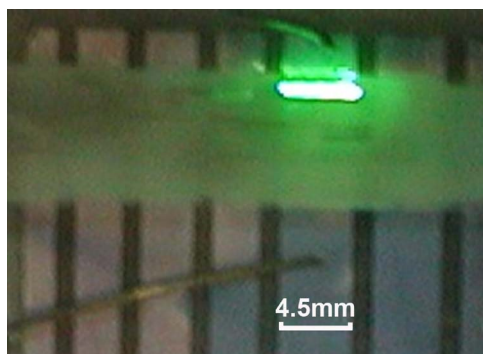


FIG. 5. (Color online) Uniform light emission displayed on the screen along the grid width (4.5 mm here) represents uniform electron emission.

the acid temperature was kept at about 18 °C and the anodizing voltage is ranged from 125 to 135 V. The PAO layer was etched in 5% phosphoric acid at 30 °C for a certain period of time to remove pore walls and part of pore bottoms. The residual part of pore bottoms (rows of densely settled honeycomblike valleys and ridges) introduced regular roughness onto the smooth glass substrate. Next, the discontinuous compound conducting film, gold-carbon, or carbon-gold-carbon, was deposited on the rough substrate at room temperature by electron beam evaporation. The thickness of each layer was controlled by monitoring the sheet resistance ( $\sim 100$  k $\Omega/\square$ ). Finally, copper cathode and grid electrode were evaporated, and a  $\phi 30$   $\mu\text{m}$  straight string was used as a mask to realize the spacing between them.

The thickness of the conducting film is supposed to be much larger at the valleys than that at the ridges. Thus the conducting film is expected to be composed of islands of several hundred nanometers in diameter. Scanning electronic microscope (SEM) images of the etched PAO layer are shown in Fig. 2. Figure 2(a) represents the surface of a fully etched PAO layer, wherein the gradual varied gray scale from bright to dark corresponds to a gradual height variation from ridge to valley. For comparison, Fig. 2(b) shows the surface of a less-etched PAO layer. Abrupt changes in gray scale means that there are still vertical walls and pores. Stable and uniform emissions cannot be obtained from a conducting film based on the less-etched PAO layer.

The forming process was performed as follows.  $V_g$  was kept at a certain value between 14 and 20 V, while  $I_c$  increased with time faster and faster. Suddenly  $I_c$  decreased violently, and uniform electron emission was observed at the same time. Local heating of the conducting film was supposed to be the critical factor of the forming process.

After the forming process,  $I_e$  and  $I_c$  were usually below 10  $\mu\text{A}$  and 10 mA, respectively. Then,  $V_g$  was increased to about 20 V and kept for about 10 min, while  $I_e$  and  $I_c$  increased to about 200  $\mu\text{A}$  and 30 mA, respectively. As  $V_g$  was slowly increased to a maximum value ( $V_{g\text{max}}=46.6$  V), voltage controlled negative resistance<sup>1,9</sup> (VCNR) was observed for both  $I_c$  and  $I_e$ , as shown by dashed curves in Fig. 3. Furthermore, if  $V_g$  was decreased to zero and reincreased to  $V_{g\text{max}}$ , the VCNR effect of  $I_c$  still existed, but that of  $I_e$  disappeared, as shown by solid curves in Fig. 3. The electron emission efficiency ( $I_e/I_c$ ) was higher than 2% at  $V_{g\text{max}}$ .

Variation of  $I_e$  with time under  $V_{g\text{max}}$  is shown in Fig. 4. Steady electron emission maintains even after 350 min with a fluctuation below 10%. In Fig. 5, light emission observed from the display screen is uniform along the grid width (4.5 mm in this case), representing uniform electron emission.

In conclusion, an emitter with compound discontinuous conducting film on etched PAO layer is proposed and demonstrated. No complicated or time-consuming fabrication process is involved. SEM images reveal that roughness of several hundred nanometers is introduced on the glass surface by fully etched PAO layer. Electron emission with good uniformity and stability is reproducibly obtained. The electron emission efficiency is higher than 2% under the anode voltage of 3 kV.

This work is supported by National Natural Science Foundation of China (No. 60571015) and Fundamental Research Funds of Tsinghua University (No. 052201011).

- <sup>1</sup>R. D. Fedorovich, A. G. Naumovets, and P. M. Tomchuk, *Phys. Rep.* **328**, 73 (2000).
- <sup>2</sup>R. Blessing and H. Pagnia, *Phys. Status Solidi B* **110**, 537 (1982).
- <sup>3</sup>V. V. Nikulov, G. A. Kudintseva, M. I. Yelinson, and L. A. Kosul'nikova, *Radio Eng. Electron. Phys.* **17**, 1153 (1972).
- <sup>4</sup>K. Yamamoto, I. Nomura, K. Yamazaki, and S. Uzawa, *SID Int. Symp. Digest Tech. Papers* **36**, 1933 (2005).
- <sup>5</sup>T. Oguchi, E. Yamaguchi, K. Sasaki, K. Suzuki, S. Uzawa, and K. Hatanaka, *SID Int. Symp. Digest Tech. Papers* **36**, 1929 (2005).
- <sup>6</sup>J. P. O'Sullivan and G. C. Wood, *Proc. R. Soc. London, Ser. A* **317**, 511 (1970).
- <sup>7</sup>S. Z. Chu, K. Wada, S. Inoue, and S. Todoroki, *J. Electrochem. Soc.* **149**, B321 (2002).
- <sup>8</sup>D. Crouse, Yu-Hwa Lo, A. E. Miller, and M. Crouse, *Appl. Phys. Lett.* **76**, 49 (2000).
- <sup>9</sup>R. D. Fedorovich, D. S. Inosov, O. E. Kiyayev, S. P. Lukyanets, A. A. Marchenko, P. M. Tomchuk, D. A. Bevzenko, and A. G. Naumovets, *J. Mol. Struct.* **708**, 67 (2004).