Field Emission Properties of Triode-Type Graphene Mesh Emitter Arrays

Chi Li, Xiaoxia Yang, Shuyi Ding, Qing Dai, Xiaohui Qiu, Wei Lei, Xiaobing Zhang, and Baoping Wang

***Abstract*— We report here an excellent field emission performance from periodic patterned graphene nanomesh (GNM) field emitter. A simulation of the relationships between external electric field and the local electric field enhancement on the GNM edges was conducted to optimize the parameters of the nanostructure. Experimental results revealed that the gate driving voltage was as low as 20 V. This kind of emitters also shows good field emission stability. It is expected that the GNM introduced here will generate impacts for the further advancement of graphene field emission devices in emerging technologies and applications.**

***Index Terms*— Field emission, back gate triode, graphene, nanomesh.**

I. Introduction

GRAPHENE exhibits excellent field emission properties and will likely be candidates as electron sources in future vacuum electronic applications, [1] due to its atomically sharp edges. The nature of sharpness is supposed to give a great enhancement of field strength as an emitter. However, most of in-situ and ex-situ graphene growth, exfoliation and deposition techniques reported thus far have yielded flat sheets lying adjacent to the substrate. It is more practical to make field emitter from graphene film parallel aligned to substrate, with certain pre- or post- treatment.

Triode structure is mostly used in practical device. There are mainly three kinds of field emission triode structure, i. normal gated structure, of which the key challenge is how to accurately grow emitters inside of the gated cavities [2]. ii. planar gated structure, in which the gate was located in the same plane with cathode. However, the reported method was complex and time-consuming [3]. iii. back gated structure, in which the gate was below the cathode, has some advantages, such as high modulation sensitivity, easy fabrication, etc. [4]. However, very few work has been done to investigate back gated triode based on patterned graphene field emitter. More important, the unique geometry of graphene could be utilized very well in this structure, which is one of the reasons why we focused our efforts on this letter.

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C. Li is with the National Center for Nanoscience and Technology, Beijing 100190, China, and also with the Display Research and Development Center, School of Science and Engineering, Southeast University, Nanjing 210096, China.

X. Yang, Q. Dai, and X. Qiu are with the National Center for Nanoscience and Technology, Beijing 100190, China (e-mail: daiq@nanoctr.cn).

S. Ding, W. Lei, X. Zhang, and B. Wang are with the Display Research and Development Center, School of Science and Engineering, Southeast University, Nanjing 210096, China.

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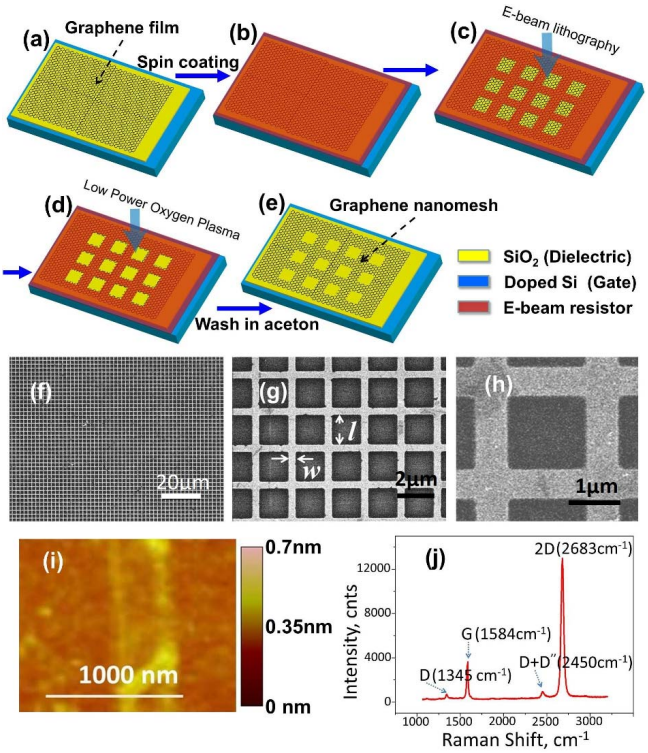

Fig. 1. (a-e) Fabrication of the triode type graphene nanomesh field emission structure. SEM images of a graphene nanomesh emitter, in low (f), medium (g), and high (h) magnification. AFM image (i) of the graphene nanomsh gave more details about the edges. Raman spectrum (h) is showing crystalline nominally single layer layer graphene.

In this letter, we demonstrated an effective approach to synthesizing high performance micro-gated graphene nanomesh field emitter arrays. High emission current density, low turn-on/ threshold field and sensitive gate modulation were obtained.

II. Experiment and Simulation Details

Graphene was synthesized by thermal chemical vapor deposition (CVD) on Cu foils at 1000 °C using CH_4 (40 sccm) and H_2 (40 sccm) at 100 Pa in a custom-built tube furnace. The pristine material was transferred, using a polymethyl methacrylate (PMMA), to the SiO_2/Si substrate by wet-etching the underlying Cu catalyst [5]. A schematic of our fabrication method can be seen in Fig. 1(a∼e). Top view scanning electron microscope (SEM) images of an as-fabricated graphene nanomesh emitter, in low, medium, and high magnification, are given in Figure 1(f) (g) (h), respectively. Moreover, an atomic force microscope (AFM) image of the graphene nanomesh

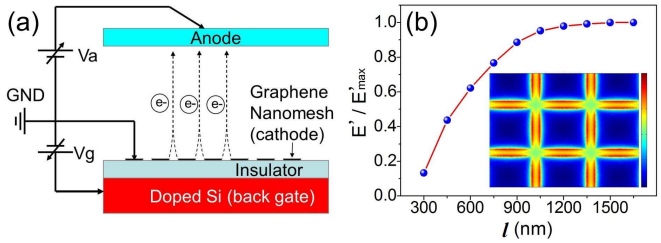

Fig. 2. (a) The model of graphene nanomesh emitter in a triode structural field emission setup. (b) The dependency of normalized electric field at the edges (E'/E'_{max}) on the length (l) of a single mesh unit. Inset of (b) Electric field distribution around the nanomesh (top view).

was enclosed to give more details about the edges, as shown in Figure 1(i). Raman spectrum in Fig. 1(h) is showing crystalline nominally single layer graphene.

It is well know that screen effect is a key issue which affects the field emission properties of the field emitter [6]. Larger screen effect could reduce the electric field enhancement factor of the emitter, resulting in high operating voltage. In our case, the size of a single mesh unit in the graphene nanomesh could determine the screen effect. To design the nanomesh emitter, we have carried out finite element electrostatic simulation, using COMSOL MULTIPHYSICS. The model of graphene nanomesh emitter in a triode structural field emission setup is shown in Fig. 2(a), in which both the width (w, 500 nm) and thickness (t, single layer graphene, 0.37 nm) of the graphene mesh line are fixed. In the simulation, the cathode (graphene nanomesh) was grounded (0 V), while the anode was applied to 200 V positive voltage.

We have calculated the electric field distribution around the nanomesh, which is shown in the inset of Fig. 2(b). It is obvious that the electric field around the graphene edge is stronger than other area, so that we can expect electron will prior emit from the edges. The electric field at the edges (E') as a function of the length (l) of a single mesh unit was calculated. The dependency of normalized E' (E'/E'_{max}) on l is recorded in Figure 2(b), indicating that the E' increased with the l increased. When l value exceed 1500 nm, the value of E'/E'_{max} was saturated, which suggested very little screen effect of electric field on the graphene nanomesh emitter. Consequently, the optimized value of l is 1500 nm.

Using the optimized electron beam lithography conditions, we were able to synthesize graphene nanomesh within a relatively large area (1000 μm $\times$ 1000 μm), as shown in Fig. 1(f, g, h). To prove the simulation results, we have fabricated graphene nanomesh with three different lengths (l) of a single mesh unit: 500nm, 1000nm, 1500nm for comparison. The experimental setup for the field emission measurements is shown in Fig. 2(a). The distance between anode and cathode was 2 mm. The thickness of the underneath insulator is around 300nm. We have tested on three samples for each type, and the average level data was recorded. To test their field emission properties, we loaded the graphene nanomesh emitter into an ultra-high vacuum (UHV) chamber with a base pressure of 10^{-7} mbar. We heated the sample to 200 °C for 24 h to eliminate water vapor or other possible residual adsorbates on the emitters.

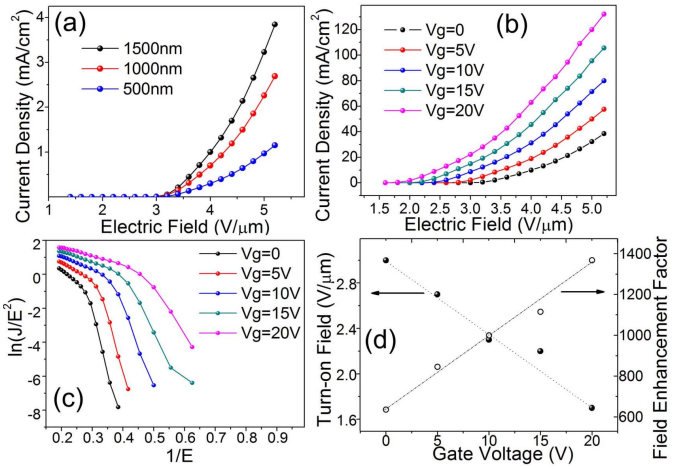

Fig. 3. (a) shows the measured current-electric field (I-E) curves from graphene nanomesh with different length (l) of a single mesh unit. (b) shows the measured current-electric field (I-E) curves at different gate voltages (0 to 20 V at 5 V increments), while (c) shows the corresponding FN plot. (d) The dependency of both turn-on field and field enhancement factor on gate voltage.

III. Results and Discussion

Fig. 3(a) shows the measured current-electric field (I-E) curves from graphene nanomesh with different length (l) of a single mesh unit. It is obvious that the graphene nanomesh with 1500nm holes has the best field emission performance, which also suggested a minimum screen effect. The experimental result proved the above simulation result.

Fig. 3(b) shows the measured current-electric field (I-E) curves at different gate voltages (0 to 20 V at 5 V increments). Fig. 3(c) shows the corresponding FN plot where the data has been fitted to the Fowler-Nordheim equation, [7] as defined by;

$$J = A(\beta^2 V^2/\Phi d^2)\, exp(-B\Phi^{3/2} d/\beta V), \qquad (1)$$

where J is the current density, A=1.56×10^{-6} (A V^{-2}eV), B=6.83×10^{9} (V $eV^{-3/2}Vm^{-1}$), β is a field enhancement factor, Φ is the work function, E=(V/d) is the applied field, d is the distance between the anode and the cathode, and V is the applied voltage. Here, the effective field enhancement factor β can be calculated from the slope of the FN plot, using 5.0 eV as the work functions of graphene.

The plots in Fig. 3 (b) and (c) clearly indicate that emission current densities can be effectively altered by gate bias. The turn on electric field, defined as the field at which current density reaches 10 μA/cm^2, decreased from 3.0 to 1.7 V/μm as a result of the increase in gate voltage (Vg) from 0 to 20 V. Similarly, the threshold field, defined as the field at which current density is equal to 1 mA/cm^2 (indicated with an arrow in Fig. 4b), decreased from 4.0 to 2.5 V/μm as a result of the increase in Vg from 0 to 20 V.

The linearity of the F-N plots confirms that the field emission results from a quantum mechanical tunneling process. We demonstrate in this field emission device that gate potential plays an important role in field emission control. The slope of the F-N plot decreased with increasing Vg, meaning the field enhancement factors increased. This phenomenon indicates that increasing Vg introduces an extra electric field that can

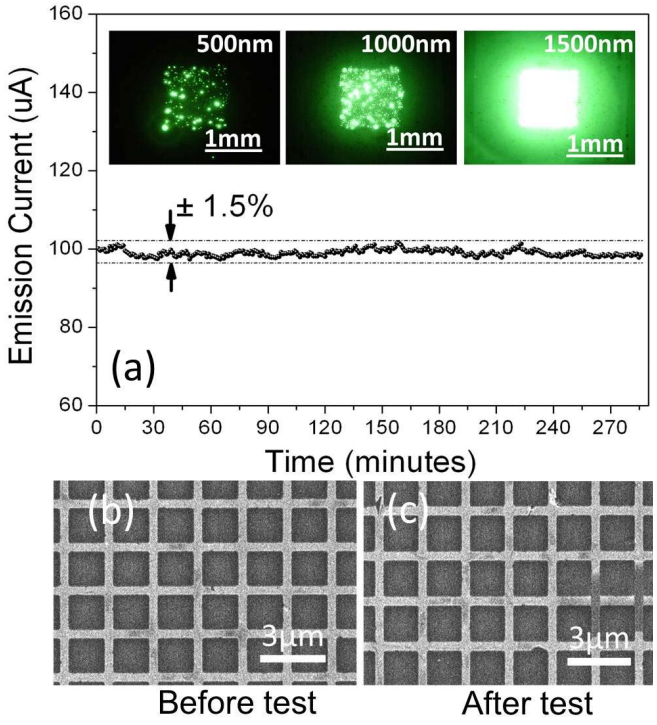

Fig. 4. (a) The stability test of graphene nanomesh emitter. A fluctuation of 1.5% was observed, which suggested a very stable emission current. The insets show the emission images, taken at anode voltage of 2000V and gate voltage of 15V, from graphene nanomesh emitters with different mesh holes' sizes. SEM images of graphene nanomesh (b) before and (c) after test.

help excite more electrons from nanomesh emitters, leading to an increase in β (from 612 to 1388) and a decrease in turn on and threshold field, as summarized in Fig. 3(d). It should be noted that the FN curves bended at high electric field region, which suggests current saturation due to the resistor effect of graphene nanomesh [8].

The temporal emission characteristics are given in Fig. 4(a), shows an stability test. In the test, the anode voltage was set to be 2000V, while the gate voltage was fixed at 15V. The stability of the graphene nanomesh emitter was greatly improved compared to some carbon nanotube emitters, showing a low emission current fluctuation of only ± 1.5 %. All three types of samples have been tested, which showed the similar stability behavior. Previous studies confirmed that the one of the reason for the unstable emission current is the difference among emitters' geometry in a field emission array. Because FE current increases exponentially with applied field, the emitters with large will emit current at lower fields and, as the field increases, will burn out before other emitters reach their threshold field. The current density is therefore limited by the number of emitters switched on at any given time. Consequently, we speculate that the high stability was attributed to the high uniformity of the nanomesh pattern fabricated by electron beam lithography, which generate balanced emission current from each graphene edge in the nanomesh.

The emission images at anode voltage of 2000V and gate voltage of 15V, taken by a camera (Nikon D600, exposure time=0.01s, ISO=1600), from graphene nanomesh emitters with different mesh sizes (l=500nm, 1000nm, 1500nm) are shown in the inset of Fig. 4(a). It is obvious that the graphene nanomesh with 1500nm mesh holes has a much better field emission uniformity, which suggests a lower screen effect.

It is worth mentioning that no obvious change of the surface morphology of graphene mesh was found before and after field emission testing, which was shown in Fig. 4(b) and (c), respectively. This can be explained as following. As the cathode was working at triode mode, the anode-cathode electric field was not that high (lower than 5V/μm in our case), which lead to an inconspicuous ion bombardment effect, avoiding the damaging of graphene layer.

IV. Conclusion

In sum, we reported here an effective technique to fabricate large-scale, reproducible graphene nanomesh emitter. This technique employs e-beam lithography and O_2 plasma etching to carve holes from a single layer graphene film. A simulation of the relationships between anode voltage and the electric field enhancement on the graphene edge was conducted to design the special hole to prevent screen effect. In testing the field emission of this triode structure, we found that increasing gate voltage from 0 to 20 V lowered the turn on field from 3.0 to 1.7 V/μm and the threshold fields from 4.0 to 2.5 V/μm, while increasing the field enhancement factor from 612 to 1388. The results demonstrate that positive gate voltages increase electric field, making electron tunneling significantly easier and thus generating a higher emission current density. It is expected that the fabrication and testing techniques introduced here will generate impacts for the further advancement of graphene field emission devices in emerging technologies and applications.

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