Conditioning of Vertically Aligned Reduced Graphene Oxide Film Electron Emitter for Terahertz Vacuum Electronic Devices

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***Abstract*— The field emission from the edge of vertically aligned reduced graphene oxide (rGO) film was examined experimentally. High current (*I* > 5 mA) and high emission current density (*J* > 100 A/cm^2) was obtained using diode configuration. The thermal runaway of sharp protrusions on emission edge are considered to be source for the destructive vacuum breakdowns due to high local emission current. A remarkable field emission stability was achieved using processed field induced evaporation, by removing the protrusions and recovering the totally field emission attributed I-V characteristics.**

I. INTRODUCTION

All classical electromagnetic radiation sources are basically depend on conversion between kinetic energy of the electron beam and field energy of the electromagnetic wave. Thus, electron beam can pass in vacuum environment without scattering, vacuum electronics devices (VED) by using convection electron are especially able to handle higher power than any other type of sources. Thanks to its high power capability, there have been many efforts to filling the terahertz gap using vacuum electronic concept [1].

One of the most key parameter in terahertz VED is current density. In order to generate the electromagnetic radiation from convection electron, it is essential to achieve collective behavior of electron with time-varying currents. The minimum current density for sufficient to overcome random thermal motion of electrons and start to time-varying collective behavior at a given frequency is shown as

$$J_{\min} = 1.27\times10^{-25} s^2 \omega^2 \frac{T}{\sqrt{V_0}} (A/cm^2) \qquad (1)$$

where ω is the angular frequency, T the temperature of electron beam, V_0 the voltage, and s the scale factor given in [2]. As shown in (1), the minimum current density is proportional to the electron beam temperature. Instead of conventional thermal cathode (T~1500K), recent development in field emission cathode (T~300K) for terahertz VED, such as spindt array emitter [3] and carbon nanotubes [4-6], are showing importance of reducing the minimum current density by decreasing the temperature of the electron beam.

Total current is also important parameter to realize the high power terahertz VED. As frequency increases, from millimeter to terahertz wave, dimension of the interaction circuits and cathode become small compared to its wavelength (~100μm) to achieve both the high current and the high current density, using conventional pencil beam [1]. Most attractive alternative is sheet electron beam. It enables generation of high power electromagnetic field via extend interaction area between electron beam and circuit.

Here, we show experimental verification of high current field emission, *I* > 5 mA, using vertically aligned reduced graphene oxide (rGO) film as isolated single emitter. Furthermore, it is observed that cathode current density above 100 A/cm^2. Due to its high field enhancement factor, excellent electrical, thermal conductivity [7, 8] and two- dimensional sheet shape with thin edge, rGO film electron emitter enables realization of the high current and the high current density sheet electron beam, without cumbersome beam shaping elements [9], [10].

In order to achieve uniform electron beam with long lifetime, one of the most fundamental issues is to avoid vacuum breakdown during aging, which is commonly observed and resulted severe damage to the emitters [11]. Non-uniform surface along the graphene edge were strongly considered as the main source of initiating vacuum breakdown due to thermal evaporation by high local emission current induced by strong field enhancement. Once breakdown occurs, it causes structural deformation and makes protrusions on the emission surface which could trigger series of breakdown through the same mechanism introduced above. Hence, controlling the graphene edge uniformity is most critical issues to avoid destructive vacuum breakdown.

II. RESULTS

Experiments of field induced electron emission from the edge of vertically aligned multi-layer rGO film were performed. Here, we present an experimental analysis on surface smoothing treatment via field induced evaporation with controlled soft and non-destructive vacuum breakdown during aging.

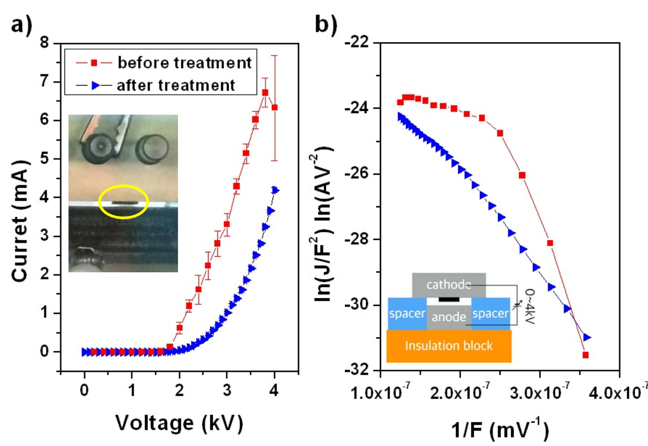

Fig. 1. (a) I-V curves of rGO field emitter before (red) and after (blue) treatment. The inset shows real picture of experimental setup and rGO film (yellow circle). (b) F-N plot of rGO field emitter before (red) and after (blue) treatment. The inset shows schematic of experimental setup.

A few-micrometer-thickness with 6 mm-width rGO film is synthesized using modified Hummer method and tightly sandwiched by well-polished cooper block (Fig. 1(a) inset). Using diode configuration shown in Fig. 1(b) inset, the I-V curve before and after the surface smoothing treatment was measured. Fig. 1(a) clearly shows the stable and repeatable emission characteristic after the treatment. Recovered Fowler-Nordheim (F-N) plot (Fig. 1(b)) after the treatment indicates that the measured current is totally originated from the field emission on the edge of rGO, not from other mechanisms.

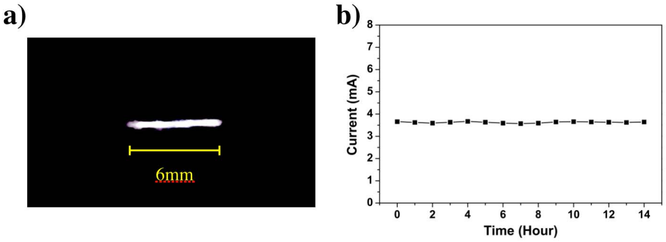

Fig. 2. (a) Striking mark of the electron beam at the anode. (b) 14 hours current stability after treatment.

The cathode life-time and emission stability verification was performed under DC voltage with continuous operation for more than one month. During operation, week luminescent at electron striking region are observed on the anode surface. Clear sheet-like beam striking mark was obtained through view port of the testing chamber (Fig. 2(a)). The width of beam striking mark is well matched with width of the rGO emitter. In Fig. 2(b) field emission current in continuous operation for initial 14 hours is presented. Despite it operated slightly less than breakdown limit voltage, it is shown that remarkable stable field emission current was degraded less than 5% during whole period of operation.

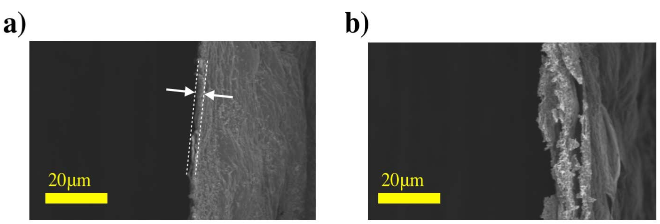

Fig. 3. Scanning electron microscopy images of rGO film edge in normal region (a) and breakdown region (b). White dotted line and arrows indicate edge of rGO.

In order to show the effect of breakdown on emission surface, scanning electron microscopy (SEM) images were obtained on destroyed emitter by hard breakdown. It mainly has two distinctive normal and attacked region by breakdown. In case of normal region, morpology of rGO is clean and well defined edge in few micrometer range (Fig. 3(a)). On the other hand, breakdown region shows damaged edge geometry (Fig. 3(b)).

III. Summary

We have experimentally examined the field emission cathode using vertically aligned rGO by diode configuration. After the controlled conditioning process, we obtained remarkable emission stability with fully originated from field induced electron emission. It is shown that deformation of morphology of rGO emission edge is originated by destructive breakdown during aging. Effect on uniformity of electron beam by non-unoform emission site due to breakdown and detailed conditioning process for prevent such destructive breakdown will be discussed.

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