Electron emission from carbon nanotube-dispersed MgO layer


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A simple secondary-electron-emission (SEE)-based source was fabricated using a carbon-nanotube-dispersed MgO precursor solution. This emission source exhibits a high SEE gain as over 10^3. In addition, the self-sustaining current was observed even after turning off the primary electron beam, then the emission current could be modulated by a small electric field variation (1.2–2 V/μm). The electron energy spectrum of the self-sustaining emission indicates that the major character of the emission is attributed to the field-enhanced SEE rather than direct field emission. © 2005 American Institute of Physics. [DOI: 10.1063/1.2048814]

There are four different kinds of electron emissions depending on the excitation mechanism, i.e., thermionic, field, photo, and secondary electron emission (SEE). Thermal electrons have been widely used as conventional electron sources, such as in cathode ray tubes and electron microscopes. 1 With a compact size and instant turn-on capability, field emission has been utilized in high performance electron microscopes and flat panel displays. 2–5 Photoemission upon ultraviolet or x-ray irradiation has been extensively adopted for surface analysis and high-energy particle detection. 4,5 SEE under a bombardment of incident particles, mostly electrons and ions, is also of importance in devices such as electron multipliers, mass spectrometers, and plasma display panels. 6–10

It is well known that the SEE yield of insulators is higher than that of semiconductors or metals, because of the low-energy loss of secondary electrons (SEs) through less electron scattering in an insulator. Also, a very high SEE yield could be obtained from a porous insulator, which is attributed to the growth of strong electric fields inside small pores and it produces a field enhanced SEE. 11,12 However, virtually limited attempts have been made to utilize SEs as an electron source, due mainly to the low SEE yield and the requirement of a primary source. And, we focus on this SEE characteristic in this letter.

The huge SEE characteristics MgO coated carbon nanotubes (CNTs) were previously reported 13,14 where the MgO was deposited by electron beam evaporation on the randomly or vertically aligned multiwalled nanotubes (MWNTs) grown by chemical vapor deposition. The highest values of the SEE yield obtained from the MgO coated CNT layers were 15 000 and 22 000, respectively. In order to achieve the same effect without expensive MgO deposition process, it is proposed to coat a CNT dispersed MgO precursor solution. Furthermore, this coating process is expected to provide advantages such as no structural restriction to coat the inner walls of micrometer scaled hole without size limitation. Here, we introduce a potential method to fabricate an electron emission source based on the SEE from the CNT-dispersed MgO layer prepared by a simple sol-gel method. This letter will present the SEE characteristics of this layer and the performance of a sample.

The MgO precursor solution was prepared by Ref. 15, then the powder of MWNTs synthesized by arc discharge 16 was added. The CNT-dispersed MgO precursor solution was coated on a Au (1000 Å) deposited Si wafer by spin coating. Then the substrate was fired at 450 °C for 2 h in air.

The SEE measurement was performed below the vacuum level of 4 × 10⁻⁸ Torr. The bombardment of primary electrons (PEs) from an electron gun (Kimball Physics, EFG-7) induced SEE from the target substrate. The SEE yield, δ, is defined as δ=I_{s}/I_{p}, where I_{s}(I_{p}) is the primary (secondary) electron current. Rather than directly measuring I_{s}, we measured the electron current of the target substrate (I_{t}). The yield was calculated using δ=1−I_{t}/I_{p} with the identity of I_{s}=I_{t}+I_{f}. The plot of SEE yields from the CNT-dispersed MgO layer as a function of the net energy of PEs is shown in Fig. 1. The net energy of PEs is obtained by the kinetic energy of the electrons from the electron gun (E_{p}) with the consideration of electron retardation effect based on the corresponding substrate bias voltage (V_{r}), i.e., E_{PE} = E_{p} − eV_{r}.

Figure 1 indicates that the highest SEE yield of the CNT-dispersed MgO layer is about 100 at E_{PE} = 200 eV (E_{p} = 1000 eV and V_{r} = −800 V). This result is significantly higher than the SEE yield (∼7) of the MgO layer made from the precursor solution without CNTs. 15 According to our previous reports, 13,14 these high SEE yields were originating from the strong electric field around CNTs due to their high aspect ratio (a few tens of nanometers diameters and several micrometers lengths). Together with this local field, the electron flows of PEs and SEs result in another electric field establishment across the MgO layer, where the surface potential of the MgO layer is relatively positive due to more of
SEs than PEs. The maximum SEE yield, 100, from the CNT-dispersed MgO layer in this work seems to be relatively small compared to those of the previously reported MgO-coated CNT films showing over $10^4$. We attribute this rather small value of the SEE yield to the poor density of MWNT bundles in the MgO layer (about 3/$\mu$m$^2$, see the inset of Fig. 1) and the lateral alignment of CNTs parallel to the substrate surface. In the previous case, the density of the grown MWNT film was approximately $10^7$/$\mu$m$^2$ and the alignment of MWNTs was vertical. Therefore, we understand that the less SEE yield is originated from the less efficiency of the field enhancement in the CNT-dispersed MgO layer.

Nevertheless, the resulting magnitude of SEE yield is quite large enough to be used as an electron emission source, if compared to the SEE yields from normal insulators, where the highest values for single crystals of MgO are around 20–25.17 Thus, we have designed a simple SEE source device employing the CNT-dispersed MgO solution coating technique. A 200 $\mu$m alumina green sheet was prepared by tape casting method, followed by punching circular hole arrays and subsequent firing.8,10 The diameter and pitch of the hole array are 300 and 400 $\mu$m, respectively. On the front side of the punched alumina substrate, Au (1000 Å) was deposited to be a conductive layer, allowing the replenishment of electrons to the MgO layer during SEE. The CNT-dispersed MgO layer was formed on the Au-deposited alumina substrate by spin coating the CNT-dispersed MgO precursor solution and subsequent firing at 450 °C in air for 2 h. A schematic diagram of the sample and the measurement setup are shown in Fig. 2.

The amplified electrons were collected on the anode, which was separated by 4 mm spacer and the anode voltage was fixed at 50 V. Under the bombardment of PEs ($E_p$ = 1500 eV, $V_p$ = −1500 to 0 V), the released SEs were accelerated towards the anode passing through the holes of the substrate. The maximum amplification gain was reached as high as $10^3$, where the corresponding current output from the substrate was 40 $\mu$A under the $I_p$ current of 40 nA. In a usual microchannel plate, the high gain was obtained by hitting of electrons through inner walls with high aspect ratio holes. However, the high gain of this sample seems to be involved with the high SEE yield from the effect of CNTs due to the low aspect ratio (~1) of our hole geometry. The SEE characteristics of the sample exhibit the strong dependence upon the net energy of PEs, similar to the result of Fig. 1. On the other hand, the output current increases as increasing the anode bias voltages, while the other experimental parameters were fixed ($E_p$ = 1500 eV, $I_p$ = 40 nA, and $V_p$ = −1300 V). The anode current was increased from 16 to 64 $\mu$A when the anode voltage was varied from 0 to 250 V, where the enhanced attracting strength is expected by the increased anode voltage.

Additional interesting result was observed from this SEE sample. That is the observation of self-sustaining emission effect known for a long time as the Malter effect, where the emission was maintained even after turning off the PEs, unlike typical SEE. Dobishchek explained that the self-sustained emission is the avalanche current initiated by electrons generated within the materials, while the general SEE current which disappears is the current initiated by electrons produced from an external source.18 Therefore, it is considered that the local field near the CNTs and across the MgO layer is strong enough to make electrons move through the MgO layer and to sustain the field enhanced SEE current even without the PEs.18,19

In order to closely investigate this self-sustained current behavior, the substrate bias voltage was varied without PE. First, −1000 V was set to the substrate with $E_p$ fixed at 1300 eV. The ground metal mesh anode was separated to 500 $\mu$m from the sample. Then, the anode current was continuously measured as a function of time through the variation of the substrate bias voltages. After reaching the steady state of SE current under the bombardment of PEs, the supply of PEs was stopped by turning off the electron gun. Figure 3 shows that the emitting current was sustained when the bias voltage of the substrate was varied from −1000 to −600 V by a step of 100 V without the PEs, resulting in the current decrease from 13 to 0.8 $\mu$A. Next, the direction of the bias voltage was reversed with a step of −50 V up to −1000 V, in which the corresponding electric field between the substrate and the anode was 1.2–2 V/$\mu$m, resulting in the current recovery from 0.8 to 14 $\mu$A. The average current at each step of the voltage is plotted in the inset of Fig. 3, exhibiting a hysteresis that may be caused by the different initial point for downward and upward directions in the voltage variation. The current fluctuation over a period of 5–10 min exhibited standard deviations around 0.5 $\mu$A.
Once after the establishment of the strong electric field within the MgO layer, which was a key requirement for the current avalanche by SEE, the collected current at the anode was maintained continuously for a quite long period over several hours even without the bombardment of PEs. Thus, this tentative SEE source sample could modulate the emission current of the sample by adjusting the substrate bias voltage, where the only initial trigger by PEs is necessary. Furthermore, this emitter has a relatively low operating field (1.2 V/µm at 1 µA). The capability of the low operating voltage and high current even at the extremely low density of CNTs compared to the chemical vapor deposition-grown CNTs suggests a promising application as an electron emission source. Therefore, we expect that a higher current at a lower operating voltage could be easily attainable using this technique, if the density of CNTs is increased in the MgO precursor solution.

In order to identify the dominant character of the emitted electrons during the self-sustaining emission, the energy distribution was measured by an electron energy analyzer (VG Science, Clam IV) at EP=1000 eV and VP=−800 V. In the energy spectrum of Fig. 4, emitted electrons have a broad range of energy distribution starting from 700 eV to the end point at about 250 eV. There is no significant energy peak around 800 eV from direct field-emitted electrons in this emission. The electron energy of most of the emitted electrons is considered to be lowered across the MgO layer, in which a strong potential drop is established, leading to the electric field-stimulated avalanche of electrons within the layer by electron-electron scattering. Therefore, most of the emission current is considered to be related to the characteristics of the field-enhanced SEE. This behavior is very similar to the results of the MgO deposited CNT film, confirming our interpretation.

In summary, an electron emissive layer with high SEE yield was obtained easily and conveniently using the CNT-dispersed MgO precursor solution. Also, we fabricated a simple SE-based electron emission source device exhibiting the high SEE gain as 10³. Adjusting the substrate bias voltage with the reversible I-V characteristics could control the self-sustaining emission current even without the PEs. The electron energy analysis of emitted electrons provides us with strong evidence that this self-sustaining current is mainly originated from field-enhanced SEEs. This emitter shows an advantage capable of controlling the emission current at relatively low electric field.

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