Enhancement of Electron Emission Efficiency and Stability of Molybdenum-Tip Field Emitter Array by Diamond Like Carbon Coating

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***Abstract*— The effect of Diamond Like Carbon (DLC) films, coated by a layer-by-layer technique using PECVD (plasma enhanced chemical vapor deposition) on the electron emission characteristics of Molybdenum (Mo)-tip field emitter array (FEA) is examined. The turn-on voltage was lowered from 80 V for the Mo-tip to 65 V for the DLC-coated Mo-tip FEA while the maximum emission current was increased from 140 μA for the Mo-tip to 320 μA for the DLC-coated Mo-tip FEA composed of 900 emitters. For an anode current of 0.1 (μA/emitter) the gate voltage for the DLC-coated Mo-tip FEA and Mo-tip FEA was about 87 and 107 V, respectively. It was also confirmed that the emission current of a DLC-coated Mo-tip FEA was more stable than that of a Mo-tip FEA.**

I. Introduction

DIAMOND FILMS possessing negative electron affinity (NEA) characteristics [1], have great potential in their application as electron emitters in vacuum microelectronics such as field emitter arrays (FEA's). The interest in diamond-like carbon (DLC) as an emission material originates from its unique emission properties: low-field cold emission and emission stability. In addition, the excellent thermal conductivity of DLC allows high maximum currents from DLC-coated emitters.

Cold cathode electron emitters obtained by depositing diamond films on Si tips [2], Molybdenum (Mo) tips [3], or W tips [4], have been widely discussed. The field strength needed for electron field emission has been reduced to less than 3×10^4 V/cm, which is substantially lower than the field strength required with conventional metal tips FEA, $>1 \times 10^6$ V/cm [5].

DLC films containing large proportions of sp^3-bonds can usually be grown at markedly lower temperatures than other method for DLC deposition, and exhibit excellent electron emission characteristics. However, the anode current dropped rapidly during operation because the transformation from sp^2 to sp^3-bonds of the bonding structure is assumed to be induced by the local heat from the DLC coating [5]. A layer-by-layer technique using PECVD (plasma enhanced chemical vapor deposition) processing is especially suitable, for it cannot only grow DLC films at room temperature, but can also produce a film having a large proportion of sp^3-bonds (-60%) with controlled hydrogen content [6].

This paper reports the fabrication of DLC-coated Mo-tip FEA using a layer-by-layer technique employing PECVD, and the electron emission behavior of the resultant tips.

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TABLE I
LAYER-BY-LAYER DEPOSITION CONDITIONS FOR THE DLC FILMS. THE SELF-BIAS VOLTAGE WAS FOUND TO BE -120 V AT A FIXED RF POWER OF 100 W, AND IT DEPENDED STRONGLY ON THE GAS PRESSURE AND ON THE RF POWER USED. THE 100 s GROWTH UNDER THE DEPOSITION MODE RESULT IN 5-nm THICK DLC LAYER. WE HAVE CARRIED OUT FIVE TIMES REPEATED DEPOSITION AND PLASMA EXPOSURE TO OBTAIN 20-nm THICK DLC FILM

Condition	Deposition	CF_4 plasma exposure
rf power (W)	100	100
Pressure (mTorr)	20	25
Flow rates (sccm)		
He	50	50
H_2	5	0
CH_4	1	0
CF_4	0	30
Substrate temperature (K)	300	300
Time (seconds)	100	200

II. Experiment

Mo tips were deposited on a silicon substrate by electron-beam evaporation (Edwards E-306A) into 1.5-μm diameter holes spaced on 10-μm centers. The process included the sequential growing of thermal SiO_2, Mo, and Al layers, followed by patterning the gate layers [7]. The DLC films were deposited at room temperature at a pressure of 20 mtorr. Conventional PECVD system, in which rf power was applied to the substrate holder, was used to deposit DLC layer by CH_4/H_2/He mixture and to produce CF_4/He plasma. Table I depicts the layer-by-layer deposition conditions for the DLC films. A thin DLC layer about 5-nm thick was grown and then the surface was exposed to a CF_4 plasma for about 200 s. The CF_4 plasma removed weak bonds, particularly C–H_n bonds and graphite C–C bonds [8]. Repeated deposition and CF_4 plasma exposure built up to a 20-nm thick hydrogen-free DLC film.

Electron emission characteristics of the tips were measured using a triode geometry. An anode plate was placed 1 mm

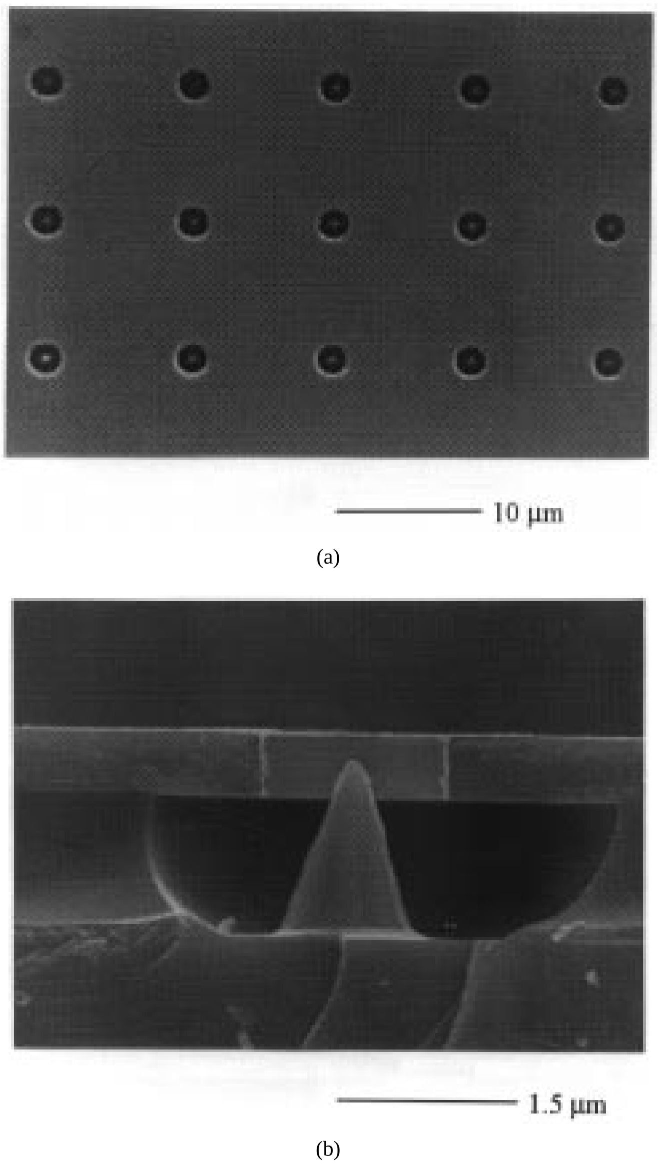

Fig. 1. (a) The top view of DLC-coated Mo-tip field emitter array with a 1.5-μm diameter gate aperture fabricated using the conventional Spindt process and then applying a DLC coating. (b) The cross-sectional view of DLC-coated Mo-tip field emitter using the new process of layer-by-layer technique employing PECVD. The DLC layer on the Mo tip is 20-nm thick.

above the gate and biased to +300 V. The variations in anode and gate currents, as functions of the gate-to-cathode bias, were measured under a vacuum of 1×10^{-8} torr using a Keithley SMU 237 meter. During these measurements, the device was in a common emitter configuration having the emitter grounded, the anode at a positive voltage and the gate driven positive to turn the device on.

III. Results and Discussion

The morphologies of the DLC-coated Mo tips observed under a Scanning Electron Microscope (SEM) are shown in Fig. 1(a). The cross-sectional view of the DLC-coated Mo tips, as shown in Fig. 1(b), reveals that the tips are typically 1.8 μm high and the gate aperture is 1.5 μm wide. The thermal SiO_2 dielectric layer is around 1.2 μm in thickness and the DLC layer coated on Mo tips is about 20 nm thick.

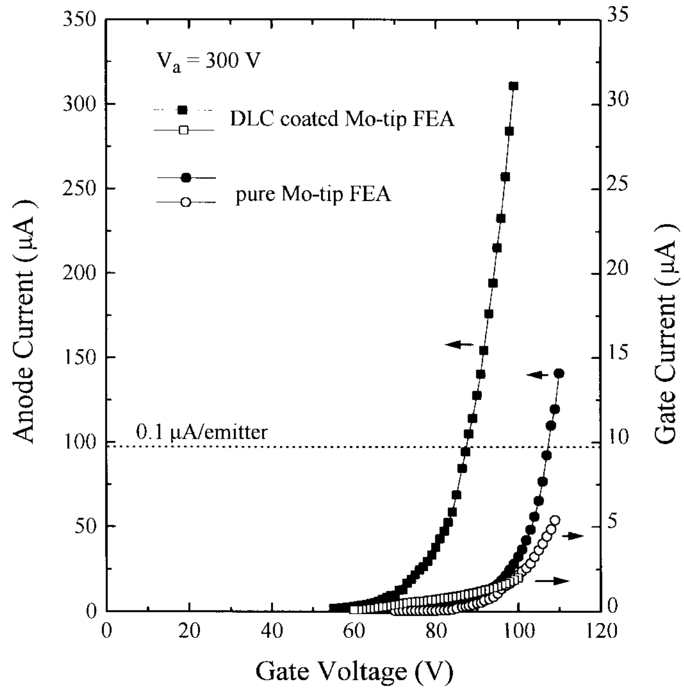

Fig. 2. The I–V characteristics of DLC-coated Mo-tip FEA and Mo-tip FEA. The gate current is less than 0.78% of the anode current for the former, while for the latter at the maximum anode current with 4.29%. Each array has 900 tips.

Fig. 2 shows the emission current–voltage ($I-V$) characteristics for a DLC-coated Mo-tip FEA and a Mo-tip FEA both consisting of 900 tips. The turn-on voltage was 80 V for Mo-tip FEA and 65 V for DLC-coated Mo-tip FEA. In addition to the decrease in the turn-on voltage for the DLC-coated Mo-tip FEA, the maximum anode current available also increases from 140 to 320 μA. Thus an anode current of about 0.1 μA per emitter is achieved at 87 V with the DLC-coated Mo-tip FEA, while the same current level is obtained at 107 V with the Mo-tip FEA. This indicates that the operating voltage can be significantly decreased simply by using this fabrication process of coating Mo tips with DLC. Further, the gate current monotonously increases with the applied gate voltage and is not significantly changed because of the DLC coating. For this experiment, the Mo- and DLC-coated Mo tips were grown on the same substrates under identical conditions. Thus, the improvement of the $I-V$ characteristics can only attributed to the enhancement on the electron emission behavior due to the DLC coating.

Fig. 3 shows the Fowler–Nordheim plots for a DLC-coated Mo-tip FEA and a Mo-tip FEA. The field enhancement factor (β) for the tips was first obtained by comparing the ϕ value calculated from the slope of the F–N plots [8] of the Mo tips with the work-function reported for Mo metal (4.5 eV). The effective work-function (ϕ) calculated for the DLC-coated tips is about 2.60 eV. These figures illustrate the significant effect a DLC coating has on lowering the work-function of Mo-tip emitters.

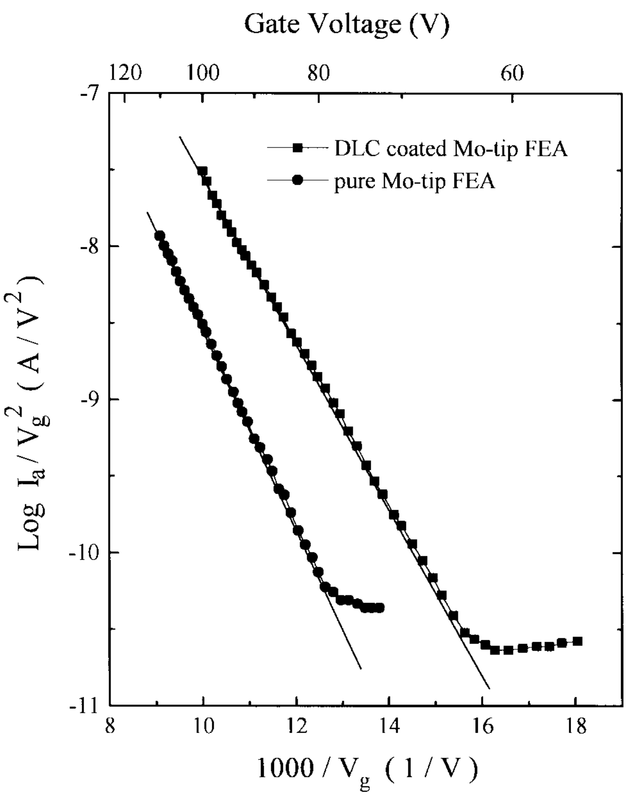

Fig. 3. The Fowler–Nordheim plots of DLC-coated Mo-tip and Mo-tip FEA. The turn-on voltage is 80 V for the Mo-tip FEA and 65 V for the DLC-coated Mo-tip FEA. The effective work-function (ϕ) and turn-on voltage were estimated from the slope of the this plot and the intercepts of the plot with the abscissa, respectively. The effective ϕ value calculated for the DLC-coated tips is about 2.60 eV.

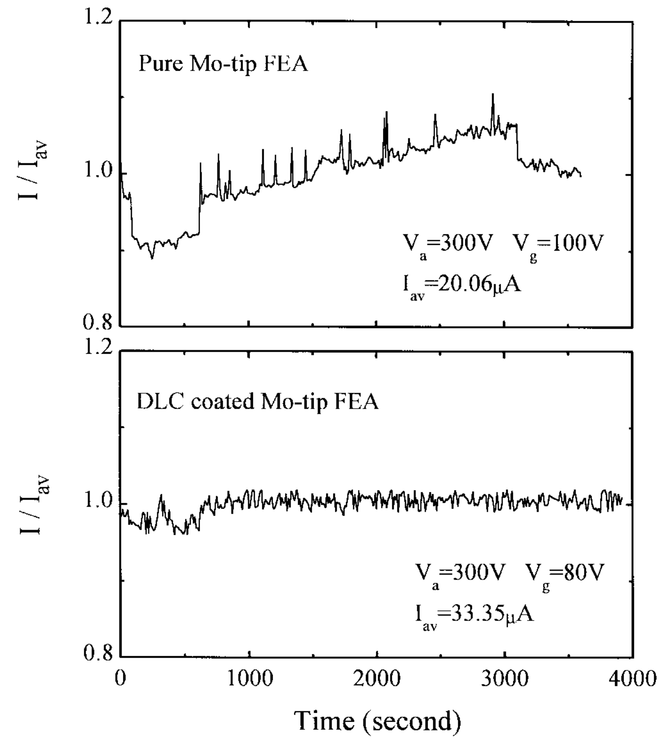

Fig. 4. The emission current fluctuations of (top) Mo-tip and (bottom) DLC-coated Mo-tip FEA. In mid-term current fluctuation, there is a 1.4% variation in current for the DLC-coated Mo-tip FEA and a 7.1% variation for the conventional pure Mo-tip FEA.

The emission current fluctuations of Mo-tip FEA and DLC-coated Mo-tip FEA with variable gate voltage are shown in Fig. 4. It was confirmed that, during the measurement of the mid-term current fluctuation, the emission current for DLC-coated Mo-tip FEA is more stable than that of a conventional pure Mo-tip FEA. And DLC-coated Mo-tip FEA also exhibited higher current stability than Mo-tip FEA (current variation of 1.9% versus 8.9%) at ~90 μA emission current which means the value of 0.1 μA per an emitter. In fact, excellent long-term current stability and reproducibility was obtained from DLC-coated Mo-tip FEA, at current level of a few 100 μAs over a time period of several hours.

IV. Conclusion

Electron emission characteristics of Mo-tip and DLC-coated Mo-tip FEA have been examined using a triode geometry. The emission characteristics of DLC-coated Mo-tip FEA is much improved, due to the stabilizing effect of the DLC coating to the emitting surface of Mo metal tips. DLC coatings 1) enhance electron emission and 2) provide field emitters with electrically stable surfaces. This technique can be used to manufacture field emission display panels that operate at low voltages with stable currents.

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