International Journal of Modern Physics B
Vol. 35, Nos. 14–16 (2021) 2140043 (5 pages)

DOI: 10.1142/S0217979221400439

Multi-layer thin-film deposition for high-performance X-ray field-emission characteristics

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Received 25 January 2021
Revised 17 February 2021
Accepted 23 February 2021
Published 22 July 2021

In this study, we developed a nanoscale emitter having a multi-layer thin-film nanostructure in an effort to maximize the field-emission effect with a low voltage difference. The emitter was a sapphire board on which tungsten–DLC multi-player thin film was deposited using PVD and CVD processes. This multi-layer thin-film emitter was examined in a high-vacuum X-ray tube system. Its field-emission efficiency according to the applied voltage was then analyzed.

Keywords: Field emission; DLC; multi-layer thin-film emitter.

PACS number: 79.70.+q

1. Introduction

Electron emitters are field-emission (FE) sources applied to X-ray and cathode ray tube (CRT). In recent years, studies have been actively made to improve emitters'

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field-emission efficiencies. Fowler–Nordheim (F–N) theory states that most electron emissions come from nanomaterials.[1,2] The CNT has an excellent performance from the perspectives of emitted current. Besides, it has high aspect ratio, thermal conductivity and chemical stability. On the other hand, emitters with CNT have a problem in terms of consistent manufacturing process and period of life, which is short, leading to a low performance. Particularly, as cathode current in an X-ray tube determines image resolution requiring higher density of cathode current, high durability and reliability are important to commercialize its application. This paper suggests a new diamond-like carbon (DLC) multi-layer thin-film emitter for field emissions of X-ray tube.[3] This study manufactured a nanoscale emitter based on a multi-layer thin-film nanostructure to maximize field emissions at a low voltage difference. Tungsten (W)–DLC multi-layer thin film was also created to improve its field-emission efficiency. Diamond-like carbon is widely used in semiconductors, machine parts and optic materials because it has low friction coefficient and high insulation. When highly insulating DLC meets highly conductive tungsten and forms a multi-layer thin-film structure, a very clear boundary plays a role as a back-plate of a metal layer which emits current at the same time. The multi-layer thin-film board was made of sapphire, which was extremely firm and heat-resistant. Tungsten and DLC were then deposited on the board in multiple layers. Field emissions of the emitter were measured using X-ray tube. Field emissions according to applied voltages were also examined.

2. Experimental Procedures

2.1. *DLC–tungsten multi-layer thin-film-emitter deposition*

The tungsten layer was processed with a physical vapor deposition (PVD) system using a direct current (DC) power, while the DLC layer was made with a chemical vapor deposition (CVD) method. The size of the board was 10×10 mm^2 with 100 μm in thickness. In a pretreatment process, the sapphire board was cleansed in a mixed liquid of sulfuric acid and hydrogen peroxide (3:7) for 15 min. Then ultrasonic cleaning was done for the board using acetone, ethanol and distilled water in order. Ensuring that the board and the DLC film were stuck together, a buffer layer ($\leq$10 nm in thickness) was deposited following the CVD process which used hexamethyl disiloxane (HMDSO). The deposition conditions are shown in Table 1. Films are from one-layered to eight-layered. Figure 1 displays the schematic diagram.

2.2. *F–N theory and plot*

The FE phenomenon can explain quantum tunneling inside a metal as it exceeds Fermi energy by work function.[1] The FE phenomenon formula is shown as follows:

$$J = A\beta^2 V^2 \exp\left(\frac{-B}{\beta V}\phi^{\frac{3}{2}}\right) [A \cdot \mathrm{cm}^{-1}],$$

Table 1. Deposition conditions for multi-layer thin films.

Layer(s)/material	Power type and voltage	Gas source (sccm)	Vacuum pressure (Torr)	Film thickness (nm)
1st/HMDSO	RF (450 W)	HMDSO (10)	2.0×10^{-2}	10
2nd/DLC	RF (450 W)	Ar (30) and C_2H_2(50)	2.0×10^{-2}	80
3rd, 5th and 7th/W	DC (1000 V)	Ar (50)	1.0×10^{-3}	60
4th, 6th and 8th/DLC	DC (400 V)	Ar (30) and C_2H_2(50)	2.0×10^{-2}	80

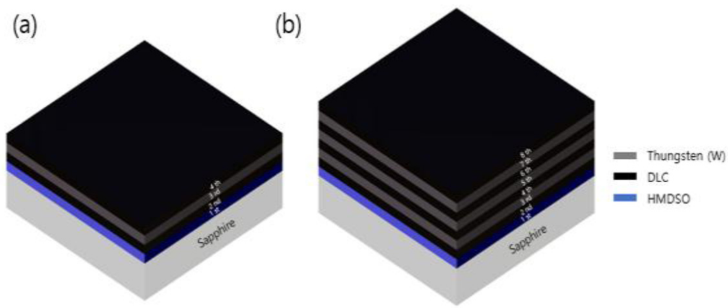

Fig. 1. (Color online) Schematic of multi-layer thin films: (a) four-layer thin films and (b) eight-layer thin films.

$$A = 1.5414 \times 10^{-6} \left[\frac{A \cdot \mathrm{eV}}{V^2}\right],$$
$$B = 6.8308 \times 10^{7} [\mathrm{eV}^{-\frac{3}{2}} \cdot V \cdot \mathrm{cm}^{-1}] \tag{1}$$

where J is current density, V is applied voltage influencing on the emitter surface and A and B are constants.[2] If the emitter is influenced by a high level of V or its surface curvature is small, the current density becomes big. As a method to check whether FE based on the F–N theory has been achieved, a curve of $\ln(1/V^2)$ versus $1/V$ is mainly used, and it is so-called the F–N plot. The multi-layer thin-film emitter was 10 μm wide and 3 mm high. The FE was measured using a two-electrode X-ray tube formed with anode target, cathode and vacuum-sealed glass bulb. The emitter was launched on the X-ray tube. The distance between the emitter and electrodes was set at 2 mm. The internal pressure was maintained between 10^{-6} Torr and 10^{-7} Torr to minimize the disturbances in field emission. Both four-layered and eight-layered emitters were used for experiments for FE under the same condition.

3. Results and Discussion

3.1. *Thin-film analysis*

In order to ensure that DLC and tungsten films were well coated by CVD and PVD, Raman and XRD analyses were performed. The results are shown in Fig. 2.

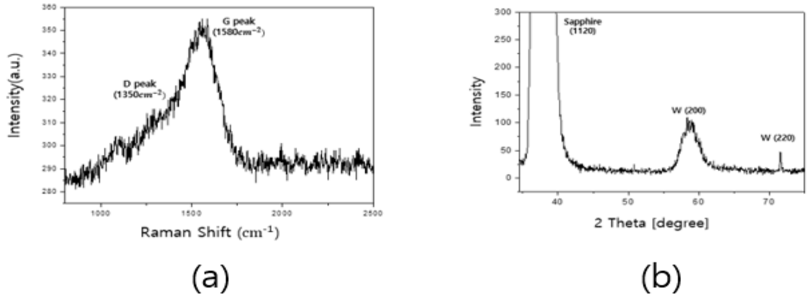

Fig. 2. Raman result of DLC layer (a) and XRD result of tungsten layer (b).

According to Raman spectroscopy, DLC film has a mix of diamond structure (sp^3) and graphite structure (sp^2). As shown in Fig. 2(a), the DLC film is well located in which D-Peak (1350 cm^{-2}) and G-peak (1580 cm^{-2}) are blended. Figure 2(b) shows the XRD analysis results of the PVD tungsten film, revealing that the tungsten thin film is deposited on the sapphire board (1120) as seen in (200) and (220).

3.2. *SEM analysis*

Figure 3 shows the SEM images of four-layered and eight-layered tungsten–DLC cross-sections. It was found that the DLC film was 80 nm thick and the tungsten film was 60 nm thick.

3.3. *Field-emission analysis*

Figure 4(a) shows the measured results of emitted current for each voltage applied to four-layered and eight-layered emitters. The maximum current of the eight-layered emitter was 337 nA at 7.2 kV, while it was 17 nA at 3.6 kV for the four-layered one. This represents that the more layers the emitter has, the higher the initial voltage for the current it has from the beginning. Therefore, increasing the number of layers from four to eight produces a higher current than an emitter with fewer layers since it can operate at higher applied voltages. Figure 4(b) shows the F–N

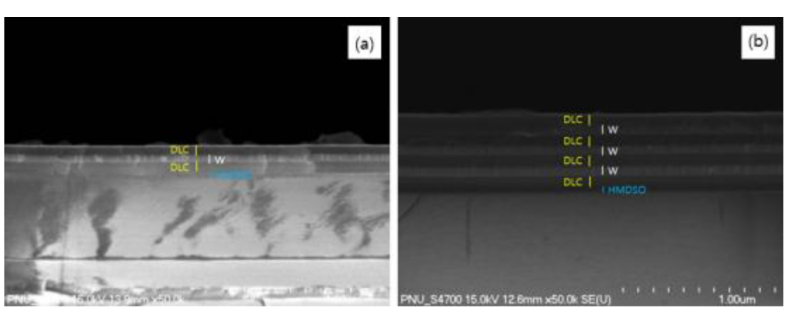

Fig. 3. (Color online) SEM images of multi-layer thin film: (a) four-layered and (b) eight-layered.

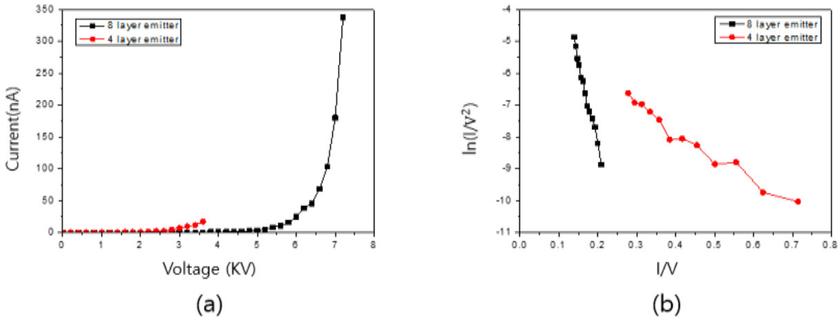

Fig. 4. (Color online) Current–voltage (I–V) curve and (b) F–N plot of multi-layer emitters.

plot of Fig. 4(a). It reveals that the eight-layered emitter has a better efficiency as per the F–N formula than the four-layered emitter.

4. Conclusion

In this study, multi-layer thin films were deposited structured with the formation of DLC and tungsten layers, respectively, on a sapphire substrate in order to fabricate an FE emitter. SEM and Raman analyses confirmed that multi-layer thin films were well coated and a multi-layer thin-film DLC emitter was produced. In X-ray field-emission calculation, the eight-layered emitter recorded 337 nA at 7.2 kV, which was the maximum current, whereas the four-layered emitter recorded 17 nA at 3.6 kV. The F–N plot assured that the eight-layered emitter was better in terms of field-emission efficiency.

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