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Influence of diamond film thickness on field emission characteristics

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Diamond films with various thicknesses (0.15–9 μm) were grown by microwave plasma chemical vapor deposition. The lowest threshold field strength for electron emission was 4 V/μm for the $\sim$1.5-μm-thick diamond film. The results were analyzed by effective emission areas and effective work function according to Fowler–Nordheim theory. It was found that the threshold voltage was strongly affected by the ratio of (111) and (110) oriented grains in the films. The larger the fraction of (111) oriented grains, the lower the effective work function in agreement with the reported negative electron affinity of (111) surfaces. © *2000 American Vacuum Society.* [S0734-211X(00)18106-5]

I. INTRODUCTION

Since the successful deposition of diamond films by chemical vapor deposition (CVD), much interest has been focused on the application of diamond in various electronic devices. This is because of the excellent physical and chemical properties of diamond such as chemical inertness and low or even negative electron affinity (NEA).[1,2] Due to its negative electron affinity field emission characterization of CVD diamond films is of great importance to applications such as vacuum electronic devices. There have been reports on field emission from diamond films deposited from gas mixtures with various methane concentrations, with different thickness, etc. The thin films exhibited lower emission.[3,4] That the crystal sizes became larger as the thickness of diamond films increased was thought to influence the field emission characteristics. In this work, we investigated the influence of thickness on the field emission characteristics of CVD diamond films with the same surface morphology and the same crystal sizes.

II. EXPERIMENT

Diamond films were prepared by microwave plasma CVD on *p*-type silicon substrates using a gaseous mixture of 3.5% methane in hydrogen, at a pressure of 15 Torr. The silicon substrates were abraded with diamond powder before deposition. The field emission testing was conducted at high vacuum ($\sim 10^{-8}$ Torr). A CVD diamond film acted as the cathode. An indium tin oxide coated glass plate was used as the anode. The distance between the CVD diamond cathode and anode was 100 μm. The emitting area was 20 mm^2. After the field emission test all samples were operated at a reverse bias voltage of about 1000 V to test the circuit insulation. A series of diamond films was grown with various thicknesses as shown in Table I.

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III. RESULTS AND DISCUSSION

Figures 1(a)–1(d) are scanning electron microscopy (SEM) micrographs of A, C, D, and G, respectively. An atomic force microscopy (AFM) micrograph of sample D is shown in Fig. 2. The other films (E, F, and H) exhibit the same morphology as sample D. The objective of this study was to hold all of the other physical properties constant so that any variation in the emission characteristics of these samples grown under the same conditions may only be influenced by thickness. Characteristic field emission current versus voltage (I–V) curves for the diamond films are shown in Fig. 3. For the films ranging in thickness from 0.15 to 1.5 μm the threshold voltage evidently decreases. For films thicker than 1.5 μm, the threshold voltage increases considerably. It shows that under our experimental conditions there is an optimum thickness of $\sim$1.5 μm (sample D) at a field strength of 4 V/μm. In Fig. 4 the threshold voltage is plotted as a function of the diamond film thickness. The threshold voltage is defined as the voltage required to produce a current density of 0.001 mA/cm^2.

The texture of the diamond films D, G, and H was measured by x-ray diffraction (XRD). The XRD spectra intensity ratio I(111)/(220) is 113% for sample D, 62% for sample G, and 34% for sample H. As the thickness increases the (111)/(220) XRD spectra intensity ratio decreases considerably.

Fowler–Nordheim (FN) theory was used to analyze the field emission results. The FN theory is shown below:

$$I = aV^2 e^{-b/V},$$

TABLE I. Deposition time for a series of CVD diamond films.

Diamond films	A	B	C	D	E	F	G	H
Deposition time (h)	0.5	1	2.5	5	6.5	10	15	30
Thickness (μm)	0.15	0.3	0.75	1.5	1.95	3	4.5	9

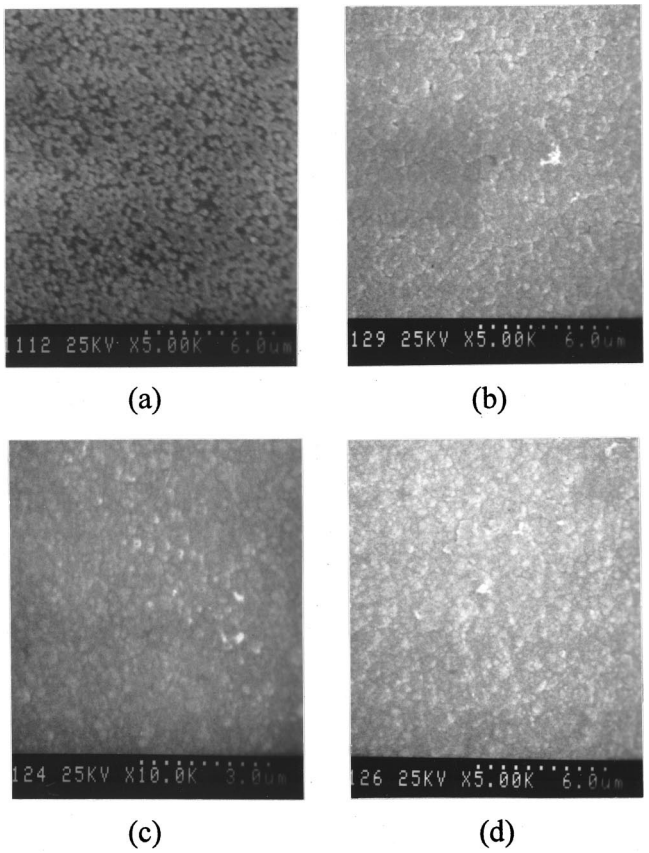

FIG. 1. SEM micrographs of diamond film A(a), C(b), D(c), and G(d).

$$a \cong 1.5\times 10^{-6}\frac{A}{E_{\varphi}} e^{10.4/E_{\varphi}^{1/2}}\beta^{2}, \tag{1}$$

$$b \cong 6.44\times 10^{7} E_{\varphi}^{3/2}\beta^{-1}.$$

According to FN theory, effective emission areas A and effective work function E'_{φ} are estimated as follows:

$$A \cong (ab^{2}e^{-14.4/E_{\varphi}^{1/2}}E_{\varphi}^{-2})/6.22\times 10^{9}, \tag{2}$$

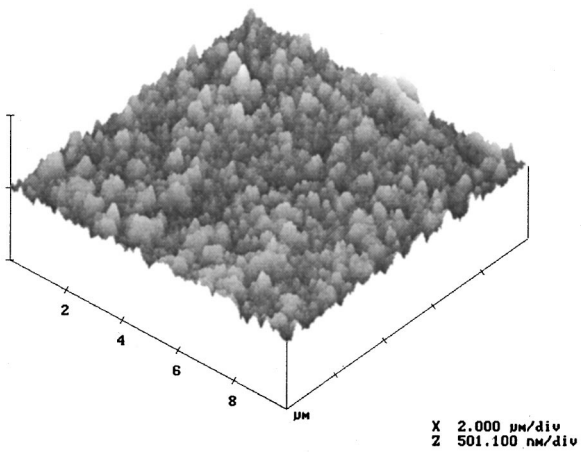

FIG. 2. AFM micrograph of diamond film D.

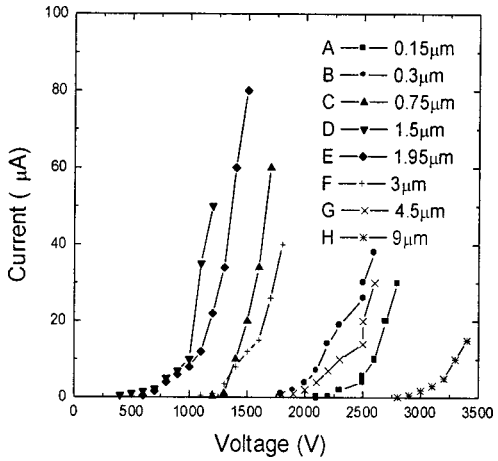

FIG. 3. I–V curves of diamond films.

$$E'_{\varphi} \cong \left(\frac{b}{6.44\times 10^{7}}\right)^{2/3}, \tag{3}$$

where E_{φ} is the work function of diamond. The effective work function E'_{φ} includes E_{φ} and the field enhancement factor β.

Differences in the XRD spectra could not be seen for thinner films (<1.5 μm).Their nucleation densities are not very similar. For thicker films (>1.5 μm), the (111)/(220) XRD spectra intensity ratio decreases considerably as the thickness increases. The relationship of the (111)/(220) XRD spectra intensity ratio versus film thickness is shown in Fig. 5. It is desirable to consider thick and thin films separately. According to FN theory, FN fitting curves of field emission current versus voltage are shown in Fig. 6. It shows that all the experiment results correspond to FN theory. So, they will be analyzed by FN theory. Since all the samples were deposited under the same experimental conditions and they all have similar surface morphologies, it was hypothesized that they have the same work function E_{φ}. So, effective emission areas A is in the ratio of ab^{2}. Effective emission areas A and effective work function E'_{φ} were estimated according to formulas (2) and (3) for thinner films (<1.5 μm) as shown in Table II, for thicker films (>1.5 μm) as shown in Table III.

Effective emission areas are explained by models in Fig. 7. Samples A, B, C, and D correspond to Figs. 6(a)–6(d). The diamond films with isolated particles have large effective emission areas. The diamond films with sharp surface features have small effective emission areas. The sharp features lead to a large field enhancement factor and a low effective work function.

It has been shown that the (111) surface of diamond has a NEA.[1,2] The (111)/(220) XRD spectra intensity decreases considerably as the thickness increases. There appears to be a relationship between the XRD intensity ratio and the threshold voltage as shown in the plot of the threshold voltage versus the ratio of the I(111)/(220) in Fig. 8. It shows that diamond films with a higher (111)/(220) XRD intensity ratio have a lower threshold voltage. The plot of the effective work function versus diamond film thickness is shown in

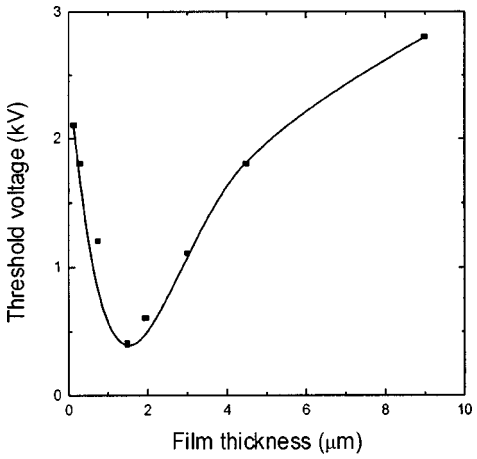

FIG. 4. Curve of threshold voltage vs film thickness.

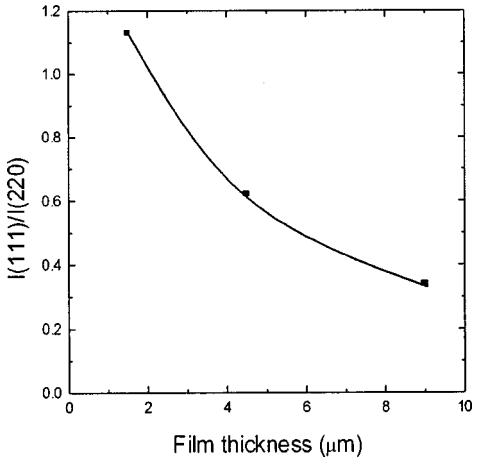

FIG. 5. Curve of XRD spectra intensity I(111)/(220) vs film thickness.

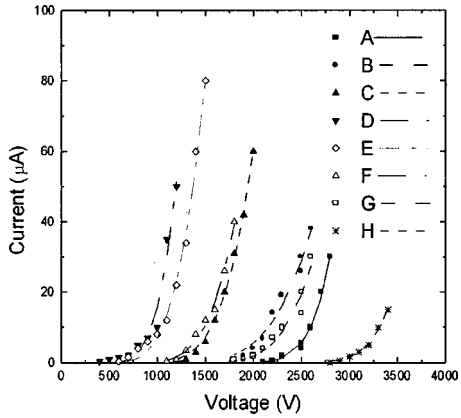

FIG. 6. FN fitting curves of field emission current vs voltage.

TABLE II. Effective emission areas and effective work function of samples A, B, C, and D.

Parameter	a	b	ab^2	E'_φ
A	0.851 74	34 410	1 008 501 128	0.006 58
B	0.000 56	11 988	80 479	0.003 26
C	0.001 55	9265.3	133 060	0.002 74
D	0.002 21	4949.1	54 131	0.001 81

TABLE III. Effective emission areas and effective work function of samples D, F, G, and H.

Parameter	a	b	E'_φ
D	0.002 21	4949.1	0.001 81
F	0.001 35	8481.4	0.002 59
G	0.004 57	18 251	0.004 31
H	3.0801	49 848	0.008 42

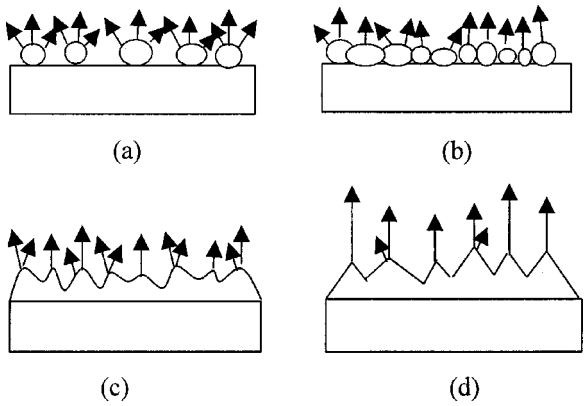

FIG. 7. Models of electron emission of diamond films.

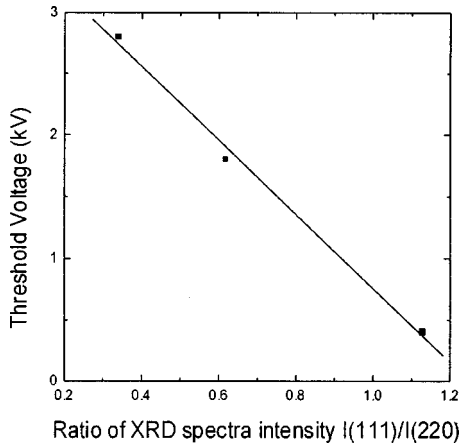

FIG. 8. Relation of threshold voltage vs I(111)/(220).

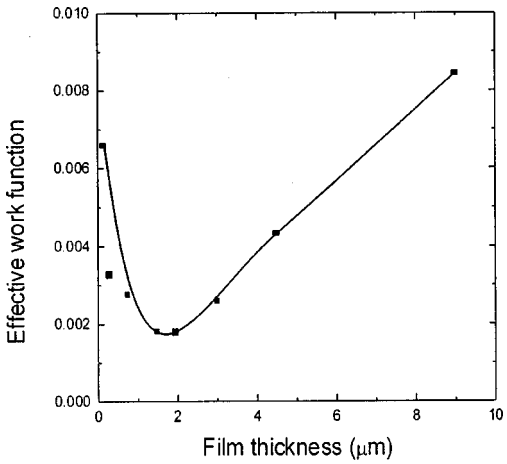

FIG. 9. Curve of effective work function vs film thickness.

Fig. 9. Its shape is similar to the function of threshold voltage versus diamond film thickness. It illustrates that the threshold voltage is greatly dependent on the effective work function, as predicted. Another reason that thicker films have high threshold voltages is thought to be due to the longer path the electrons must travel through a highly insulating film.

IV. CONCLUSIONS

Although thin films have a large effective emission area, they have a high effective work function. So, thin films have high threshold voltages. For thick films, the I(111)/I(220) XRD intensity ratio decreases. It suggests that the (111) surface orientation with negative electron affinity is reduced. Thick films impose a longer path for electron flow. So, thick films have high threshold voltages. Films with an intermediate thickness exhibit the optimum results. For diamond films deposited under the same conditions for different times, threshold voltages at fields as low as 4 V/μm were obtained from the $\sim$1.5-μm-thick film. These films have a high I(111)/I(110) XRD intensity ratio, a low effective work function and a short path length for electron movement. As a result, these films exhibit the lowest threshold voltage.

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