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Influence of silicon tip arrays on effective work function of diamond

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The diamond films were deposited on silicon tip arrays by the microwave plasma chemical vapor deposition technique. The field emission property of diamond films deposited on tips (D tips) was compared with that of diamond on silicon wafers (D wafer). It shows that the effective work function becomes large at the high electrical field for the D tip sample, and that can be explained as an effect of the diamond films being in a breakdown state. © *1998 American Vacuum Society.* [S0734-211X(98)07802-0]

I. INTRODUCTION

Recently field emission display (FED) has attracted many researcher's attention[1] because the FED is near to an ideal display device using such properties as full color, flat, and low power. The FED is similar to the cathode ray tube (CRT) in display mechanisms, the only difference being that the FED uses cold cathode arrays instead of the electron gun. The cathode materials are usually formed on silicon, high temperature metals, and chemical vapor deposition (CVD) diamond films. Silicon itself is not a perfect material as a field emitter, but the microelectronic devices based on silicon are easy to use and therefore the FED based on silicon will be useful in the future. On the other hand, it has been demonstrated that the selective growth of CVD diamond films on silicon wafer is difficult,[2] which may reduce the display quality, especially the contrast of FED. A way to solve this problem, perhaps, is to deposit diamond films on silicon tip arrays. In this article the emission property from diamond films deposited on silicon tip arrays is discussed.

II. EXPERIMENT

Silicon cone-tip arrays were prepared through oxidation, photoetching, and chemical etching. The tips are about 7 μm high and the distance between tips is 20 μm. The number of tips is about 2000. The diamond films were deposited by microwave plasma chemical vapor deposition technique on a 5×5 mm silicon wafer in which the tip arrays are formed under the following conditions: MW power was 500 W, the substrates temperature was about 850 °C, the gas compositions were 3% methane in a balance of hydrogen, and vacuum pressure in the deposition chamber was about 20 Torr. The deposition lasted for 3 h. All samples were abraded with diamond powder about 5 μm in diameter for 10 min. The field emission property was measured at a high vacuum of about 10^{-8} Torr, while the distance between cathode and anode was 120 μm. All samples were operated at a reverse bias of about 1000 V to test the circuit insulation.

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III. RESULTS AND DISCUSSION

Figure 1 shows diamond films deposited on tip arrays including 2000 tips, where a continuous film is formed. The size of the diamond particles is about 1 μm in diameter. The films deposited on the silicon wafer look similar to the flat part in Fig. 1.

Figure 2 is the emission plot. It shows that the emission property of diamond-coated tips (D tips) is better than that of the diamond-coated wafer (D wafer): for the D tip sample, the turn-on voltage was 700 V, which corresponds to the field by about 6 V/μm, and the maximum current was about 200 μA at 20 V/μm. For the D wafer sample, they were about 10 V/μm and 10 μA, respectively. The turn-on voltage was the voltage when the emission current became 4 μA. In other words, the electron emission from flat parts could be neglected for the diamond-tip sample.

The diamond films prepared by different authors show different emission properties, and do not follow the Fowler–Nordheim (FN) theory.[3,4] This indicates that the emission mechanism of diamond films is complex. The FN theory was used in this article to estimate the emission parameters. The FN theory is shown below:

$$\ln\frac{I}{V^2}\equiv a-\frac{b}{V}, \tag{1}$$

where a is a constant, and the slope b is related to the effective work function. So the $\ln(I)/V^2$ and $1/V$ shows a linear relation.

The FN plots shown in Fig. 3 show that the emission property of the D wafer samples is in accord with the FN theory. However, the D tip sample did not show a linear relation, but it shows that the plot includes two lines while the slope in the high electric field is large.

The data of slope and intercept about the FN plot of the D tip sample was given in Fig. 3. For the D wafer sample, the slope and intercept was about -2.63 and -10.20, respectively. But for the D tip sample shown in Fig. 3, the value of slope/intercept was about $-1.91/-9.08$ in low electric field, and $-7.99/-1.29$ in high electric field, respectively. This indicates that there are two different region of emission. The

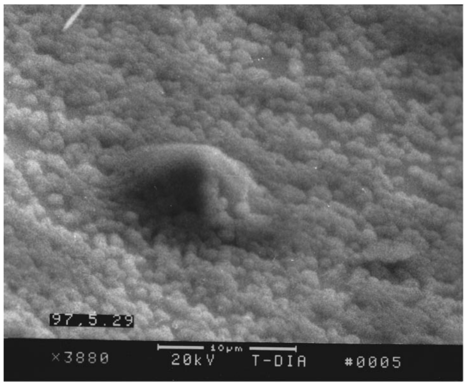

FIG. 1. SEM graph of diamond films.

effective work function of the D tip sample, in low electric field, is about 80% of that of the D wafer sample

$$\left[\frac{\psi_{D\ \text{tip}}}{\psi_{D\ \text{wafer}}}=\sqrt[3]{\left(\frac{1.91}{2.63}\right)^2}\approx 0.8\right],$$

but it is twice the value at high electric field

$$\left[\frac{\psi_{D\ \text{tip}}}{\psi_{D\ \text{wafer}}}=\sqrt[3]{\left(\frac{7.99}{2.63}\right)^2}\approx 2\right].$$

The effective work function in different regions shows different values. This indicates that at a high electric field region, the ability of electron emission from diamond films was limited by the relatively high effective work function.

The electric field will be concentrated on silicon tips, so the effective work function will be reduced. In this experiment, the concentration of electric field on the tip will be small (about 1.25 times the D wafer in low electric field) because the tip arrays were abraded with diamond powder. The diamond particles on tips (especially on top) could concentrate on the electric field, too, so high emission was obtained and the effective work function was reduced. But in the case of the high electron emission, the effective work function increased in this experiment, probably because the diamond films are in the breakdown state.[5] In other words, the band structure of diamond films is changed to a metal-like structure and limitation of conductivity is removed for field emission from diamond films, but the potential barrier that the electron has to transit becomes higher and/or wider (the electron has to transit the potential barrier between graphite and diamond and between diamond and vacuum), so the effective work function increased but high emission was obtained. In other words, the ability of electron emission from diamond films was limited.

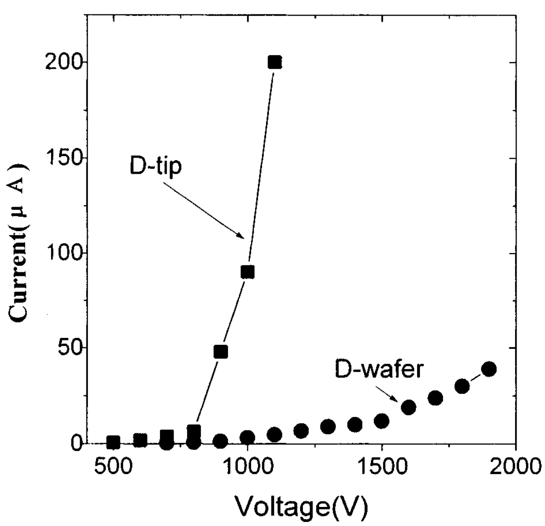

FIG. 2. Electron emission current–voltage ($I-V$) plots.

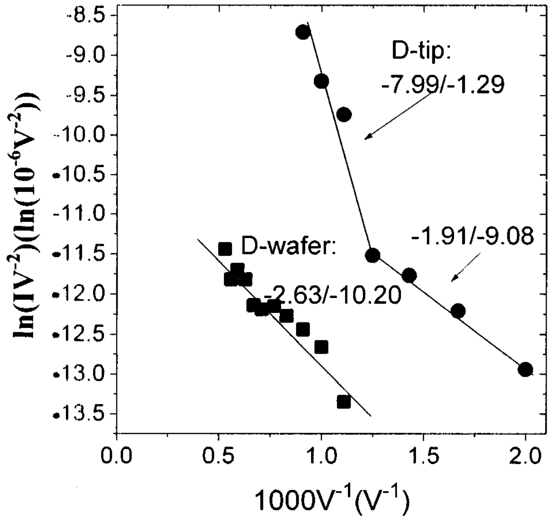

FIG. 3. FN plots of D tips and D wafer samples.

As discussed above, the concentration of electric field on silicon tips made the effective work function decrease in the low electric field region or in low emission, but the emission will be limited in breakdown state in the high electrical field or high emission. The problem of contrast of display would be reduced if diamond films deposited on tip arrays are used as cathode material. It can be solved by using silicon tip arrays because there is little emission from the flat part compared with the emission from tips.

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