Influence of temperature and vacuum on nano-diamond filed emission

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Abstract—In order to obtain the stabilized operating temperature and vacuum of nano-diamond filed emission display, the influence of temperature and vacuum changes on nano-diamond filed emission was studied, and the mechanism of field emission under high temperature and low vacuum was analyzed. It was found that nano-diamond filed emission turn-on filed decreases, and current density increases as the temperature increases. After the temperature increases to 130 °C, filed emission starts to deviate from the traditional Fowler-Nordheim theory. Under low vacuum, nano-diamond field emission is very unstable. As the vacuum increases, turn-on filed decreases, and current density increases. However, when the vacuum increases to 10^{-4} Pa level, turn-on filed, current density, and luminescence effect becomes stable. vacuum can decrease with the increase of temperature. When the temperature is below 150 °C, the decrease of the vacuum will not influence the stability of field emission. When the system operates stably, the temperature of cathode surface should be below 130 °C, and the vacuum should be above 10^{-4} Pa level.

Keywords-temperature; vacuum; nano-diamond; field emission

I. INTRODUCTION

Diamond is a special kind of semiconductor material with good properties,^[1] such as high hardness, broad-band gap, high heat conductivity, thermal stability, resistance to chemical attack. Meanwhile, with negative electron affinity, diamond films have low work function. Emitter, made of semiconductor materials, has very bad heat dissipation when operating at high current.^[2] However, the high heat conductivity of diamond ensures a good heat dissipation of diamond field emission display (FED), so it is generally believed that diamond is a kind of excellent field electron emission material. On the other hand, semiconductor emitter, easy to be oxidized, has an influence on the stability of electron emission. Because of the chemical activity of semiconductor, the remaining particles adsorb and are desorbed easily on the surface of semiconductor so that emission stability is influenced. Therefore, semiconductor field emission devices should operate in the higher vacuum. Some researches indicate that activity and size effect of nano particle has certain influence on field emission.^[3] Besides, the traditional Fowler-Nordheim field emission theory is put forward for metal material, so diamond field emission does not follow this theory fully, and the mechanism of diamond field emission has yet to be

revealed wholly. Especially there is less study on the influence of temperature and vacuum on filed emission. Studying the influence of temperature and vacuum on filed emission characteristics is favorable for exploring the mechanism of nano-diamond electron emission, for determining its limit operating parameter, and for providing the basis to the design and manufacture of nano-diamond field emission display.

II. EXPERIMENT

The test system, placed in vacuum chamber, mainly consists of diode structure FED cathode sample, anode, temperature thermocouple, vacuum gauge, tungsten lamp, applied excitation power supply, etc. Firstly, using vacuum-pumping system keeps the furnace vacuum at a point within 10^{-4} Pa level. Then, heating the sample in the furnace by tungsten lamp makes the temperature of sample surface rise gradually from 20 °C to 170 °C. In the process, to measure field emission current of the sample, each measurement should be done after one minute when the temperature reaches at sampling point. The experiment of the influence of vacuum on field emission will test the field emission characteristics of nano-diamond cathode sample when the furnace vacuum is in the range from 10^{-1} Pa level to 10^{-5} Pa level.

III. RESULTS AND ANALYSIS

A. Influence of temperature on field emission

1) *Influence of temperature on field emission turn-on filed*: Figure 1 is relation curve between turn-on field of typical sample and temperature. It can be observed that as the increase of temperature beginning with 20 °C, the field emission turn-on filed shows a downward trend. The higher the temperature is, the lower the field emission turn-on filed will be.

Figure 1. Relation curve between turn-on field of typical sample and temperature

2) *Influence of temperature on field emission current density*: Figure 2 is J-E characteristic curve of typical sample at different temperatures. It can be seen that with the increase of temperature, field emission current density presents an upward trend. The higher the temperature is, the larger the field emission current density will be.^[4]

Figure 2. J-E characteristics curve of typical sample at different temperatures

3) *F-N curve of typical sample at different temperatures* : Figure 3 is F-N curve of typical sample at different temperatures. At low temperatures, with the field emission current of the sample as the dominance, the curve is approximately a straight line, which conforms to the F-N theory. As the increase of temperature, the slope of F-N curve

becomes smaller, the steepness reduces, and the field emission characteristics are improved. After the temperature increases to 130°C, F-N curve starts to rise and gradually deviates from the theory of field emission. Furthermore, the higher the temperature is, the more the deviation will be.

Figure 3. F-N curve of the typical sample at different temperatures

Due to the influence of size effect, thermal conductivity of nano-diamond particles is lower than the one of bulk diamond. Field emission cathode adopts nano-diamond as its electron emitter, and the approach of its heat dissipation is heat exchange. Due to size effect, in applied field, the heat dissipation of the particle surface becomes slow, and its temperature increases as its thermal conductivity reduces. The sum of the temperature produced by field emission current of diamond surface and the temperature applied makes the temperature of emitter tip far above the environmental temperature.^[5] With the rise of the temperature and the electron energy to a certain extent, the phenomenon of thermal electron emission, represented by the deviation of F-N curve from theory curve, will be generated.

B. Influence of vacuum on field emission

1) *Influence of vacuum on turn-on field* : Experiments show that field emission turn-on field is particularly high in the vacuum of 10^{-1} Pa level, and the ammeter pointer shakes strongly with large swing amplitude, unreadable. Because of more gas molecule in field emission furnace collides with electron and scatters, which makes the current unstable. Turn-on field is still relatively large in the vacuum of 10^{-2} Pa level, and the ammeter hand still shakes. The big reading error means little to data analysis, so the test and record will start with the vacuum of 10^{-3} Pa level. Figure 4 is relation curve between the experimental vacuum and turn-on field.

Figure 4. Relation curve between the experimental vacuum and turn-on field

In lower vacuum, field emission turn-on field is higher. As the rise of vacuum degree, turn-on field reduces gradually. Turn-on field will reach up to 15V/ μ m in the vacuum of 7.0×10^{-3} Pa; Turn-on field is 11V/ μ m under the vacuum of 3.0×10^{-3} Pa; Turn-on field reduces to 6.0V/ μ m when the vacuum is 1.3×10^{-3} Pa. After the furnace vacuum rises to 10^{-4} Pa level, turn-on field becomes stable. Turn-on field is still 6.0V/ μ m under the vacuum of 4.6×10^{-4} Pa. The test turn-on fields are all 4.5 V/ μ m in the vacuum from 2.0×10^{-4} Pa to 5.0×10^{-5} Pa. the lower and stable turn-on field will be obtained instantly as long as the vacuum rises to 10^{-4} Pa level.

2) *Influence of vacuum on current density*: Under different vacuum, the current density will be tested in the applied field of 20V/ μ m. The relation between system vacuum and current density is shown as in the Figure 5. In the vacuum from 7×10^{-3} Pa to 3×10^{-3} Pa, current density has little change about 15~35 μ A/cm². In the vacuum from 3×10^{-3} Pa to 1.1×10^{-3} Pa, as the rise of vacuum, current density will increase quickly from 35 μ A/cm² to 117 μ A/cm². When the vacuum is close to 10^{-4} Pa level, field emission current becomes stable gradually. Respectively, the measured current density, which has already been stable, is 117 μ A/cm², 118 μ A/cm², 119 μ A/cm², and 118 μ A/cm² in the vacuum of 1.1×10^{-3} Pa, 5.0×10^{-4} Pa, 3.0×10^{-4} Pa, and 5.0×10^{-5} Pa.

Figure 5. Relation between system vacuum and current density

3) *Influence of vacuum on luminescence effect*: Figure 6 is the anode luminescence pictures of the typical sample in different vacuum when the applied field is 20V/ μ m. As shown here, in the vacuum of 3.8×10^{-3} Pa, the luminescence picture is darker with less luminous point. However, in the vacuum of 8.4×10^{-4} Pa, 1.5×10^{-4} Pa, and 5.0×10^{-5} Pa, these luminescence pictures are lighter with more luminous point, which indicates that after the vacuum reaches to 10^{-4} Pa level, the amount and the illumination of luminous point has already reached a better level. The further increase of vacuum has little improvement on luminescence effect.

Figure 6. The anode luminescence pictures of the typical sample in different vacuum (E=20V/ μ m)

C. Influence of temperature on vacuum

It is found that furnace temperature has an influence on vacuum when the experiment of the influence of temperature on field emission is done. Figure 7 is the relation curve between vacuum and surface temperature of vacuum furnace heated after the vacuum of field emission test system reaching to 5.0×10^{-5} Pa level. As the increase of temperature, the vacuum will decrease gradually. When the diamond coating temperature rises to 150°C , the system vacuum will decrease to 10×10^{-4} Pa. This is because the gas molecule adsorbed on the inner wall of vacuum chamber and desorbed with the increase of temperature leads to the decrease of the vacuum. With the further increase of temperature, although the gas molecule has been desorbed, vacuum will still decrease as a result of the steam leakage from the soften rubber on the sealing surface of vacuum chamber.^[6] Therefore, the increase of temperature will cause the decrease of vacuum. However, as long as the temperature is not higher than 150°C and the vacuum still remain in 10^{-4} Pa level, the vacuum change caused by temperature will have no influence on nano-diamond field emission characteristics and the influence of temperature on vacuum can be ignored.

Figure 7. Curve of influence of temperature on vacuum

IV. CONCLUSION

By the test experiment of field emission, the influence of temperature and vacuum on nano-diamond field emission characteristics was studied. The results show that temperature has a big influence on nano-diamond field emission. As the increase of temperature, field emission turn-on field decreases,

and field emission current density increases. After the temperature rises to a certain degree, the increase of cathode thermal electron emission will submerge the field emission electron. The influence of thermal electron emission can be ignored at the temperature below 130°C . In low vacuum, scattering effect will make the field emission electron unstable.^[7] However, when vacuum reaches above 10^{-4} Pa level, scattering has little influence on field emission electron, meaning that the cathode sample can emit the electron stably. Furnace temperature has certain influence on vacuum. With the rise of temperature, furnace vacuum will decrease. However, at the temperature below 150°C , the change of vacuum caused by change of temperature will have no influence on nano-diamond field emission characteristics.^[8] Considered synthetically from the two aspects, the stable field emission conditions of nano-diamond are at the temperature below 130°C and in the vacuum above 10^{-4} Pa level.

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