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Electron emission mechanism of carbon fiber cathode*

LIU Lie, LI Li-min, WEN Jian-chun, WAN Hong

(College of Photoelectric Science and Engineering, National University of Defense Technology, Changsha 410073, China)

Abstract: Models of electron emission mechanism are established concerning metal and carbon fiber cathodes. Correctness of the electron emission mechanism was proved according to micro-photos and electron scanning photos of cathodes respectively. The experimental results and analysis show that the surface flashover induces the electron emission of carbon fiber cathode and there are electron emission phenomena from the top of the carbon and also from its side surface. In addition, compared with the case of the stainless steel cathode, the plasma expansion velocity for the carbon fiber cathode is slower and the pulse duration of output microwave can be widened by using the carbon fiber cathode.

Key words: Carbon fiber cathode; Electron emission mechanism; Microwave pulse duration

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High-current electron beams produced by high-voltage pulse generators have widespread use in such diverse applications as high-power microwave generation, free lasers and so on[1,2]. In these various devices, the beam electrons are often generated from a cold cathode by a process generally termed explosive electron emission. Through diverse mechanisms, the application of a strong electric field results in plasma formation on the cathode surface. The electric field then extracts a space-charge-limited electron flow from this plasma. The ensuing expansion of the cathode plasma into the anode-cathode gap reduces the diode impedance, and can ultimately result in diode shortening of the high voltage pulse.

Carbon fibers as new cathode material in high power diode have been widely investigated for some years. This type of cathodes is consisted of either bare carbon fiber or carbon fiber with a coating of cesium iodide (CsI). CsI not only is well known as an emitter of ultraviolet (UV) radiation when stimulated properly, but also has the advantage that the cesium has a very low ionization potential. Carbon fiber has the advantage of low outgassing rate, which keeps the gas evolution and thus plasma formation in the diode to a minimum. Thus, carbon fiber cathodes would appear to have many good characteristics as electron emitters for long pulse cathodes. In this article we will at first investigate the electron emission mechanism of the carbon fiber and metal cathode including the experimental results and then introduce the effect of the carbon fiber cathode on the pulse duration of output microwave and the plasma expansion velocity of the diode cathode.

1 Electron emission mechanism

Nowadays there are a number of literatures in which the mechanism of electron emission from the cathode was investigated[3,4]. Our experimental results indicate that there are differences between the carbon fiber cathode and the conventional metal cathode.

Typical explosive field emission cathodes suffer from large amounts of outgassing rate, nonuniform emission, and very high emittance. However, the carbon fiber cathode can overcome the above disadvantages of the explosive field emission cathodes. So it is necessary to compare the electron emission process of the carbon fiber cathode with that of the stainless steel cathode. In general, the electric field at the needles on the cathode, whether cathode material is either stainless steel or carbon fiber, is hundreds of times larger than

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Biography: Liu Lie (1960—), male, born in Changchun Jilin, postgraduate, research on the cathode technology for intense current diode.

the externally applied electric field. In this case, plasma forms on the surface of the cathode, and then the electrons are emitted from the cathode plasma sheath due to the field emission or explosive emission mechanism.

Figure 1 shows the micrographs of the needles on the surface of the stainless steel cathode after electron emission at different magnifying power. We can see from Fig. 1 (a) that after the electron emission the tips of the needles are ablated but there is no ablation on the side surfaces of the needles. In Fig. 1 (b), the tips of the needles are flat after the electron emission, which implies plasma formed explosively at the tips of the needles but not on the side surfaces of the needles. We conceive a process of plasma formation at the tips of the needles of the cathode, which is shown in Fig. 2. In the process of plasma formation, the tips of needles becomes flat and the needles are depleted gradually. The electron emission mainly concentrates on the tips of the needles, which could lead to cathode destruction and affect the lifetime of the stainless steel cathode.

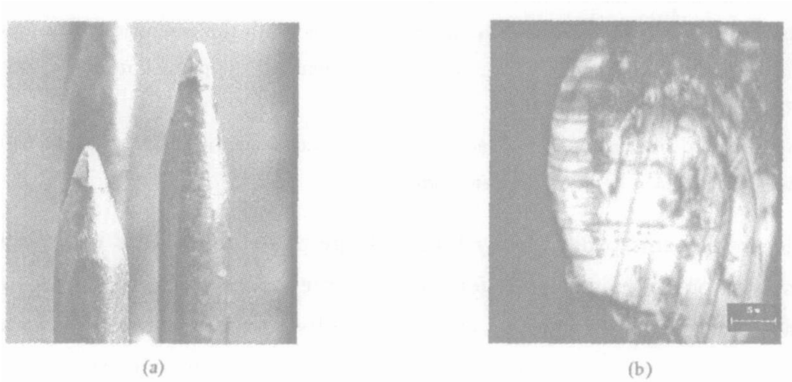

Fig. 1 (a) photo of the needles on the surface of the cathode and (b) electron scanning micrograph of the tip of the needle on the cathode after emission

In the case of a carbon fiber cathode, the process of plasma formation is quite different, which is related to the microstructure of the carbon fiber material. It has been understood that the carbon fiber consists of three layers assurface, crust, and the core[5~8]. The surface, which is parallel to the axis of the fiber, is a layer of graphite. The medium crust layer includes carbon granules that distribute randomly. Manders investigated the carbon fiber microstructure by using the electrolytic etching to show the three layers of carbon fiber[9]. The complexity of carbon fiber microstructure shows that the electric polarization of the carbon fiber is not uniform[6,9], which is favorable for occurrence of flashover and thus for the formation of a plasma.

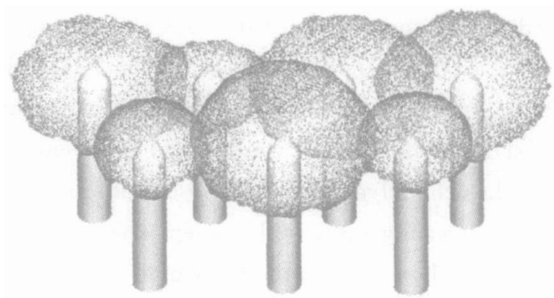

Fig. 2 Model of electron emission mechanism regarding metal cathode

Figures 3 and 4 show the electron scanning micrographs of carbon fibers. Figure 3 gives the comparison between the carbon fiber tips before electron emission and those after electron emission. Figure 4 illustrates the comparison between the side surfaces of carbon fibers before electron emission and those after electron emission. In these figures, there are some spots at the tips and on the side surfaces of the carbon fibers after the electron emission. These spots could only be attributed to the flashover discharge along the side surfaces of the carbon fibers. So we believe that the plasma not only formed at the tip of carbon fiber but also on its side surface. In Ref[10], it has been demonstrated that during the formation of the plasma, light emission was not only observed from the tip of carbon fiber but also from its side surface. In addition, the process of the plasma formation around the carbon fiber during the electron emission can be conceived using the model shown in Fig. 5. In this case, the plasma gas cylinders around the carbon fibers an expand and form uniformly on the surface of the carbon fiber cathode. This is different from the case of a stainless steel cathode shown in Fig. 2 , in which no plasma formed on the side surfaces of the stainless steel needles of the cathode.

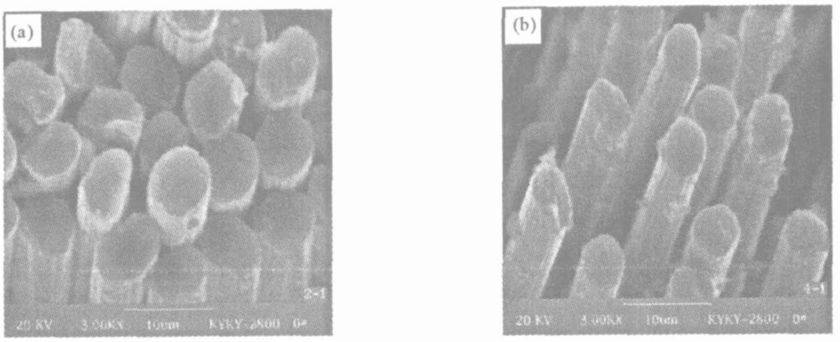

Fig. 3 Scanning electron micrographs of the tips of carbon fiber cathode (a) before and (b) after emission respectively

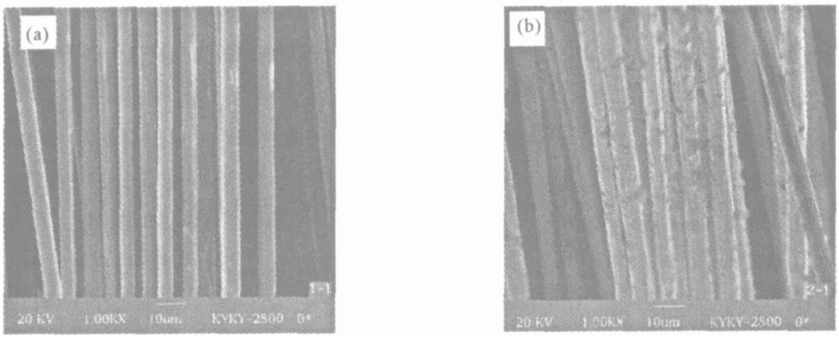

Fig. 4 Scanning electron micrographs of the side surface of carbon fiber cathode (a) before and (b) after emission respectively

A series of the electron scanning micrographs clearly show that the model is reasonable. The electron emission of the carbon fiber cathode is not only from the tip of the carbon fiber but also from its side surface , which is obviously different from that of metal cathode. The plasma formation mechanism of the carbon fiber cathode could be attributed to the field enhancement at the tip of the fiber and the surface flashover along the length of the fiber. And the surface flashover discharge plays an important role in the plasma formation on the surface of the carbon fiber cathode. The surface flashover makes the plasma formed on the whole surface of the carbon fiber , which increases the electron emission area and the uniformity of the cathode plasma sheath. Therefore , it is expected that the plasma formed on the surface of a carbon fiber cathode is more uniform than the one formed on the surface of a stainless steel cathode , and therefore the electron beam generated by the carbon fiber cathode has a better quality , which is favorable for generating high-power microwaves by the vircator.

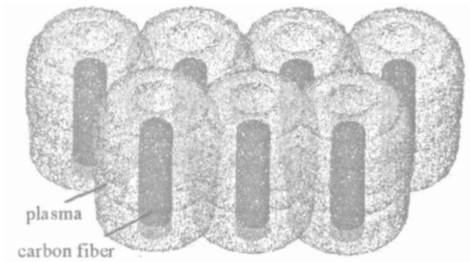

Fig. 5 Electron emission model of carbon fiber cathode

In addition , the melting point of the carbon fiber is very high , which makes the cathode material not prone to evaporate. The carbon fiber is exposed to high temperature conditions in the fabrication process and has predominant structure stabilities[11] . Consequently , in the electron emission process , there are no serious ablation and devastating destruction so that the tips of carbon fibers will not remarkably charge. The properties of the carbon fiber cathode present the extraordinary stability. The operation stability of the carbon fiber cathode may be related to the graphite structure of surface layer of the fiber.

2 Effect of carbon fiber cathode on microwave pulse duration

Several materials have been used as cold cathode explosive emitters in a variety of cathode configurations. A limiting factor for all these cathodes is that they typically suffer impedance collapse. For pulse durations in excess of several hundred nanoseconds , the impedance collapse can often lead to radio frequency (RF) pulse shortening in HPM tubes. The impedance collapse is usually attributed to closure of the anode-cathode (A-K) gap by either radial expansion of the cathode plasma, axial expansion of the cathode plasma, or a combination of both. Either effect can be enhanced by large amounts of gas evolving from the cathode or anode surface. The resultant plasma speeds in these situations are on the order of 1 to 5 cm/s. This impedance collapse effectively limits the pulse length and thus total energy which an HPM tube can deliver.

Among many physical problems involved in relativistic diode, the cathode plasma expanding is prior to be investigated, which is the foundation and the key of the long pulse intensive electron beam accelerator. What to be pointed out is that, because of the Debye screen effect, the cathode plasma will keep neutral, thus its expansion does not depend upon the electric field force, but upon the pressure gradient variance. For the long-pulse diodes, the close time (breakdown time) is decided by the cathode plasma expansion velocity, that is to say the beam current pulse width is restricted by the cathode plasma expansion velocity. In addition, the cathode plasma expansion has important impact on the diode impedance too. Figure 6 shows the impedance versus time for both the stainless steel and carbon fiber cathode diodes. As can be seen from Fig. 6, the impedance of the carbon fiber cathode diode is higher than that of the stainless steel cathode diode. The increased impedance and longer closure time of the carbon fiber cathode diode strongly imply that the plasma expansion velocity decreases obviously. We experimentally investigated the effect on the output microwave pulse duration of carbon fiber cathode, as showed in figure 7. The pulse duration of the stainless steel cathode is approximately 150 ns. In the condition of the same magnitude, the microwave pulse duration, in case of the carbon fiber cathode, increases to about 200 ns. The widening of the microwave pulse duration is to large extent attributed to the improvement of the electron beam quality. It is demonstrated that the interaction time between electron beam and microwave fields can be prolonged by carbon fiber cathode. And the microwave pulse widening is favorable for the enhancement of the RT efficiency.

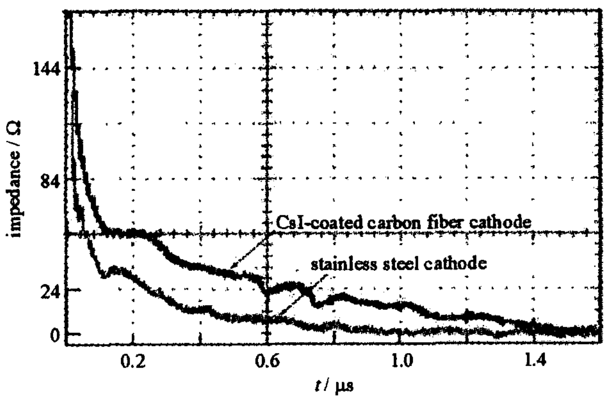

Fig. 6 Temporal behavior of diode impedance with stainless steel and carbon fiber cathodes

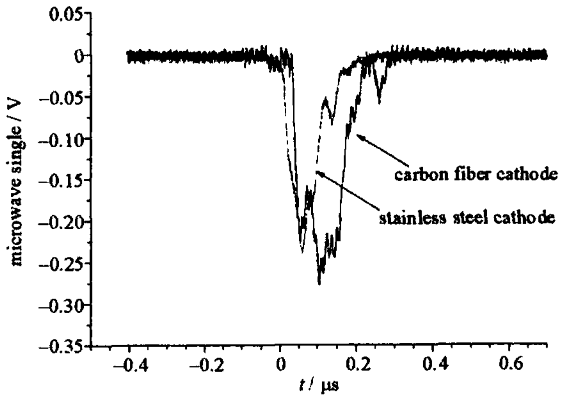

Fig. 7 Comparison of the output microwave singles using carbon fiber and stainless steel cathodes respectively

3 Conclusions

In summary, the electron emission mechanism of the carbon fiber cathode is discussed and the model of emission mechanism is established accordingly. It should be pointed out that the electron emission mechanism of the carbon fiber cathode is mainly the result of surface flashover along the fiber surface. In general, the mechanism of the plasma initiation for the dielectric fiber cathodes can be attributed to field enhancement at the tip of the fiber, or surface flashover along the side surface of the fiber, or both. However, in our experimental condition of long pulse (300 ns), the electron emission mechanism of the carbon fiber cathode can only be both the surface flashover and the field emission at the tip of carbon fiber.

The application of the carbon fiber cathode in high power diode can obviously improve the interaction between the electron beam and the microwave field due to the existence of the surface flashover during the process of the electron emission. Using the carbon fiber cathode, in addition, makes the expansion velocity of cathode plasma slower and then the closure time of the diode A-K gap longer than the case of the stainless steel cathode, which is favorable for the increase of the microwave pulse duration. As a final point, the pulse duration of output microwave was increased by approximately 50 ns, which can illustrate advantages of the carbon fiber material. In conclusion, the carbon fiber cathode has broad perspective in the field of high power diode.

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碳纤维阴极的电子发射机制

刘　列,　李立民,　文建春,　万　红

(国防科学技术大学 光电科学与工程学院,湖南 长沙 410073)

摘　要: 建立了金属阴极和碳纤维阴极的电子发射机制模型,发射后的阴极和碳纤维阴极的微观照片证实了模型的正确性。实验结果与分析表明:一种优化的阴极应该具备多种电子发射机制,整个阴极的电子发射更均匀,碳纤维阴极的电子发射不仅具有尖端的场发射,而且伴随着侧向的表面闪络(随纹)。此外和金属阴极相比较,处理后碳纤维阴极具有较慢的等离子体膨胀速度(≤1 cm/μs)并使该实验用微波源具有较宽的微波脉冲输出(≥200 ns)。

关键词: 碳纤维阴极; 电子发射机制; 微波脉宽