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Citation: Physics of Plasmas **24**, 073104 (2017); doi: 10.1063/1.4990557
View online: http://dx.doi.org/10.1063/1.4990557
View Table of Contents: http://aip.scitation.org/toc/php/24/7
Published by the American Institute of Physics

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Ping Wu,[1,2] Jun Sun,[2] Guozhi Liu,[1,2] Zhanfeng Yang,[2] Shaofei Huo,[2] and Wenyuan Liu[2]
[1]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2]*Science and Technology on High Power Microwave Laboratory, Northwest Institute of Nuclear Technology, Xi'an 710024, China*

(Received 7 May 2017; accepted 14 June 2017; published online 29 June 2017)

Explosive emission cathodes are widely used in high power microwave generation. Conventional metallic cathodes have the disadvantages of bad emission uniformity and short lifetime. In order to improve the emission property of metallic cathodes, a new metal-dielectric cathode is fabricated with the plasma spraying technology. Unlike previous metal-dielectric cathodes, our metal-dielectric cathode adopts a ferroelectric ceramic which possesses a large permittivity. The results of lifetime experiments show the metal-dielectric cathode presents just slight performance deterioration within 2.5×10^5 pulses and thus has a much longer lifetime than the normal copper cathode. The morphology observation demonstrates that the good emission property of the metal-dielectric cathode may benefit from the appearance of irregularities on the dielectric surface, which will have large microscopic field enhancement factors with the help of large permittivity of the ferroelectric material. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4990557]

I. INTRODUCTION

Explosive emission cathodes (EECs) are widely used in high power microwave (HPM) generation systems due to their support of large current and their convenience of installation. In the mechanism of explosive electron emission (EEE), dielectric inclusions on the cathode surface can serve as potential emission micro-points and play an important role in the generation of pre-breakdown current and cathode plasmas.[1–5] Accordingly, metal-dielectric cathodes (MD) have been proposed in an attempt to improve emission uniformity and prolong lifetime of conventional metallic cathodes. Some typical examples are as follows. A planar metal-dielectric cathode has been proposed in Ref. 6 and shows stable emission within 10^8 pulses. The dielectric material adopted here is ceramic with permittivity of 5–6. In Ref. 7, a cylindrical metal-dielectric cathode is fabricated by alternately arranging bronze foils and double-sided printed boards on a stainless steel base. This cathode is adopted in a magnetically insulated transmission line oscillator and shows a stable emission property and much longer lifetime than conventionally used velvet cathode. Besides large-area cathodes, annular metal-dielectric cathodes are also proposed, aiming at the application in O-type HPM devices. For instance, in Ref. 8, an annular copper-dielectric cathode "made of double sided foil-covered glass Textolite" is fabricated and shows a good emission property within 10^6 pulses, which is close to the performance of graphite cathode and much better than that of pure copper cathode; in Ref. 9, a similar copper-dielectric cathode is manufactured, which is made of fiber glass and copper films, and is used in a transit-time oscillator. Some other metal-dielectric cathodes have also been fabricated for various applications.[10–12] Most of these metal-dielectric cathodes adopt dielectric material whose permittivity is moderate (<10), such as fiber glass and cordierite. In our research, a ferroelectric ceramic whose permittivity is very large is adopted to fabricate a metal-dielectric cathode. In fact, ferroelectric cathodes, whose basic emission mechanism is rapid polarization switching,[13,14] have already been researched for decades. However, the emission current of ferroelectric cathodes is usually smaller than 1 kA,[15–18] and a large electric field may trigger explosive electron emission,[18,19] which has attracted less attention maybe due to intentional avoidance of electrode ablation.

II. CATHODE FABRICATION

The structure of our metal-dielectric cathode is outlined in Fig. 1(a). At the location of the cathode blade, a film of ferroelectric is manufactured on the outside of a metallic foil. An annular electron beam is generated from the blade end. The materials of metal and ferroelectric adopted are copper and $BaTiO_3$, respectively. Under room temperature, $BaTiO_3$ is in the ferroelectric phase with permittivity of several thousand;[20,21] when the temperature exceeds the Curie point ($\sim$130 °C), $BaTiO_3$ will turn to the paraelectric phase, and its permittivity will gradually decrease according to the Curie-Weiss law.[21] The fabrication method is manufacturing a $BaTiO_3$ ceramic layer on the side of an annular copper base with the plasma spraying technology. Both the copper layer and the ceramic layer have a thickness of about 0.15 mm, leading to a cathode blade thickness of about 0.3 mm. The manufactured metal-dielectric cathode is shown in Fig. 1(b). The outer radius of the cathode is 19.5 mm.

III. LIFETIME EXPERIMENT

We have performed lifetime test of our metal-dielectric cathode, and compared its result with that of a normal copper cathode. The lifetime experiment is performed on the accelerator TPG1000 which can deliver high-voltage pulses with duration of about 50 ns.[22] The experimental configuration is shown in Fig. 2. The annular electron beam generated by the

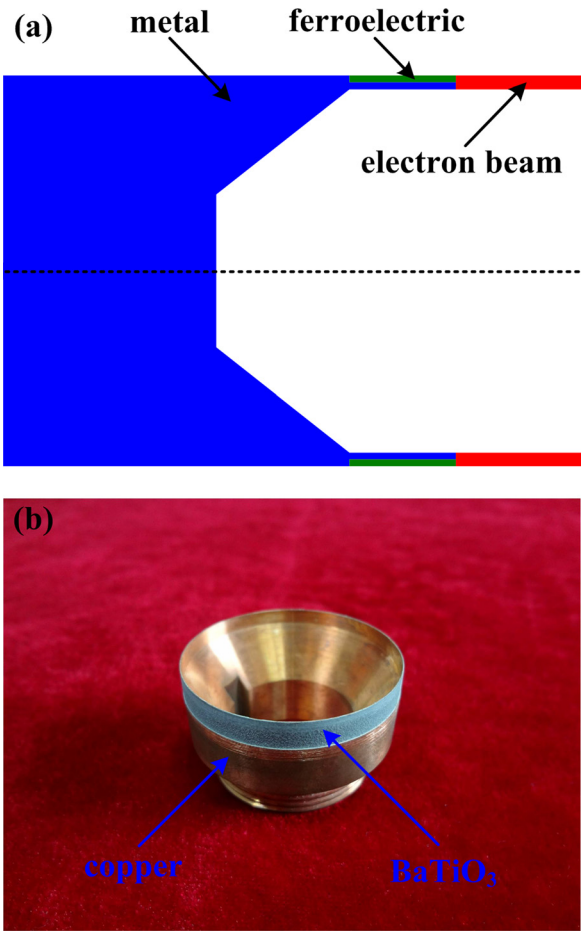

FIG. 1. Schematic (a) and photograph (b) of our metal-dielectric cathode.

cathode is constrained by a guiding magnetic field which is produced by a superconducting magnet. An X-band relativistic backward wave oscillator (RBWO), whose structure is described in Ref. 23, is used to generate HPM. The diode voltage and current are measured by a capacitive divider and a Rogowski coil, respectively. The waveform of the HPM is measured with a directional coupler which is located at the middle of the output waveguide. All waveforms are recorded by one Agilent oscilloscope. The guiding magnetic field is 4.3 T, the effective anode-cathode gap of the foil-less diode is 60 mm, and the vacuum of the system is about 1×10^{-3} Pa. The accelerator operates at a repetition rate of 20 Hz and pauses for 1–2 min after continuous operation of 20 s. In lifetime experiments, the diode voltage is maintained to be about 940 kV, and the corresponding current amplitude is about 9.3 kA. The current amplitude maintains quite stable

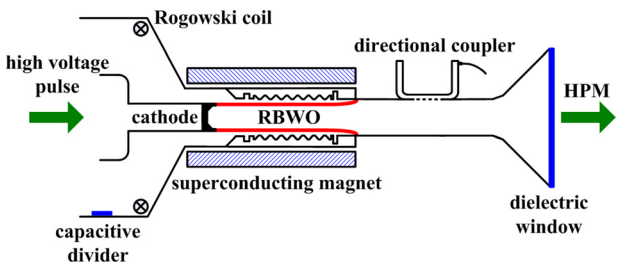

FIG. 2. Schematic of the lifetime experimental configuration.

in lifetime test for both the metal-dielectric cathode and the copper cathode, and no significant difference is observed between these two cathodes regarding the current amplitude. The typical waveform of the metal-dielectric cathode is shown in Fig. 3. The peak of displacement current at the rise edge of the diode current waveform is very apparent, which indicates a moderately long explosive emission delay time.[24] Meanwhile, the microwave waveform falls at the same time with the waveforms of the voltage and current, demonstrating that pulse shortening does not occur in lifetime test. Similar waveforms are obtained for the copper cathode.

The lifetime experimental results of the two cathodes are shown in Fig. 4. The copper cathode and the metal-dielectric cathode have been tested for 3×10^4 pulses and 2.5×10^5 pulses, respectively. Five parameters are monitored in the lifetime test. The current-voltage delay time t_d is defined as the time interval between the half maximum point of the current waveform and that of the voltage waveform, which can partially reflect the explosive emission delay time and the current increase rate. The current duration t_I and the microwave duration t_P are FWHM (full width at half maximum) of the corresponding waveform. For t_d and t_I, the peak of displacement current is excluded since that it is not induced by electron emission. The microwave conversion efficiency η indicates the microwave power amplitude divided by the electron beam power amplitude, and the starting time t_s is defined as the time interval between the 10% maximum point of the microwave waveform and that of the voltage waveform. Clearly, the current-voltage delay time of the metal-dielectric cathode is much shorter than that of the copper cathode, which makes the current duration of the former is apparently longer than that of the latter. For the copper cathode, the current duration decreases to 38.5 ns within 3×10^4 pulses, whereas for the metal-dielectric cathode, the current duration still maintains to be about 40 ns even after 2.5×10^5 pulses. This demonstrates that the electron emission is promoted by the introduction of dielectric layer. The shortening of current-voltage delay time can certainly expedite the starting process of microwave and thus lead to the lengthening of microwave duration. Although the two experimented cathodes have the same microwave duration (~25 ns) at the beginning of lifetime test, which is physically reasonable since that dielectric inclusions and absorbed

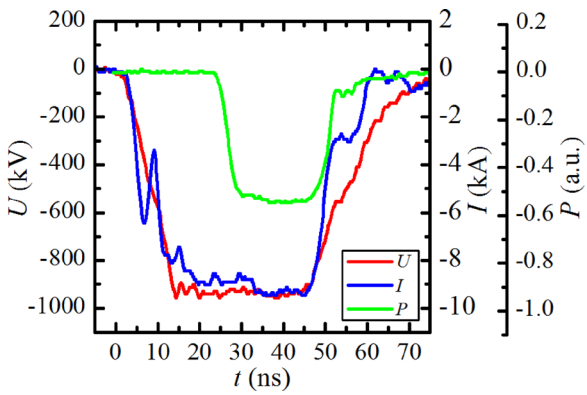

FIG. 3. Typical waveforms of voltage U, current I and microwave signal P for the metal-dielectric cathode in the lifetime test.

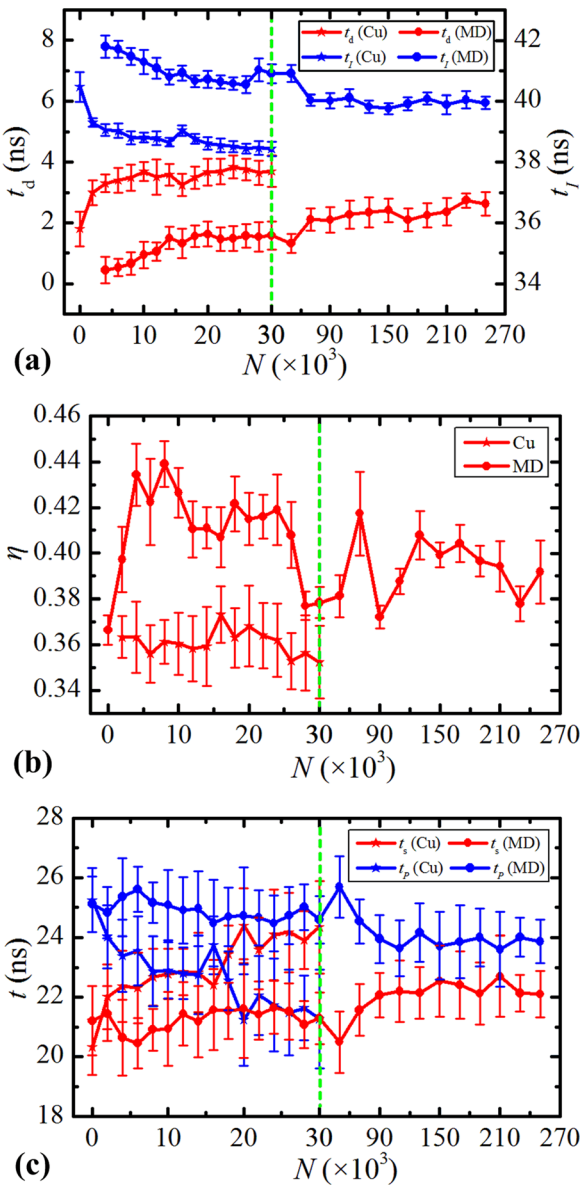

FIG. 4. Changes of the current-voltage delay time t_d, current duration t_l, microwave conversion efficiency η, starting time t_s, and microwave duration t_P with pulse number N for copper cathode (Cu) and metal-dielectric cathode (MD) in the lifetime test. Each data point is averaged over 20 successive shots. It should be noted that the scale of transverse axis is different between before and after $N = 3 \times 10^4$.

gases play an important role in electron emission at this time, for the copper cathode, the starting time increases by about 4 ns within 3×10^4 pulses, leading to a microwave duration of about 21 ns at the end of lifetime test, while for the metal-dielectric cathode, the increase rate of starting time is much slower and thus the microwave duration still maintains to be about 24 ns after 2.5×10^5 pulses. But the difference in current-voltage delay time may be unable to fully explain the difference in microwave duration, since that the latter is much more apparent than the former. We believe that the difference in emission uniformity between the two cathodes contributes here. Although there is no direct evidence supporting the viewpoint that the emission uniformity of the metal-dielectric cathode is better than that of the copper cathode, better emission uniformity can indeed expedite the starting process of microwave, which has already been verified in numerical simulations.[25] Besides, the microwave conversion efficiency of the metal-dielectric cathode is obviously higher than that of the copper cathode, which gives an indirect support for the better emission uniformity of the metal-dielectric cathode. The fluctuation of the microwave conversion efficiency mainly originates from the fluctuation of the voltage amplitude and the reading error.

Therefore, the metal-dielectric cathode has a much longer lifetime than the normal copper cathode. In fact, the emission property of the metal-dielectric cathode maintains quite stable after 9×10^4 pulses and does not present further deterioration in the following pulses. Accordingly, we have much confidence that the lifetime of the metal-dielectric cathode is much longer than 2.5×10^5 pulses before it presents obvious performance deterioration.

IV. MORPHOLOGY CHANGE AND MASS LOSS

The good emission property and long lifetime of the metal-dielectric cathode must have something to do with its surface morphology. Therefore, we observe the morphology of the cathode blade with a scanning electron microscope after the lifetime test, and that is shown in Fig. 5. Clearly, both the metallic layer and the dielectric layer suffer severe melting and erosion, and some dielectric components are deposited on the metal surface, which can promote the electron emission from these locations. Besides, many irregularities emerge on the surface of the dielectric layer. Since the dielectric material is ferroelectric and has a large permittivity, these irregularities will possess large microscopic field enhancement factors, which can expedite the electron emission process and improve the emission uniformity of the cathode. In fact, if the dielectric material is paraelectric and has a much smaller permittivity, the microscopic field enhancement factor of the same irregularity will be much smaller. Therefore, the introduction of ferroelectric material is beneficial to the metal-dielectric cathode.

Meanwhile, the mass loss of the metal-dielectric cathode is also obtained with a balance whose precision is 0.0001 g. The mass losses before and after $N = 1.74 \times 10^5$ pulses are 141 μg/C and 94 μg/C, respectively. The larger mass loss at the initial stage may originate from the severer ablation of

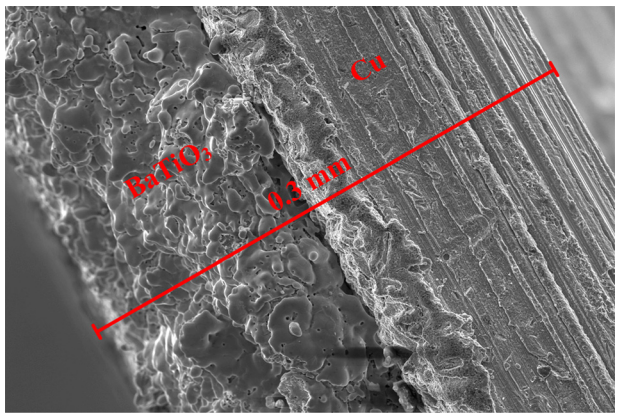

FIG. 5. The surface morphology of the metal-dielectric cathode after the lifetime test.

dielectric components. When the emission property of the metal-dielectric cathode reaches a stable state, its mass loss is close to that of the copper cathode, which is about 98 μg/C.

V. CONCLUSION

A metal-dielectric cathode is fabricated by spraying a layer of ferroelectric material on the side of an annular copper base. The metal-dielectric cathode is tested for 2.5×10^5 pulses under a voltage close to 1 MV and a repetition rate of 20 Hz, and the results show that the metal-dielectric cathode possesses a better emission property and a much longer lifetime than the normal copper cathode. The morphology observation uncovers that the good performance of the metal-dielectric cathode may have connections with the appearance of abundant irregularities on the dielectric surface, and the large permittivity of the ferroelectric material may promote electron emission by enhancing the microscopic field of these irregularities.

ACKNOWLEDGMENTS

The authors would like to thank Chunming Deng for his help in cathode preparation and Xiangguo Wu, Guanjia Liu, and Changfeng Ke for their help in experiments.

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