Theoretical Research of the Breakdown 
Mechanism of the Pseudospark Discharge in
the Field of Pulsed Power Engineering

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Abstract—Pulsed power technology is the key technologies of the future of national defense, while the intense electron beam source development is the high-power microwave bottlenecks. Based on previous experimental, a pseudospark discharge is a viable possibility in this respect, a small-scaled and intense PS electron beam source was conceived to drive a high energy microwave tubes. The electrons emission is the first step of Pseudospark discharge plasmas breakdown, due to high-field emission. Based on filed emission mechanism, a cathode spot heat conduction model of Pseudospark discharge is set up to deduce the microscopic transport characteristics of initial plasmas by mathematics model building method and thermodynamics motion equations. The microscopic transport characteristics of initial plasmas are embodied mainly in the breakdown phase of discharge. So, the breakdown time(trigger delay) of Pseudospark is calculated from the heat conduction model. This research of plasmas discharge microscopic transport characteristics in order to lay the theoretical foundation for the optimize and improve Pseudospark device design.

Keywords-Analytical theory; Breakdown mechanism; Pseudospark discharge; Field emission; Superdense glow discharge

I. INTRODUCTION

Discovered 1970s, The pseudospark discharge is recognized as unique type of discharge which is capable of producing electron beams with highest combined current density and brightness of any known type of electron source. pseudospark discharge continues to be studied with regard to its discharge physics mechanism, its applications as a high power pulsed power technology and as a high quality electron beam source[1-5]. A pseudospark is an axially symmetric, self-sustained, transient, low pressure (typically 50-500 mTorr) gas discharge in a hollow cathode/planar anode configuration, which operates on the left-hand side of the hollow-cathode analog to the Paschen curve. This discharge is characterized by a very rapid breakdown phase, during which high-density particle beams can be extracted and rapid increasing rate of current can be achieved. Based on these, it has been widely applied in plasma processing (ion-etching, thin film deposition, surface processing), gas laser, electron gun, microwave generation, electron beam melting, welding, surface treatment, plasma chemistry, radiation technologies, laser pumping, light source and spectrum analysis. The breakdown phase of Pseudospark discharges is very essential in the whole hollow cathode discharge procedure, because a potentially useful property of this type of discharge is the formation of an electron beam during the breakdown process. At present, the many research people used experiment tools to study the discharge breakdown formation process (ultra fast shutter camera, probe and so on). In this condition, the plasma is generated in the closure cavity and the electron is extracted from some boundary of the plasma and accelerated to form the Ebeam. Physically, the electron is emitted from the flashover plasma on the surface of cathode, although the plasma density is significantly higher than that of any material cathode, the damage owing to high-energy ion impacts will become the least since the resultant cathode is essentially a plasma. Pseudospark discharge offers the electron beam of high current density ,high brightness and narrow beam diameter. Our focus is to develop high energy, intense current, annular electron beams which are very attractive as an electron beam source for high pulse power.

This paper is outlined as follows: in section2, pseudospark discharge apparatus is briefly. In section3, Analytical theory model is briefly described, including the mathematics model building method and thermodynamics motion equations considered. Then a short summary is given in section4.

II. PSEUDOSPARK DISCHARGE APPARATUS

A new multi-gap Pseudospark discharge experiment cavity has been carried out to prove the concept of the generation of a narrow electron beam as shown in Fig .1 The experimental setup has already been described
III. ANALYTICAL THEORY OF BREAKDOWN MECHANISM

Experimental research and theoretical analysis of the gas discharge are important in understanding the law of gas discharge, making use of electrical characteristic of gaseous dielectric, developing new type gas switch. Researchers have done lots of researching work in breakdown phenomena of gas discharge and gained great achievement but there is no an ideal model to describe it, because the process of gas discharge concerns lots of affecting factors. The field emission is considered very important, the electron current density emitted from the cathode surface due to the field emission $j_1$ is described by the modified Fowler-Nordheim formula for the cold cathode

$$j_1 = \frac{AE^2}{q}\exp\left(-\frac{C\varphi^{1/2}V(t)}{E}\right)$$

where $j_1$ in A/cm², $y = BE^{1/2}/\varphi$ is a function of the cathode field strength $E$ (in V/cm) and work function $\varphi$ (in eV) of cathode material, $t(y)$ and $V(y)$ are functions related to the elliptic function, $f_1 = z/\sin(z), z = DT\varphi^{1/2}/E$

$A = 1.54\times10^{-6}, B = 3.79\times10^{-4}, C = 6.83\times10^2, D = 2.77\times10^3$

Numerical calculation for (1) shows that only when the electric field must be larger than $3 \times 10^7$ V/cm, does $j_1$ have significant growth.

Field-enhanced thermionic emission appears in the middle of the pseudospark discharge phase due to energy deposition and heating effects. An initial cathode is cold because additional heating effects and energy deposition can be ignored in the early part of pseudospark discharge process. Joule heating, which is caused due to emitting electrons from inside the cathode under the influence of electrical field. The resistive heating and the ion impacting make the cold cathode surface become hotter with the time. The current density can be described by the Richardson-Schottky(RS) formula

$$j_2 = \frac{4\pi m_e(kT)^2}{h^3} \exp\left(-\frac{\varphi - \sqrt{\varphi^2 - 4E}}{kT}\right)$$

Follow the above formula, it can be seen when $E$ is lower than $5 \times 10^6$ V/cm, the cathode temperature must be over 3300 K. Note that field strengths at the tips of micropoints (in the discharge cathode) can reach, even are higher than, $1 \times 10^7$ V/cm.

Assuming that the ion and electron bombardment is the transiently heat source which heats the cathode surface. Mathematics model building method and thermodynamics motion equations as a function of time with a constant power flow density $F_0$ is given as follows

$$T(0,t) = T_0 + (2F_0/K)\sqrt{kT/k\pi}, x = 0$$

where $K, \rho, C$ and $k = K/\rho C$ are the thermal conductivity, mass density, specific heat, and diffusivity.

However, it is quite difficult to know the detailed pseudospark discharge process in the hollow cathode cavity in the experiments. Particularly few investigations were reported on the physical mechanisms for this type of gas discharge breakdown process. Nevertheless, these researches that have still not been fully explored is that of pseudospark discharge.
of the cathode material, respectively, and $x$ is the heat-penetrating depth into the cathode surface. Follow the above the formula, we can get the heated cathode temperature, to produce the observed current density of breakdown process of pseudospark discharge.

Naturally, there have clear bombardment traces on the copper deeply due to high energy particle in the Fig. 2. Therefore, a clear distinction between this kind of pulsed intense electron beam and the conventional electron beam sources based on thermoionic or field emission cathodes must be made.

Figure 2. Photograph of typical beam damage shape on copper

IV. SUMMARY

We successfully designed the analytical theory of the Pseudospark discharge breakdown mechanism. After triggering, the plasma in the pseudospark is formed and is terminated by plasma-cathode wall breakdown and the formation of cathode spots. This results in plasma density increase and the onset of high current phase. A cathode spot heat conduction model of Pseudospark discharge is set up to deduce the microscopic transport characteristics of initial plasmas by mathematics model building method and thermodynamics motion equations. New mechanisms are proposed for later phases in the development of the pseudospark discharge. This research of plasmas discharge microscopic transport characteristics might bring a new insight on the physical model of this complex breakdown transient discharge.

V. ACKNOWLEDGEMENTS

This work was financially supported by the National Natural Science Foundation of China (11347125), Zhejiang Provincial Natural Science Foundation of China (Y14E070029), Zhejiang Qianjiang Talent Project (2013R10064), China Postdoctoral Science Foundation (2014M551735), Science Foundation of Zhejiang Sci-Tech University (1104826-Y).

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