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Effect of secondary electron emission on subnanosecond breakdown in high-voltage pulse discharge

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Abstract. The subnanosecond breakdown in open discharge may be applied for producing superfast high power switches. Such fast breakdown in high-voltage pulse discharge in helium was explored both in experiment and in kinetic simulations. The kinetic model of electron avalanche development was developed using PIC-MCC technique. The model simulates motion of electrons, ions and fast helium atoms, appearing due to ions scattering. It was shown that the mechanism responsible for ultra-fast breakdown development is the electron emission from cathode. The photoemission and emission by ions or fast atoms impact is the main reason of current growth at the early stage of breakdown, but at the final stage, when the voltage on discharge gap drops, the secondary electron emission (SEE) is responsible for subnanosecond time scale of current growth. It was also found that the characteristic time of the current growth $\tau_s$ depends on the SEE yield of the cathode material. Three types of cathode material (titanium, SiC, and CuAlMg-alloy) were tested. It is shown that in discharge with SiC and CuAlMg-alloy cathodes (which have enhanced SEE) the current can increase with a subnanosecond characteristic time as small as $\tau_s = 0.4$ ns, for the pulse voltage amplitude of 5-12 kV.

1. Introduction

In the experiments with high-voltage open discharge in helium [1,2] a new method was proposed for switching of power pulses with time less than a nanosecond. The high-voltage open discharge proved to be an useful tool for producing high-energy electron beams or subnanosecond high-power electrical switch. But the mechanism of this fast current rise in this type of discharge was not completely clear.

Recently the current exponential growth within a subnanosecond was registrated [1,2] during breakdown in high voltage open (HVO) discharges in helium. The discharge operates between two parallel plane cathodes and a mesh anode with 90% transparency between them. Applying high voltage leads to the generation current with density of 200 - 400 A/cm² and current increase rate of 500 A/(cm²ns). Such type of discharges with unique parameters can be used as a source of electron beams or as subnanosecond high-power switches.

The earlier developed models of breakdown in helium [3] are not able to explain such ultra-fast development of current. The electron emission from the cathode due to ions or fast atoms bombardment is usually considered as a main process of breakdown development. However the subnanosecond times of breakdown in HVO discharge can not be supported by emission with ions and fast atoms bombardment due to their inertia. The photoemission by resonant radiation from atoms excited by electron impacts is also unable to maintain the observed current growth rate since for these
times the resonant photons are trapped in plasma due to reabsorption. In works [1,2] it was proposed that the key role in photoemission play the photons of resonant radiation, having Doppler shift. The fast atoms, appearing after elastic scattering of fast ions, have large energy (1-500 eV) and due to their large velocity, radiate resonant photons with a Doppler shift. The same occurs, due to momentum transfer, when atom of buffer gas is excited by ion impact or fast atom impact. Another significant source of Doppler-shifted (DS) photons is reaction of resonant excitation transfer from excited buffer gas atoms to fast atoms. The DS photons are not reabsorbed in buffer gas and reach the cathode surface immediately, producing intensive photoemission. In first attempts to simulate ultra-fast breakdown [4] the account of photoemission by DS photons allowed to explain the nanosecond times of plasma accumulation before the final stage of breakdown. But, as was found next, the real explanation of subnanosecond current front rise belongs to secondary electron emission (SEE) from cathode surface at the final breakdown stage. When the discharge current reaches magnitudes of tens A/cm², the voltage on the discharge gap begins to diminish due to properties of electric circuit. The hot electrons, accumulated in bulk plasma, become able to overcome the cathode potential fall and begin to bombard the cathode. This leads to enlarging of current and thus to further decrease of cathode voltage. So the SEE grows exponentially and becomes the dominant process in subnanosecond current growth at the final stage of breakdown. In this work, the aim was to study the influence of cathode SEE yield on the minimal achievable time (or maximal rate) of current growth. The experimental investigations and simulations were performed for three different types of cathode materials, having different SEE yield, namely: titanium, silicon carbide and CuAlMg-alloy cathodes.

2. Experimental technique

In experiment, the breakdown in helium is studied in a planar pulse discharge with generation of two oppositely directed electron beams. The scheme of experimental cell is shown in Figure 1. It has two round cathodes with area of 16 cm² and a mesh-anode with the geometric transparency of 0.9 is placed between them. The inter-cathode distance is 6 mm. The cathodes and anode are isolated with a set of plates from glass. The pulse voltage is simultaneously applied to the cathodes and its amplitude ranges from 4 kV to 12 kV in different experiments. The gas pressure varies from 10 Torr to 35 Torr.

The voltage shape is recorded using oscilloscope Tektronix DPO 70804C with a bandwidth of 8 GHz. The registration circuit and other experimental conditions were described in details in [1].

In the experiments three types of cathodes made from different materials were tested. All these materials, titanium (Ti), silicon carbide (SiC), and CuAlMg alloy have enhanced secondary electron yield, but the dependences of secondary electron emission coefficient (SEE) \( \gamma_e \) from the electron
energy $\varepsilon_e$ are very different. For Ti the SEE coefficient $\gamma_e$ varies from 0.4 to 0.9 in the range from 50 eV to 5 keV, with maximum at 300 eV [5]. For SiC the $\gamma_e$ has similar behavior as for Ti for energy range 20 eV - 400 eV [6], but it is nearly three times larger, $\gamma_e = 0.9 - 2.5$. For CuAlMg alloy $\gamma_e$ can be very different depending on the state non-activated and activated by annealing [7]. It should be noted that for non-activated CuAlMg alloy the $\gamma_e$ is close to observed for SiC. The activation occurs due to diffusion of Mg to the surface and its oxidation. So, the annealed CuAlMg alloy demonstrates $\gamma_e$ up to 12.5 in the electron energy range 500 eV - 2 keV.

The energy dependence of $\gamma_e$ for all three types of cathode material is shown in Figure 2. The values of $\gamma_e$ for inactivated CuAlMg alloy from [7] are also shown in Figure 2 by crosses. There is lack of empirical data for inactivated CuAlMg at low-energies. The comparison of the measured current growth times in the discharge with different cathodes allows us to estimate the contribution of SEE in the electron avalanche development.

3. Physical model

The discharge plasma is described with the system of equations including the Boltzmann equations for electrons, ions and fast neutral atoms. The distribution functions for electrons $f_e(t,x,v)$, ions $f_i(t,x,v)$ and fast atoms $f_a(t,x,v)$ are calculated from the Boltzmann equations

$$\frac{\partial f_e}{\partial t} + v_e \frac{\partial f_e}{\partial x} + \frac{eE}{m_e} \frac{\partial f_e}{\partial v_e} = J_e, \quad n_e = \int f_e dv_e,$$

$$\frac{\partial f_i}{\partial t} + v_i \frac{\partial f_i}{\partial x} + \frac{eE}{m_i} \frac{\partial f_i}{\partial v_i} = J_i, \quad n_i = \int f_i dv_i,$$

$$\frac{\partial f_a}{\partial t} + v_a \frac{\partial f_a}{\partial x} = J_a, \quad n_a = \int f_a dv_a,$$

and the Poisson equation for the electric potential $\phi$:

$$\Delta \phi = 4\pi n_e - n_i, \quad E = -\frac{\partial \phi}{\partial x}.$$ 

where $v_e, v_i, v_a, n_e, n_i, n_a, m_e, m_i, m_a$ are the velocities, densities and masses of electrons, ions and fast atoms respectively. $E$ is the electrical field, $J_e, J_i, J_a$ are the collisional integrals for electrons, ions and fast atoms, which include elastic and inelastic scatterings with He atoms. The PIC MCC method was applied to solve the Boltzmann equations. The system of equations are solved self-consistently. For the electrons, the model includes the following collisions: 1) elastic, or momentum transfer; 2)
Figure 4. Characteristic time of current front rise $\tau$ from pulse voltage amplitude for cathodes made from Ti (a), SiC (b) and for CuAlMg-alloy (c) for different gas pressures.

electron impact excitation of He atom; and 3) electron impact ionization of He. For the He$^+$ ions, four types of collisions with the background atoms are taken into account: 1) elastic collision; 2) resonant charge exchange collision, or backward elastic scattering; 3) ion impact excitation of He atom; 4) ion impact ionization of He atom. The fast neutral atoms He appear during ions scattering on the background gas. We include into consideration only the fast atoms with the energy $\varepsilon_a > 1$ eV.

The collisions of the fast atoms include also four types of reactions: 1) elastic scattering; 2) atom impact excitation; and 3) atom impact ionization. The scattering of heavy particles are assumed to be isotropic in the center of mass system. Also, the 4-th reaction of collisional excitation transfer (CET) is taken into consideration, as a possible source of excited fast atoms. The details of physical model and the crossections of described above reactions can be found in publications [4,8,9].

The most important process, defining the development of breakdown, is the electron emission from the cathode. As was mentioned above, the resonant photons with a Doppler-shifted frequency can reach the cathode instantly without reabsorption. Also electrons are emitted by incident ions or fast atoms. As was shown in [8,9], the secondary electron emission (SEE) becomes a dominant process in current growth at the final stage of breakdown.

At the stage of preliminary plasma accumulation, the high energy electrons are trapped between two cathodes by the kV-potential drop over the cathode sheaths. While current rise, the discharge voltage begins to decrease and cathode potential drop diminishes. The high energy electrons accumulated in the discharge volume start to bombard the cathodes and the breakdown current grows.
exponentially with subnanosecond characteristic time. With increasing gas pressure the contributions from the photoemission and secondary electron emission enlarge and the characteristic time of breakdown decreases. The purpose of this work was to study the effect of SEE yield emission on the breakdown time for three types of cathode materials with enhanced SEE emission yield, and to find minimal breakdown time with a combined effects of cathode material with high SEE and variation of the gas pressure.

4. Results

The typical waveform of voltage pulses on the discharge gap are shown in Figure 3 for the discharge cells with Ti, SiC and CuAlMg-alloy cathodes for the voltage amplitude $U_a = 10$ kV and for helium gas pressure $P = 25$ Torr. For the case with CuAlMg-alloy cathode the simulated $dU/dt$ is larger than observed in the experiment, likely because of the specific state of the CuAlMg-alloy surface in the experiment. The value of $\gamma_e$ for CuAlMg-alloy cathode is very sensitive to a degree of alloy activation due to magnesium diffusion to the surface and its oxidation by heating. For the case with SiC-cathode $\tau_s \approx 0.4$ ns and computed and measured voltage profiles are in good agreement. For Ti-cathode $\tau_s \approx 2$ ns. Calculated profile demonstrates the pronounced oscillations likely due to the simplified external circuits taken in simulations.

As seen in Figure 4, the switching time is very sensitive both to the gas pressure and the cathode material (SEE yield). An increase of gas pressure diminishes the breakdown time. However if the secondary electron emission coefficient is small like for titanium, $\tau_s$ remains larger than 1 ns even with a variation of gas pressure between 20 Torr and 40 Torr (see Figure 4(a)). For the materials with enhanced SEE like SiC and alloy, an decrease of gas pressure from 10 Torr to 30 Torr allows us to reduce $\tau_s$ from 2 ns to 0.4 ns (see Figure 4 (b),(c)).

In conclusion, the experimental study and simulations of SEE yield, voltage magnitude and gas pressure confirmed that the SEE makes main contribution in current growth on the final stage of breakdown. The $\tau_s \approx 0.4$ ns were observed for SiC and CuAlMg cathodes, but for titanium cathode only $\tau_s \approx 2$ ns was obtained. The results of experiment and simulations are in good agreement. We also found out that the increase of gas pressure from 10 Torr to 30 Torr helps to decrease the $\tau_s$. Altering pulse voltage amplitude within 5 kV - 10 kV weakly changes $\tau_s$.

5. Acknowlegements

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