THE FORMATION OF ELECTRONS BEAMS IN GAS UNDER ATMOSPHERIC PRESSURE

V.A.Shklyaev*, K.P.Artyomov, S.Ya.Belomyttsev, A.A.Grishkov, V.V.Ryzhov,
I.Yu.Turchanovsky, Institute of High Current Electronics SB RAS, 2/3 Akademichesky Av.,
Tomsk, 634055, Russia

Abstract

In this work results of numerically researches of the formation of runaway electrons beam in gas under atmospheric pressure presents. It is showed that runaway electrons beam was formed in highly inhomogeneous electric field near the cathode. This beam consists of electrons emitted from cathode and electrons arising as a result of gas ionization. It was showed that duration of the beam of run-away electrons nearby cathode mainly depend on outer electrical field screening by plasma and was equal to 10-20 ps. Dynamic of acceleration electrons in gas similar to dynamic of acceleration electrons in vacuum.

INTRODUCTION

With high electric field to gas pressure ratios ($E/P > 10^3$ V/cm/Torr), the time it takes for a discharge to develop can be a mere few nanoseconds or even fractions of a nanosecond [1]. This effect is attributed to electrons for which a runaway condition is fulfilled. The runaway condition implies that in rather high electric fields ($E > E_{cr}$), the energy gained by electrons between collisions is greater than that lost in inelastic collisions, and the electrons pass to continuous acceleration. The runaway electrons assist in preliminary ionization in the gas discharge gap and in its rapid breakdown. It is thought that similar effects may take place in gas-filled diodes during the formation of subnanosecond runaway electron beams in an inhomogeneous electric field [2].

MODEL

The paper presents the results of numerical research on the formation of a runaway electron beam in gas at atmospheric pressure. It is shown that the runaway electron beam is formed near the cathode in a highly inhomogeneous electric field. The dynamics of electron acceleration in gas is found to be similar to that of electron acceleration in vacuum.

A way of studying the processes occurring in the gas discharge gap on its breakdown is numerical simulation of ionization electron multiplication in the gas by the Monte-Carlo method [3-5]. However, the majority of models used in the above works ignore the space charge produced by avalanche charged particles. Moreover, the applicability of these models is limited due to a rapidly increasing number of particles involved in the calculations.

For studying the processes occurring early (10 – 30 ps) in the discharge in an inhomogeneous electric field, a PIC-based one-dimension model of the discharge development [6] was proposed in which electron collisions with gas atoms and molecules are taken into account by the Monte-Carlo method (a PIC/MC model). In the model, the equations of particle motion in an inhomogeneous external electric field are solved in terms of the space charge. The electric field is considered as the superposition of an external electric field on a particle-produced electric field. For the cylindrical edge cathode – plane anode system, the external field distribution along the z axis is adequately described by the formula [7]:

$$E(z) = \frac{U}{\left(R_c \ln\left(\frac{R_a}{R_c}\right)(h + 2\pi z)^{1/2} \right)} \left(\ln\left(\frac{R_a}{R_c}\right) R_c \right)^{1/2},$$

where U is the diode voltage, R_c, R_a are cathode and anode radii, respectively, and h is the cathode edge thickness. The particle-produced field was calculated using approximate numerical solutions of the Poisson equation for pseudoinhomogeneous grids.

The electron collisions with N molecules at atmospheric pressure were simulated taking into account the excitation (24 level) and nitrogen ionization cross-sections in a wide energy range (0.1 eV – 300 keV). The problem of the avalanche increase in the number of electrons due to gas ionization was solved in the framework of a particle coalescence model. In the model, particles of energy (ε) – ($\varepsilon + \Delta\varepsilon$) in one spatial grid mesh coalesce into a new particle with a weight equal to the sum of weights of all these particles. The coalescence algorithm was checked for conservation of the space charge and energy spectrum of the particles before and after coalescence.

The geometry of the computation domain is shown in Fig. 1. The domain geometry corresponds to the diode geometry used in experiments [2, 8]. The simulation region is a hollow cylinder of diameter and thickness equal to those of the cathode. The characteristic times of the processes under study are tens of picoseconds, and hence the near-electrode simulation region along the diode axis D is no greater than 2 mm.

The cathode emissivity was specified assuming that the electron source is field emission [9]. The injection current densities calculated by the Flower –Nordheim $j_{in} = 10^{-4}$ - 1 A/cm^2.

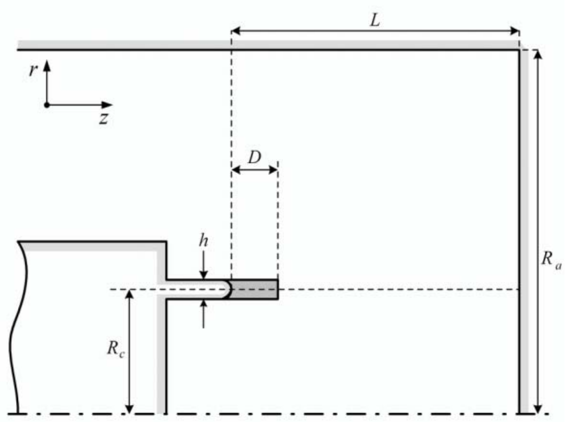


Fig. 1. Geometry of the computation domain: $R_c = 0.3$ cm, $R_a = 2.35$ cm, $h = 100$ μm, cathode – anode spacing length $L = 1$ cm, length of the computation domain $D < 0.2$ cm

RESULTS

The processes responsible for the formation of runaway electrons were investigated by simulating the early stage of the discharge development at a constant voltageя $U = 100$ kV. The simulation shows that the electrons injected from the cathode are continuously accelerated in the region of a strong electric field, gain energy, and ionize the gas. Note that the electrons produced near the cathode due to gas ionization are also involved in the acceleration, since the electric field unaffected by the space charge at a distance of ~300 μm from the cathode is such that the energy gained by the electrons between collisions is greater than that lost in collisions. These electrons form a beam with a current several orders of magnetite greater than the injection current due to gas amplification. The beam of runaway electrons ionizes the gas, thus forming a near-cathode plasma layer with conductivity sufficient for shielding the external electric field.

The positive charge of ions left in the near-cathode region after the runaway of the electrons distorts the external electric field, forming a near-cathode layer (region *I* in Fig. 2) with an increased electric field. However, the electrons in the near-cathode layer are no longer capable for continuous acceleration, because they arrive in the region of a weak electric field inside the plasma (region *II* In Fig. 2) after passing a short acceleration path.

Experimental time-of-flight measurements [8] show that the rate of energy gain for an electron beam in a gas-filled diode is identical to that in a vacuum diode. This problem was examined by simulating the energy characteristics of the beam formed in a gas-filled diode. The simulation was performed for a constant voltage of 100 kV and a constant density of the electron injection current from the cathode.

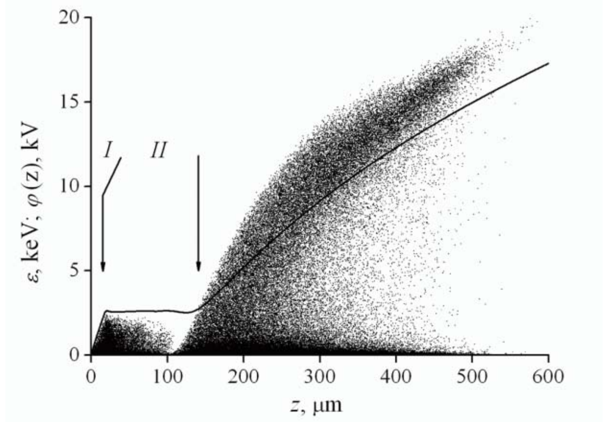


Fig. 2. Phase portrait of electrons and electric field potential distribution (solid curve) in the gap at $t = 10$ ps, $U = 100$ kV, and $j_{in} = 10^{-2}$ A/cm^2.

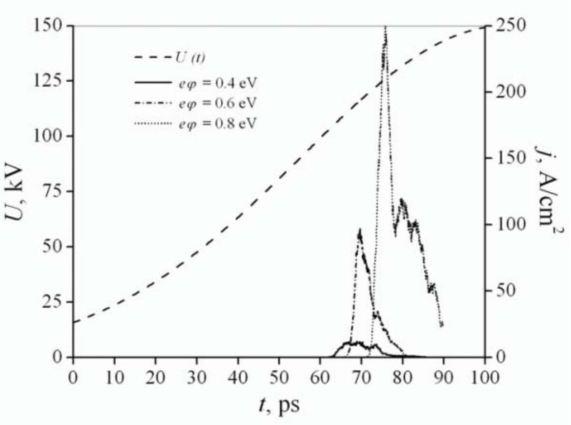
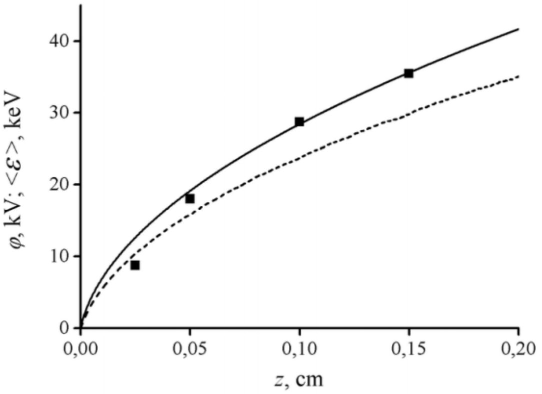


Fig. 3. Oscillograms of the diode voltage and current density of the runaway electron beam for cathode materials with different work functions.

Fig. 4 shows the potential distribution $\varphi(z)$ in a “cold” vacuum diode and the average electron energy $<\varepsilon>$ in different cross-sections corresponding to the point in time at which the current density of the runaway electron beam peaks.

The good agreement between the average energy of the runaway electron beam (circles in Fig. 4) obtained taking into account the losses in the gas and the average electron energy in a vacuum diode (solid curve in Fig. 4) was unexpected. It was thought that they are an order of magnitude lower than the average electron losses in the gas (dotted line in Fig. 4). Analysis shows that at distances greater than 1 mm, the electrons are accelerated by a field higher than the initial one (the field of the cold vacuum diode) due to amplification at the plasma boundary (Fig. 5). It is seen from Fig. 5 that the amplification of the field distorted by the space charge at the boundary of the plasma region $z \sim 0.4$ mm is about 10 - 15 % of the field of the cold vacuum diode. This field is sufficient for compensation of the electron energy losses in the gas.



Fi. 4. Potential distribution *φ (z)* in a “cold” vacuum diode near the cathode (solid curve) and average electron energy (dotted line) with regard to collisions. Circles indicate the average electron energy $<\varepsilon>$ in different cross-sections (0.25, 0.5, 1.0, and 1.5 from the cathode).

Thus, the PIC/MC simulation of the early stage of the gas discharge development in an inhomogeneous electric field shows that for E/P > 1 kV/cm*Torr, a runaway electron beam consisting of both emission electrons and electrons resulting from gas ionization is formed near the cathode within ~ 10 ps. The duration and amplitude of the runaway electron beam is determined mainly by the mechanisms of shielding of the external electric field with the formed plasma and is 10 – 20 ps, and the rate of energy gain of electrons in a gas-filled diode corresponds to that in a vacuum diode, which agrees with experimental data [2, 8].

The work was supported by RFBR grant No. 06-08-00637

REFERENCES

[1] Yu.D. Korolev, G.A. Mesyats, Physics of pulsed gas discharge, Nauka, Moscow, 1991, p. 224.
[2] G.A. Mesyats, S.D. Korovin, K.A. Sharypov, V.G. Shpak, S.A. Shunailov,M.I. Yalandin, Pisma Zhur. Tekh. Fiz., V. 32, No. 1, pp. 35–44 (2006).
[3] V.F. Tarasenko, S.I. Yakovlenko, Usp. Fiz. Nauk, V. 174, No. 9 pp. 953–971 (2004).
[4] A.N. Tkachev, A.A. Fedenev, S.I. Yakovlenko, Zhur. Tekh. Fiz., V. 75, No. 4, pp. 60–66 (2005).
[5] W.Jiang, K.Yatsui, V.M. Orlovskii, V.F. Tarasenko // Proc. Int. Conf. Beams-2004, Saint-Peterburg (2005), P. 174–177.
[6] S.Ya. Belomyttsev, I.V. Romanchenko, V.V. Ryzhov, V.A. Shklyaev, Pisma Zhur. Tekh. Fiz., V. 34, No. 9, pp. 10–16 (2008).
[7] S.Ya. Belomyttsev, I.V. Romanchenko, V.V. Rostov, Izv. Vyssh. Uchebn. Zaved., Fiz., V. 51, No. 3, pp. 71-76 (2008).
[8] G.A. Mesyats, V.G. Shpak, S.A. Shunailov, M.I. Yalandin, Pisma Zhur. Tekh. Fiz., V. 34, No. 4, pp. 71–80 (2008)
[9] G.A. Mesyats, Pisma Zhur. Tekh. Fiz., V. 85, No. 2, pp. 119–122 (2007).
[10] G.A. Mesyats, Ectons (Part 2), Nauka, Ekaterinburg, 1994, p. 248.