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Intense Charged-Particle Emission in a Diffuse Vacuum Discharge

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Abstract

The well-known effects of plasma-assisted emission of electrons from a cathode and of ions from an anode are used in experiments in order to generate intense particle beams in a vacuum gap. The plasma is produced mainly by sputtering of the electrons and ions impinging on the electrode surfaces. When the initial electron beam, which here is generated by ferroelectric emission, reaches a threshold current density of about 1 A/cm^2 , a homogeneous vacuum discharge takes place provided an electric field of the order of 10 kV/cm is applied between the anode and the cathode. The vacuum gap is short-circuited and the sum of the electron and ion beam currents is uniquely determined by the charging voltages and by the parameters of the external electric circuit. Beam currents of electrons and ions are extracted through holes or grids in the corresponding electrodes and measured with Faraday cups.¹

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1. INTRODUCTION

The intensity of conventional electron sources based on thermionic emission, photoemission, secondary emission, or field emission is limited by the work function of the emitter and by the space-charge fields. Conducting materials, used mostly as emitters, are characterized by a finite work function, and the space-charge limitation is caused by the presence of high charge densities in a vacuum that is in contact with the cathode.

Recently, two new methods of inducing electron emission from perovskite ceramics have been demonstrated. This was done either by spontaneous polarization change¹⁻⁵ of the ferroelectric phase or by laser irradiation of an oxygen-vacancy-enriched surface layer⁶. Neither of these methods is concerned with significant work function limitations, but, owing to the vacuum environment, the space-charge limitations persist, as in conventional types of emitters.

Current densities of 10^4 A/cm² and more can easily be obtained in high-current gas and vacuum discharges.⁷⁻⁸ Even higher current densities are observed in the hot spots of vacuum arc discharges or in high-density z-pinch devices. Nature does not seem to establish an upper limit on the emission process; the current is mainly determined by external electric circuit parameters. The common reason for this virtually unlimited current emission is the presence of a plasma in contact with the emitting cathode. The plasma eliminates the space-charge forces between the charge carriers, and the electron beam current can largely exceed the Langmuir Child limit. Even with a small external positive potential, a very strong electric field is generated across the cathode fall of the plasma, and the resulting field emission may be enhanced by heating and by sputtering due to the ions impinging on the surface.⁷

Conventional ion sources generally work on the basis of the extraction of ions from a plasma, of sputtering, of interaction between ions and electrons (EBIS, ECRIS), and of evaporation. The small velocity near the source results in space-charge limitations that are even more stringent for ions than for electrons. Ionized gas neutralization is not desirable in this case, since charge exchange and recombination reactions would reduce the ion intensity severely. The ion beam current intensities reached in conventional ion sources are, therefore, rather modest, especially for heavy ions.

Proper control of the plasma density distribution and geometry, as well as of the potential distribution and of the electrode arrangement, may lead to the optimal generation of intense, multiply charged, heavy ion beams. An ion beam transported away from the source through a vacuum channel is usually fully space-charge dominated. The space-charge limit can be overcome to some extent by sacrificing a small part of the ion beam in order to sputter off electrons from grids along the transport channel. These electrons are accelerated in the opposite sense and partially neutralize the ion beam.

This article describes a device which, with minor modifications, can be used for the generation of either a very strong electron beam or an intense ion beam. During beam generation the whole vacuum gap becomes homogeneously conducting, — a phenomenon that can be considered as a 'diffuse vacuum discharge' (DVD).

2. EXPERIMENTAL SET-UP

Figure 1 shows the discharge chamber as version of an electron beam source. As the emitter of the initial electron beam we used a ferroelectric, ceramic disk made of lead-lanthanum-zirconium-titanate (PLZT) of composition 2/95/5, where the three numbers refer to the La concentration and to the ratio of Zr to Ti.⁴⁻⁵ This beam can be considered as the trigger beam for the subsequent processes. The trigger beam (FE beam) is emitted from the bare parts of the sample surface with the grid electrode (GE) by the fast change of the spontaneous polarization of the ferroelectric disk (FE) induced by a negative HV pulse on the rear electrode (RE). The FE beam is accelerated towards the anode (A) by means of a d.c. potential of the order of 10 to 20 kV/cm. The electrons can be extracted and transferred to an external transport channel (TC) through a hole or a grid (G1) in the anode. When G1 is closed, the anode can also be used as a Faraday cup for measuring the emitted electron beam current and the charge. The sample FE (cathode C) can be kept at a negative potential. A highly transparent grid (G2) inserted between FE and A is grounded via 50 Ω and serves to monitor the main emission current. The vacuum of the volume between FE and A is below 10^{-5} mbar, but it could also be worse.

When the FE beam current density exceeds a threshold of the order of 1 A/cm², ions are sputtered off from the anode (A and G1) and accelerated towards the surface GE of FE. The surface plasma, which is produced by ion sputtering on GE, transforms the vacuum gap into a short-circuit, and from now on the circuit current is converted directly into beam current (DVD electron beam current). According to the conditions that are valid in the transport channel TC (vacuum, plasma, low-pressure gas), a part or the whole of the DVD electron beam can be extracted and guided to its destination.

Figure 2 shows the device as a source of ions. The grid G1 of the anode A is replaced by a target (TG) that consists of the material containing the desired ion species. The sample FE is perforated by a hole, 3 mm in diameter, to allow for the extraction of the ion beam that is generated by the DVD electron beam during the short-circuit phase of the vacuum discharge. An acceleration potential HV_{TG} of about 10 kV is applied between TG and GE. In order to fight the severe space-charge limitations on the ion beam (IB) in the vacuum of TC behind RE, an extraction potential HV_{FE} of several kV is applied between the sample FE and the extraction grid with high transparency (G2) in TC downstream from RE. Electrons sputtered off from G1 by ion impact are accelerated backwards to FE, while partially neutralizing the ion beam.

In the adjacent part of TC a grid (G2) and a Faraday cup (FC) define a drift space (DS) of 50 mm length for the ions, which, by proper choice of the potentials HV_{G2} and HV_{FC} , can be accelerated or decelerated. In this way, time-of-flight measurements are possible. The ion current amplitudes are more difficult to determine, since all ions hitting an obstacle (FE, G1, G2, or FC) will sputter off electrons, which partially neutralize the ion beam but also contribute to the current signals S1, S2, and S3 measured on TG, G2, and FC. Accurate amplitudes of the total and partial ion beam currents may be measured only after field deflection and separation of the different types, masses, and charge states of the contributing ions. Detailed results of mass and charge-state analysis will be reported elsewhere.

3. RESULTS

The electron beam current emitted from FE (Fig. 1) can be measured directly with G1 or with a Faraday cup in the extraction channel TC. In addition, the electron beam current can be conveniently probed by the grounded grid G2. Figure 3 shows the part of the total beam current that flows across the $50\ \Omega$ resistor connected to G2, with the extraction channel closed at A. Most of the total current is carried by electrons. An external charging capacitor of 1 nF and two $50\ \Omega$ resistors were connected in series with the vacuum gap. The peak amplitude of the primary FE beam must exceed several hundred mA/cm², when the DVD is to be initiated. For a distance of 1 cm between G1 and G2 (and also between G2 and GE), for a total acceleration potential of 15 kV ($HV_{FE} = -5\text{ kV}$; $HV_A = +10\text{ kV}$), and by using a brass anode, the ion transition time between G1 and GE was measured approximately as 100 ns, in agreement with singly charged Cu or Zn ions. After the delay of 100 ns, ion sputtering on GE leads to a rapid charge-carrier multiplication and the DVD is initiated. The delay of the DVD is determined by the distance between A and GE, by the accelerating d.c. potential, and by the ion species. The total beam-current amplitude between GE and G2 can be deduced from the circuit impedances and from the current measured on G2. In this example, it reaches 150 A, distributed over the whole electroded surface area of GE. The waveform shape is also determined by the impedances and the charging voltages of the complete discharge circuit.

During DVD, homogeneous light emission is observed from the volume between FE and G1. Unlike in normal vacuum discharges, hot spots are not observed. The homogeneous current distribution can be attributed to the intense, large-area emission of the initial FE beam from the active surface of the PLZT disk.

The ion beam characteristics were examined only very roughly with the simple diagnostic arrangement shown in Fig. 2. The main problem of measurement lies in the separation of the ions and the counter-running electrons produced by the ions on their way. At high current intensities, the potential differences, set up to hold back electrons sputtered from one grid or cup electrode, will cause immediate attraction of electrons from the adjacent electrodes, provided these are also subject to ion sputtering. By systematically changing the grid and the FC potentials, and by taking into account sputtering yields of more than 10 of the ions involved,⁹ an order of magnitude estimate of the total ion beam current can be attempted. It is assumed that at least as many electrons as ions are liberated through the impact of a single ion. Figures 4a and 4b show the synchronized waveforms of the same current pulse measured at the beginning (G2) and the end (FC) of the 50 mm long drift space (DS). The target (TG) was charged to +12 kV d.c., the sample FE to +2.7 kV d.c. and pulsed with -3 kV for 300 ns on RE, and the grid potentials of G1, G2, and of the Faraday cup FC were set to d.c. potentials of 0, +0.5, and +3 kV (deceleration!), respectively. By applying positive or negative potential differences to DS, the electron currents to or from the chosen electrode (G2 or FC) can be amplified or decreased. The measured signals depend also on the impedances in both the main and the measuring circuit, and they are the sum of ion currents hitting the electrodes and of the electron currents sputtered off and leaving the same electrode in the opposite direction. Total ion beam-current amplitudes of several milliamperes can be deduced for the case shown in Figs. 4. The partial currents of a distinct ion species of defined charge state cannot be determined with this method. The time taken by the ions of the first peak to cross DS (in about 100 ns) indicates that a significant number of multiply charged ions were emitted from the CuZn target (TG). The total current (and hence the ion current) measured on G2 is reduced in DS by almost two orders of magnitude owing to the decelerating field of +3 kV. A large tail of slow ions arrives at FC after the second current maximum, which can be attributed to ions from TG at a late stage of the discharge.

4. DISCUSSION AND OUTLOOK

The initiation of a DVD, and thus the generation of strong electron and ion beams, is an example of application of the ferroelectric electron emission method. The superdense electron emission produced in a DVD by means of controlled generation of surface plasmas through electron and ion sputtering is characterized by a diffuse, homogeneous current density inside an originally empty gap. The short-circuit, into which the vacuum gap is transformed during DVD, allows full conversion of the electric circuit current into beam current, the major part of which consists of electrons. A proper choice of the geometry of the FE sample and the vacuum gap, and of circuit parameters such as storage capacity, inductances, resistances, and driving voltages, will enable the geometrical shape, the current, the current density, and the pulse duration of the DVD beam to be adjusted over a wide range.

The initialization of the DVD can be achieved with a large-area, intense electron beam emitted from the surface of a FE disk with a grid electrode. The delay before DVD occurs depends on the time of flight of the sputtered ions through the vacuum gap. For switching applications in the 10 kV range, delay times of less than 20 ns can be obtained with light ions in a gap of a few millimeters. The DVD can be considered as a switch, with a minimum of matter between the gap electrodes. The extraction of the electrons and their guidance into an adjacent transport channel can be done through single or multiple holes of arbitrary shape, either again into vacuum or into a low-pressure gas. The highest extraction efficiency and the lowest beam emittance could be realized in a plasma-loaded transport channel.

The ion beam intensities, which can be extracted through the cathode hole of a DVD gap, compare favourably with conventional ion sources, especially in the case of heavy ions. Since a minimum of matter is involved in the ion production process, multiply charged ions could be produced with much higher intensity than in conventional sources. Recombination and charge-exchange processes are also minimized owing to the high speed of the counter-running charge carriers. Outside the main vacuum gap, partial ion space-charge neutralization can be achieved by generating electrons from grids of high transparency inserted throughout the transport channel.

The dense electron beams of a DVD may be applied in many cases where high-current electron beams are needed, e.g. in accelerators, free-electron lasers, X-ray and microwave sources, in high-power switches, pre-ionizers, and laser systems, and in electron-beam machining applications. Ion beams from DVD may be injected into heavy-ion accelerators and heavy-ion fusion drivers, or they may be used for the purpose of ion implantation into semiconductor material.

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FIGURE CAPTIONS

1. Schema of the experimental set-up for an electron beam source:

FE = PLZT-2/95/5; GE = grid electrode; RE = rear electrode; G1 = grid; A = anode; C = cathode; G2 = intermediate grid; T = transformer; I = insulator; VA = vacuum; TC = transport channel; EB = electron beam; $HV_{FE,A}$ = d.c. potentials.

2. Schema of experimental set-up for the ion beam source:

FE = PLZT-2/95/5; GE = grid electrode; RE = rear electrode; G1 = grid 1; G2 = grid 2; FC = Faraday cup; GR = graphite; TG = target; A = anode; C = cathode; DS = drift space; $HV_{TG,FE,G1,G2,TG}$ = d.c. potentials; T = transformer; I = insulator; VA = vacuum; TC = transport channel; IB = ion beam; S1, S2, S3 = signals.

3. Waveform of differential electron currents (current GE/G2 minus G2/A) measured on grid G2 for an externally stored charge of 4 μC , a total accelerating field of 15 kV/cm, and an HV pulse excitation (30 kV/cm during 200 ns) of the 1mm thick PLZT-2/95/5 sample: First peak = FE beam; second peak = DVD beam.

2 A per small division (attenuator 1:100); 100 ns per small division.

4. Waveforms of ion beam current from a DVD emitted through a cathode hole of 10 mm² cross-section measured on G2 (a) and FC (b). Charging potentials: $HV_{FC} = +3$ kV; $HV_{G2} = 0.5$ kV; $HV_{G1} = 0$; $HV_{FE} = +2.7$ kV; $HV_{TG} = +12$ kV; $HV_{PULSE} = -3$ kV. 50 Ω -Impedances in all measuring circuits S1, S2, and S3.

200 ns per small division; G2: 1 A per small division (attenuator 1:10); FC: 10 mA per small division.

FIG. 1

FIG. 2

FIG. 3

FIG. 4a

FIG. 4b

REFERENCES

1. H. Gundel, H. Riege, E.J.N. Wilson, J. Handerek and K. Zioutas, *Fast Polarization Changes in Ferroelectrics and their Applications in Accelerators*, Nucl. Instrum. Methods **A280**, 1 (1989).
2. H. Gundel, J. Handerek, H. Riege, E.J.N. Wilson and K. Zioutas, *Fast Polarization Changes in PZT Ceramics by High-Voltage Pulses*, Ferroelectrics **94**, 337 (1989).
3. H. Gundel, H. Riege, J. Handerek, and K. Zioutas, *A Low-Pressure Hollow Cathode Switch Triggered by a Pulsed Electron Beam Emitted from Ferroelectrics*, Appl. Phys. Lett. **54**(21), 2071 (1989).
4. H. Gundel, H. Riege, E.J.N. Wilson, J. Handerek, and K. Zioutas, *Copious Electron Emission from PLZT Ceramics with a High Zirconium Concentration*, Ferroelectrics **100**, pp. 000 – 000 (1989).
5. H. Gundel, J. Handerek, H. Riege, E.J.N. Wilson and K. Zioutas, *Pulsed Electron Emission from PLZT Ceramics*, preprint CERN PS/89 – 47 (AR) 1989, paper presented at the 7th Int. Meeting on Ferroelectricity, Saarbrücken 1989, to be published in Ferroelectrics.
6. K. Geissler, H. Gundel, J. Handerek, and H. Riege, *Intense Laser-Induced Electron Emission from Prepoled PLZT Ceramics*, preprint CERN PS/89 – 54 (AR) 1989, submitted to Applied Physics Letters.
7. W. Hartmann and M. A. Gundersen, *Origin of Anomalous Emission in Superdense Glow Discharge*, Phys. Rev. Letters, **60** (23), 2371, (1988).
8. H. Riege, *New Ways of Electron Emission for Power Switching and Electron Beam Generation*, preprint CERN PS/89 – 42 (AR) 1989, to be published by Plenum Press.
9. H. H. Andersen and H. L. Bay, *Sputtering Yield Measurements*, in *Sputtering by Particle Bombardement*, ed. R. Behrisch (Springer Verlag Heidelberg 1981), p. 145.