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Ferroelectric cathodes in transverse magnetic fields

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Experimental investigations of a planar ferroelectric cathode in a transverse magnetic field up to 3 kG are presented. It is shown that the transverse magnetic field differently affects the operation of ferroelectric plasma cathodes in ‘‘bright’’ and ‘‘dark’’ emission modes in vacuum. In the bright mode, when the surface plasma is formed, the application of the transverse magnetic field leads to an increase of the surface plasma density. In the dark mode, the magnetic field impedes the electron emission. This result indicates the similarity of the dark emission mode to the surface preflashover, where the transverse magnetic field inhibits the development of secondary electron avalanches along the surface. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1556568]

INTRODUCTION

During the last decade, the phenomenon of strong ferroelectric emission has been studied widely. It has been shown that the application of a driving pulse of a few kilovolts, between solid rear electrodes and patterned front electrodes, which cover ferroelectric ceramics, results in electron emission from the side of the front electrode.[1] The current density of this electron emission varies from tens of milliamperes to hundreds of amperes per cm^2, depending on various experimental conditions: the polarity, the amplitude, and the shape of the driving pulse; the pattern geometry and the composition of the front electrode; the thickness and the composition of the ferroelectric ceramics; and the amplitude, the duration, and the time delay of application of the extracting voltage.[2] Ferroelectric cathodes are able to produce uniform electron beams with low beam divergence, without delay of the beam appearance with respect to the accelerating voltage application, and without significant vacuum deterioration.[3] These features make ferroelectric cathodes very promising for powerful microwave devices like gyrotrons,[4–6] magnetrons,[7] and traveling-wave tubes,[8] which are all operated at accelerating fields less than 50 kV/cm.

Most of microwave applications also require operation of the cathode in magnetic fields. In gyrotrons, Advani *et al.*[6] and Einat *et al.*[4,5] placed ferroelectric cathodes in a magnetic field of 400–1500 G directed transversely to the cathode surface. Shur *et al.*[9] used pulsing transverse magnetic fields up to 3 kG in their study of the formation of intense electron beams with low energy spread. A transverse magnetic field of about 250 G was applied at the location of the ferroelectric cathode in an electron gun for TWT amplifiers, which was studied by Ivers *et al.*[8] Krasik *et al.*[7] reported about a 25% increase of the output power of a relativistic magnetron with a tubular ferroelectric cathode operated in a longitudinal magnetic field of 2.4 kG.

Ferroelectric cathodes might also be good candidates for a cathode neutralizer for ion or Hall thrusters due to their ability to supply electron current with densities up to several A/cm^2, with long lifetime and without gas feeding. Alternatively, the ferroelectric cathode might supply charge along the channel of segmented electrode Hall thruster, thereby controlling the voltage drop, much in the same way as do surface electrodes.[10–12] All thruster applications require the operation of ferroelectric cathodes in transverse magnetic fields.

In recent publications,[13–16] ‘‘dark’’ and ‘‘bright’’ modes were distinguished from the electron emission observed from ferroelectrics. The dark emission appears at driving electric field amplitudes less than 10 kV/cm, usually without visible light emission from the ceramic surface.[14–16] The current pulse in dark mode has a duration less than 0.5 μs at a current density amplitude $\leqslant 1$ A/cm^2. The bright mode, which is accompanied by intense light emission,[17] requires driving electric field higher than 10 kV/cm. The current density in this mode can reaches hundreds of A/cm^2, and the current pulse may last tens of microseconds.[18] Recent investigations showed that, in the bright mode, strong electron emission occurs from the surface discharge plasma formed on the ceramic surface near the edges of the front electrode pattern.[19] This plasma has a density of $\sim 10^{12}$ cm^{-3}, an electron temperature of 2–3 eV, and consists mostly of the materials of ferroelectric ceramics and the front electrode.[20] The nature of the dark emission, however, is still unclear. Angadi *et al.*[16] and Shannon *et al.*[14] explain the electron emission in this mode by polarization switching, while Boscolo and Cialdi[15] consider the field emission mechanism from triple junctions at the edges of the patterned front electrode, which is not strong enough for the ignition of the surface discharge.

In all previous works, where ferroelectric cathodes operated in magnetic fields, the driving pulse amplitude was sufficient for the generation of electron beams with current densities about of several A/cm^2 or higher. This implies the bright mode of the electron emission. The dark mode of the electron emission in magnetic fields apparently has not been studied yet. Also, in the bright emission mode, the scaling of the emission parameters with the magnetic field remains to be clarified. The scope of the present work is to study how the emission properties in both bright and dark modes depend on the transverse magnetic field.

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EXPERIMENTAL SETUP

The ferroelectric samples used in these experiments were lead zirconate titanate (PZT) ceramics type APC-850 ($\varepsilon = 1750$) supplied by American Piezo Ceramics, Inc. The disk samples with a diameter of 38 mm and a thickness of 2 mm were covered by solid rear and striped front electrodes made of copper, which were affixed to the samples with a conducting glue. The strips of the front electrode have a width of 2 mm with opening of 2 mm between them. The total active area had a diameter of 20 mm. The front electrode was grounded, while a negative driving pulse was applied to the rear electrode. The rectangular driving pulse had a duration of 500 ns and was supplied by a Blumlein pulse generator. The amplitude of the driving pulse can vary from 0.5 to 25 kV with a repetition rate up to 1 kHz. The driving voltage and driving current were measured by Tektronix high voltage probe and Pearson Rogovski Coil, respectively.

The ferroelectric cathode was mounted on an iron core of a solenoidal magnetic coil. The diameter of the core was 50 mm. The magnetic field at the front surface of the sample can reach up to 6 kG. The nonuniformity of the magnetic field along the active area was less than ±2.5% according to measurements by FD Bell gaussmeter. A grounded output grid with a transparency of 87% was placed at a distance of 4.4 mm from the front surface. The full setup was placed in a vacuum chamber pumped down to $\sim 3 \times 10^{-6}$ Torr.

Visible light emission from the surface was observed by Andor I-Star ICCD camera. The image intensifier of this camera had an increased sensitivity in near-UV range, while the image sensor chip was cooled down to $-16\,°\mathrm{C}$, which allowed registration of images with ultralow intensities. Electrons emitted from the cathode in dark mode were collected by a biased collector. The collector had a diameter of 27 mm and was placed at 8 mm from the sample surface in order to collect all electrons in the fringing magnetic field.

In the bright emission mode, no extracting electric field was applied. The ion saturation current of the surface discharge plasma, which is formed in the bright emission mode, was measured by a cylindrical Langmuir probe placed at 5.6 mm from the output grid (10 mm from the front surface of the sample) in parallel to the sample surface. Spectroscopic measurements of the plasma parameters in the bright emission mode[20] showed that the plasma has a density of $\sim 2 \times 10^{12}$ cm^{-3} with the electron temperature of about 3 eV and the ion temperature of $\leqslant 0.5$ eV. The Debye length for plasma with such parameters is $\lambda_D \sim 8 \times 10^{-4}$ cm. The electron gyroradius in the magnetic field of several kilogauss is $r_{ce} \sim 1.4 \times 10^{-3}$ cm and the ion gyroradius (for proton plasmas) is $r_{ci} \sim 1$ cm. Thus, $r_{ce} > \lambda_D$ and $r_{ci} \gg \lambda_D$. At the background pressure of $\sim 10^{-6}$ Torr and the probe radius of 0.25 cm, the probe can be considered in the mode of collisionless thin sheath, and the magnetic field can be accepted approximately constant across the sheath.[21] In this case, the electron collection by the probe will be described by the diffusion motion across the magnetic field. However, the ion collection by negatively biased probe in saturation will be determined by the Bohm condition, and the effect of the magnetic field will be negligibly small.

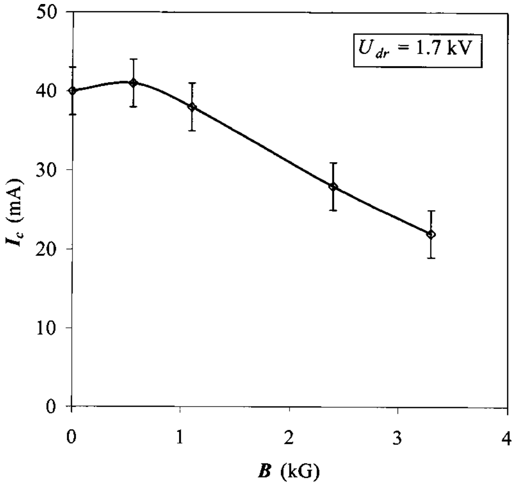

FIG. 1. The electron current I_c measured by the biased collector vs applied magnetic field B. The bias voltage is +50 V.

EXPERIMENTAL RESULTS

The dark emission mode was realized at a driving pulse amplitude of 1.7 kV, which corresponds to a driving electric field of 8.5 kV/cm. The duration of the driving pulse was ~500 ns. In this series of experiments, the emitted current was measured by the collector biased positively to 60 V.

The emission current appeared almost simultaneously with the application of the driving pulse, and lasted ~200–250 ns. The amplitude of the emission current was in range of 30–50 mA, so the current density averaged over the entire cathode area can be estimated as 10–16 mA/cm^2. The amplitude of the emission current did not depend on the magnetic field in the range of 0–0.7 kG. Further increase of the magnetic field leads to the decrease of the emission current, as it shown in Fig. 1. The decrease of the electron current in dark emission was observed with different patterns of the front electrode and with poled and unpoled PZT samples.

In order to check the presence of plasma formation in the dark emission mode, we applied negative bias voltage of 1 kV to the collector and looked at the current of extracted ions. We did not find any ion current either with or without magnetic field application. The lower limit of sensitivity of these measurements was 1.7×10^{-7} A/cm^2, which would correspond to a plasma density less than 10^7 cm^{-3}. Thus, in the dark emission mode, we conjecture that there is no surface plasma with density higher than 10^7 cm^{-3}.

However, the dark emission was found not to be completely dark. Under maximal image amplification we observed diffuse light emission from the ceramic surface between the front electrode strips. The emission becomes visible during the rising of the driving pulse, namely at 20–30 ns from the beginning of the pulse having a rise time of ~70 ns. It reaches the maximal intensity in about 80–100 ns and then decreases gradually up to 800–900 ns. The application of a transverse magnetic field higher than 1 kG leads to decrease of the light intensity and to a delay of the

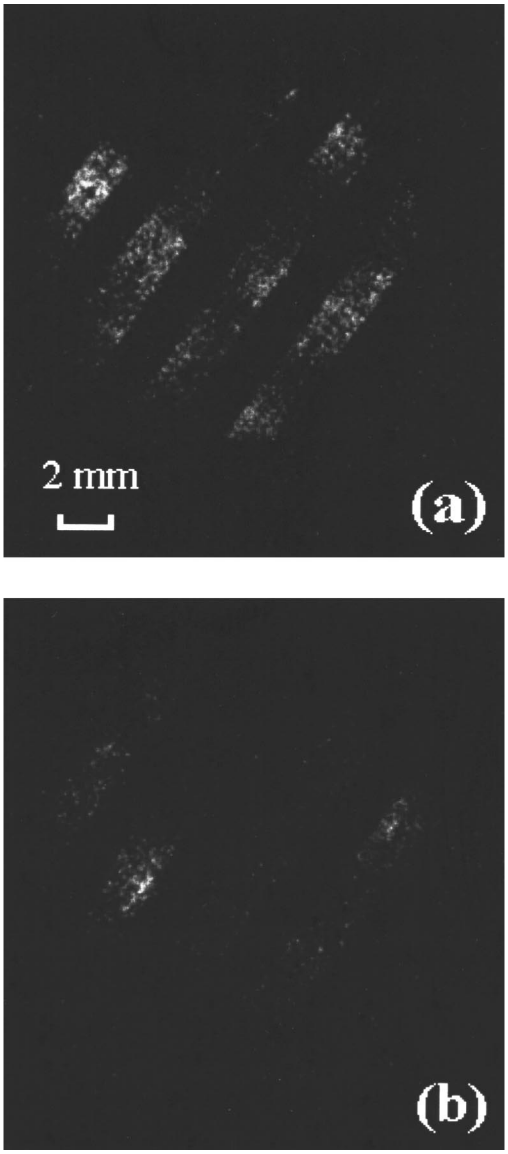

FIG. 2. Images of the surface of ferroelectric cathode in dark emission mode at $B=0$ (a) and at $B=3.3$ kG (b). The driving pulse amplitude is 1.7 kV. The frame duration is 50 ns, the delay from the beginning of the driving pulse is 50 ns.

light appearance. Images obtained at the same time delay from the beginning of the driving pulse are shown in Fig. 2 for the case of $B=0$ (a) and for $B=3.3$ kG (b).

Note that the features of images in the dark mode presented here differ from images of surface discharge observed in the bright emission mode.[17] The emission does not have the typical pattern of separate discharge "trees," but is rather diffuse and covers almost the entire ceramic surface between the strips. Only the region in the middle between the strips, at the null of the tangential electric field, remains dark.

In the bright emission mode, the application of the magnetic field leads to an increase of the plasma density of the surface discharge. In Fig. 3, the ion saturation current density measured by the probe is shown versus the magnetic field. For the driving pulse amplitude of $U_{\mathrm{dr}}=8.5$ kV, one can see that at $B\sim5$ kG the measured current density is almost twice the current without magnetic field. The higher the driving

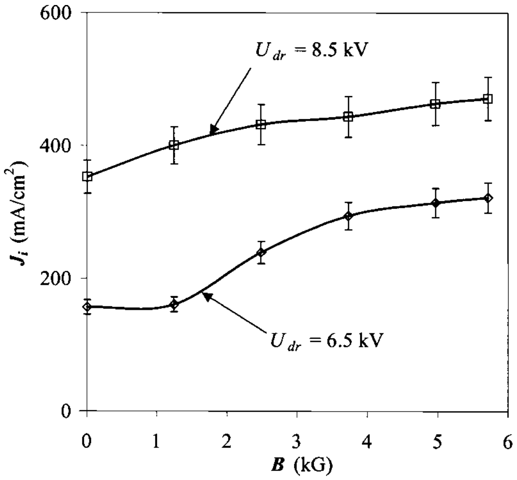

FIG. 3. The ion saturation current density J_i vs the applied magnetic field B, for different driving pulse amplitudes U_{dr}.

pulse amplitude, the lower the threshold at which the magnetic field causes the increase of the ion saturation current and the intensity of the visible light emission from the surface plasma.

The obtained images of the surface discharge plasma in the bright emission mode in presence of the transverse magnetic field were not visibly different from the images observed in Ref. 17 without magnetic fields.

DISCUSSION

The observed diffusive light emission from the surface is similar to light emission in preflashover mode of the surface breakdown.[22,23] In pulse surface breakdown it appears as a first stage of the breakdown, when the discharge current is still low. It usually lasts from a few nanoseconds to several tens of nanoseconds and follows by the exponential growth of the discharge current and formation of the bright tree-like discharge channel.[24,25] Diffusive light emission from the surface was also observed at slow gradual increase of the applied voltage with the rate of several kilovolts per minute.[26]

The observed diffusive light emission from the surface, as well as the inhibition of the emission in the magnetic field, indicate similarity of the dark emission mode to the preflashover mode of the surface breakdown. It appears here that the electron current in the dark mode should not be assumed to be purely field emission current from triple junctions, as it was assumed in Ref. 15. Indeed, the field emission current does not depend on the magnetic field, while here a decrease of the current was observed with the increase of the magnetic field (see Fig. 1). Thus, in addition to the field emission current, there should exist another phenomenon, which can be affected by magnetic fields.

Based on our experimental results, we suppose that field emission from triple points at the edges of the front electrode, similarly to the bright emission mode, will lead to the formation of electron avalanches along the surface. There is still a tangential component of the driving electric field, which can accelerate emitted electrons along the surface and form secondary electron emission avalanches. However, in the dark emission mode, the tangential electric field is lower than the threshold of the formation of saturated avalanches, which is accompanied by plasma formation. At the low electric fields along the surface, avalanches should be unsaturated and weak, and therefore should produce dilute plasma or do not produce plasma at all. Low electron current density and the absence of the ion current indicate the absence of plasma formation with significant density. Indeed, plasma with small density will erode rapidly in the electric field of the negative polarization charge. This charge appears due to polarization of the ferroelectric sample by the negative driving voltage applied to the rear electrode.

It is known that surface discharge is initiated by electrons emitted from triple junction due to field or thermal-field emission mechanisms.[27] The final stage of the discharge is the plasma formation due to ionization of neutrals, desorbed from the dielectric surface, by the avalanching electrons. The explosive plasma can be formed at the triple junctions as well.[28] However, the intermediate process of the development of the electron avalanche is still unclear. Magnetic fields can change the frequency of electron collisions with the dielectric surface in surface flashover.[29–31] According to the model of electron avalanches suggested by Pillai and Hackam,[32] the critical angle θ between the surface and the vector of the electric field is determined by the secondary emission properties of the dielectric material

$$tg(\theta)=\frac{E_\perp}{E_\parallel}=\sqrt{\frac{2\omega_0}{\omega_1-\omega_0}},$$

where ω_0 is the mean energy of emitted secondary electrons, ω_1 is the energy of incident electrons correspondent to the unit yield of the secondary electron emission, and $E_\parallel$ is the electric field applied along the surface. The mean free path between two collisions with the surface can be estimated as[28]

$$\lambda_s \sim \frac{4\omega_0 E_\parallel}{eE_\perp^2}.$$

The mean free path λ_s becomes longer than the electron gyroradius $r_{ce}=\nu_e m_e c/eB$ in the magnetic field of $B \geqslant 1.5$ kG at driving voltages of $\sim$1.5 kV, which coincides with the beginning of the observed decrease in the emitted current (see Fig. 1). However, this estimation is very rough. Indeed, the transversal component of the electric field, $E_\perp$, in the model of Pillai and Hackam is determined only by the surface charge induced by electron avalanche. In the case of ferroelectric cathodes, the applied driving electric field leads to the appearance of additional, polarization surface charges, which have to be taken into account in $E_\perp$.

Therefore, the model of the dark ferroelectric emission suggested in Ref. 15 should be supplemented with the existence of secondary electron emission avalanches. The observed inhibition of dark electron emission in magnetic field happens at the intermediate stage of the formation of secondary electron avalanches, similarly to the preflashover mode of the surface breakdown.

The dependence on the magnetic field in the bright emission mode might be explained by the magnetization of electrons, which would cause an increase in the residence time of electrons in the layer of desorbed neutrals near the ceramic surface. While the frequency of ionizing electron-neutral collisions does not depend on magnetic fields, the longer residence time of electrons in the layer of desorbed neutrals near the surface would then result in the increase of the total amount of collisions, similarly to most types of gas discharges in magnetic fields. The tangential component of the driving electric field in the bright emission mode is high; hence, the mean free path between two collisions of avalanching electrons with the surface is not significantly changed by applied magnetic field. Any further increase of the magnetic field will probably inhibit the emission in the bright mode as well, as has been observed for the dark emission mode and other types of surface discharges in magnetic fields.[25–27]

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