Influence of field emission on microwave microdischarges

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Abstract: An instability in the stable operation of microdischarges sustained at microwave frequencies, is investigated by a self-consistent one-dimensional particle-in-cell Monte Carlo collisions model. The instability is caused by the field emission from electrodes and is triggered by the high electric fields at the sheaths in a dense microplasma. For an operating frequency of 9 GHz, and electrode gap of 60 µm, the field emission (FE) is not active at the breakdown voltage. However, once a stable dense plasma is produced post-breakdown, a strong sheath results in an electrode electric fields that exceed the threshold for FE causing a runaway in the electron generation in the plasma.

1 Introduction

Periodic array structures with embedded microplasma discharges are being studied as reconﬁgurable metamaterials that can manipulate electromagnetic waves in the microwave and terahertz regime (see [1, 2] and references therein). The discharges can themselves be generated with independent stripline excitation at microwave frequencies regime to generate plasma with the density \( \sim 10^{13} \)–\( 10^{14} \) cm\(^{-3}\). At these densities, the plasma frequencies are comparable or even greater than the incident wave frequencies that need to be manipulated [1].

During the last decade, the microdischarges for a wide range of interelectrode gaps were extensively studied both experimentally and theoretically (see, for instance, [1–8] and references therein). It was found that for gaps <10 µm the dominant electron emission mechanism is the field emission (FE), while for larger gaps it is the secondary electron emission (SEE) due to the ion bombardment. It is predicted that for large gaps FE does not play any role.

The use of high frequency (>1 GHz) excitation of the microdischarge has several advantages including the power efficient generation of high plasma densities and increased device lifetime. The high plasma densities are owing to better charged species conﬁnement resulting from a lower plasma potential and the consequent low ion impact energies at the electrode surfaces which improves lifetime through low/negligible sputter damage. The high plasma densities can also result in strong sheaths adjacent to the electrodes where the electric ﬁelds can be much higher than the vacuum electric ﬁelds.

Microplasma can be subjected to a variety of instability mechanisms. For example, microwave (1 GHz) sustained microplasmas with interelectrode gap sizes of ∼100 µm are subject to the ionisation overheating instability (IOI) [7, 8]. In brief, IOI results from electron collisional heating of the gas, which leads to a decrease in the background density and an increase in the reduced electric field \( (E/N) \) [9]. The consequent electron temperature increase causes a further increase in the electron density, heating of the gas and so on leading to a runaway situation. The gas heating also causes an increase in the electrode surface temperature that adds to the electron density increase through increased thermionic electron emission from the electrodes. The overall consequence is the transformation of microdischarge operation from glow to arc mode.

In nitrogen gas discharges, fast gas heating occurs due to the energy relaxation of electronically excited state of N\(_2\) [10]. For \( E/N_2 \sim 150 \) Td, rate coefﬁcient of N\(_2\)(A\(_3^+\)) excitation is \( k_1 \sim 10^{-10} \) cm\(^3\)/s [10]. In N\(_2\), the collision between two excited states A\(_3^+\) and N\(_2\)(A\(_3^+)\) releases 2 eV of energy, which heats the gas [10]. Rate coefﬁcient of the quenching reaction is \( k_2 \sim 10^{-10} \) cm\(^3\)/s [10]. Assuming the gas heating becomes signiﬁcant only above a certain threshold value of N\(_2\)(A\(_3^+)\), where the threshold is determined by balance of the electron-impact generation and collisional quenching destruction we can estimate a time scale for the IOI as \( \tau = 1/\sqrt{k_1k_2n_2N_2} \), where \( n_2 \) is the plasma density. For \( n_2 \sim 10^{14} \) cm\(^{-3}\) one has \( \tau \sim 0.2 \) µs.

In this paper, we use a self-consistent one-dimensional (1D) particle-in-cell Monte Carlo collisions model to report another possible instability of microdischarge driven at microwave frequencies. This instability is caused by FE and develops on the time scales comparable with or shorter than the time scale of IOI.

2 Results and discussion

The numerical model, which is used in the present study, was detailed in our previous paper [11]. In brief, this model includes the solution of the Poisson’s equation, the propagation of electrons and ions into new positions in the self-consistently deﬁned electric ﬁeld, FE and SEE due to ion bombardment from both electrodes \( (\gamma = 0.2) \), and electron–neutral collisions described by the Monte Carlo method. The boundary conditions for the Poisson’s equation are the grounded right electrode and potential of the left electrode \( \phi \) = \( U_t \). The breakdown voltage, \( U_t \), is the applied voltage frequency. The ﬁeld enhancement factor for FE is \( \beta = 70 \) [12]. It takes into account the presence of microprotrusions at the surface of metal electrodes.

It is important to note that the external circuit was not included in the model and instead a constant voltage excitation is imposed on the microdischarge electrodes. Note that a constant voltage excitation on the microdischarge is readily realised when the excitation source is connected to the microdischarge electrodes in parallel with a low impedance load. This abstraction for the microdischarge excitation is necessary to emphasise the essential physics associated with the FE instability mechanism reported here.

In our previous paper [11] we studied the breakdown of atmospheric pressure microplasmas at excitation frequency of 1 GHz. It was found that for the interelectrode gap of 60 µm SEE due to the ion bombardment plays an important role. Also, at these conditions, FE does not play any role because the vacuum electric...
field at the electrode surface is insufficient to cause FE. The steady-state value of plasma density at the breakdown threshold was predicted at \( \sim 1 \times 10^{12} \) cm\(^{-3} \), which is insignificant to screen external electric field, produce plasma sheaths and, as a consequence, enhance electric field at the electrode surface [13].

Also, our simulation results have shown that the increase in the frequency \( v \) of applied voltage results in the increase in the plasma density. As a consequence, starting from \( v = 3 \) GHz one obtains the plasma sheaths in the vicinity of electrodes. This results in the enhanced electric field at the surface of electrodes in comparison with the vacuum electric field.

Intense FE from the electrodes is obtained for a threshold electric field strength \( E_{FE} = 2 \times 10^7 \) V/cm [9]. In the presence of roughness (microprotrusions) at the electrode surface, the electric field is locally enhanced and thus the threshold external electric field is lower (\( E_{FE} \approx 2.9 \times 10^5 \) V/cm for a roughness enhancement factor \( \beta = 70 \)). We present modelling results for atmospheric pressure microdischarges sustained microwaves frequency of 9 GHz with an interelectrode gap of 60 µm. Our results have shown that for this frequency electric field at the electrodes exceeds \( E_{FE} \) due to the presence of plasma in the interelectrode gap. The breakdown voltage for this frequency is 150 V for which the pre-breakdown peak vacuum electric fields that are well below the FE threshold.

Fig. 1 shows electron and ion densities and electric potential in the interelectrode gap during the discharge ignition at time of peak negative voltage. The peak plasma density is \( \sim 6 \times 10^{15} \) cm\(^{-3} \) in the discharge centre (Fig. 2b), which is enough to screen the external electric field (Fig. 1b). The sheath thickness near the left electrode is \( \sim 10 \) µm, while potential difference between biased electrode and plasma is \( \sim 110 \) V. Thus, electric field at the electrode is \( \sim 1.2 \times 10^5 \) V/cm. This electric field is enough to initiate FE current.

The simulation results show that the discharge breakdown is facilitated by SEE only, but once the dense plasma is formed, electric field at the electrodes becomes comparable with \( E_{FE} \). At the time of FE initiation, FE current is much smaller in comparison with the SEE current. However, FE electrons contribute significantly in the plasma generation. The mean free path of FE electrons is estimated as \( \lambda = \frac{1}{N_e} \sigma \sim 4 \) µm, i.e. it is comparable with the sheath thickness (Fig. 2). Thus, FE electrons gain sufficient energy in the plasma sheath to ionise N\(_2\). The ionisation of the background gas by FE electrons increases plasma density leading to further decrease of sheath thickness. The latter increases electric field at the electrode and, as a consequence, further increases FE current resulting in a runaway situation.

Fig. 2 shows space-time diagrams of electron and ion densities and electric field after sufficiently large FE currents are attained. The sheath thickness is already \( \sim 1 \) µm, i.e. FE electrons propagate through the sheath without collisions and gain energy \( \sim 100 \) eV. In N\(_2\) gas, electrons with the energy of 100 eV have the largest value of ionisation cross-section. Electrons, which are accelerated in the sheath, enter the plasma and ionise gas in the vicinity of electrodes. Ions do not respond to oscillations of external electric field because electric field in plasma is shielded and small (see Figs. 1b and 2c). Ions are therefore accumulated in the vicinity of electrodes (Fig. 2b). One can see from Figs. 2a and 2b that the plasma density in the vicinity of electrodes reaches the value \( \sim 10^{15} \) cm\(^{-3} \) with electric field at the electrodes \( > 3 \times 10^7 \) V/cm leading to intense FE.
One can see the sharp increase in the plasma density at comparison between plasma densities obtained in these two cases.

Fig. 3 accounting for the FE

Plasma density in the centre of the interelectrode gap obtained with and without b FE and secondary emission current

Fig. 3 Time evolution of a FE and secondary emission current b Plasma density in the centre of the interelectrode gap obtained with and without accounting for the FE

Note also that FE can heat microprotrusions at the surface of electrodes [14] and cause the transition from FE to explosive electron emission [14]. The latter leads to erosion of electrodes.

To demonstrate that the instability is caused by FE, we carried out the simulation in which FE is excluded. Fig. 3b shows the comparison between plasma densities obtained in these two cases. One can see the sharp increase in the plasma density at \( t > 0.17 \mu s \), when FE is taken into account, and stable (steady) plasma density in the case, when FE is excluded. This proves that the obtained instability is indeed caused by FE.

3 Conclusion

In conclusion, an instability of atmospheric pressure microdischarge sustained at microwave excitation frequency of 9 GHz is reported by 1D particle-in-cell Monte Carlo collisions modelling. This instability is induced by FE, which becomes possible for large density of plasma in the interelectrode space. The instability reported here is purely related to enhanced current generation in the microdischarge and is therefore readily mitigated through a careful design of the components/circuit elements that are external to the microdischarge itself but contribute to the overall impedance of the system. For example, in a simple microdischarge circuit one can imagine introducing a ballast resistance in series with the microdischarge such that the amplitude of external voltage imposed on the microdischarge electrodes is decreased when large currents owing to the FE instability is initiated.

4 Acknowledgments

This work was supported by the Air Force Office of Scientific Research (AFOSR) through a Multi-University Research Initiative (MURI) grant titled ‘Plasma-Based Reconfigurable Photonic Crystals and Metamaterials’ with Dr. Mitat Birkan as the program manager.

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