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A mechanism of PFM erosion and redeposition in gaps

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Abstract

Uni-polar auto-oscillating secondary emission discharges (UASED) can arise between two surfaces with different electron emission connected by a magnetic field. High secondary e–e coefficient and primary electrons of high energy are necessary for development of UASED. High voltage oscillations lead to enhanced erosion of the contacting surfaces and deposition of C:H films stimulated by RF plasma–surface interaction. The RF discharge broadens, transverse transport increases, so the surfaces far from the main plasma also participate in plasma–surface interaction. UASED induces high electric fields in shadowed and remote gaps. These fields stimulate a-C:H films growth due to activation of polymerization on the surface of volatile hydrocarbons penetrating the gaps.

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Keywords: Erosion and deposition; Hydrocarbons; Ion–surface interactions; RF

1. Introduction

Plasma–surface interaction is a key issue in the design of the International Thermonuclear Reactor (ITER). One of the problems to be solved is the reduction of erosion of the plasma facing material and redeposition of the eroded material on the surfaces of the tokamak construction. The redeposited layers often contain large concentrations of fuel gas, and this can be a problem for tritium fueled ITER [1]. It has been observed in many tokamaks that redeposited a-C:H layers are formed not only on the plasma facing surfaces, but also in the shadow regions.

Investigations show a very complicated erosion–deposition pattern formed by release of volatile hydrocarbons from PFM and their deposition on remote and cold surfaces with formation of polymer layers. During transport of hydrocarbons to the place of rest in shadow regions, hydrocarbons undergo multiple erosion–deposition cycles [2]. Though the formation of polymer layers on walls and electrodes of gas discharge devices was observed many years ago, the underlying mechanisms in the case of the tokamak periphery are not well established.

This work presents a new mechanism of the redeposited film formation in the shadow regions. It is based on the possibility of development of UASED in tokamak periphery accompanied by parasitic RF discharges in the regions far separated from the main plasma column.

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2. Experimental

Experimental investigations of RF discharges between two electrically shorted electrodes were performed in the linear magnetic trap PR-2 [3,4] operating in the beam plasma discharge (BPD) regime. An electron gun with a hot cathode is installed on one of the ends of the trap. A flat externally cooled collector electrode is installed on the opposite end of the installation. Other electrodes could be installed in various parts of the installation. For example, a two electrode system shown in Fig. 1 was investigated.

Plasma beam discharge was obtained in the working gas (H_2) in the range of 5×10^{-3}–1 Pa. Accelerating voltage of the electron gun and the electron beam current could be varied in the range of 0–2 kV and 0–1 A, respectively.

It was observed in certain conditions that oscillations of the potential and current appear on the electrode accompanied by light radiation from the near electrode area dependent on parameters of the main plasma.

2.1. Auto-generating RF discharges in PBD

In experiments with one collector electrode, the electrode was kept under a negative bias with the use of external DC power supply. The parameters of the BPD always fluctuate, so the potential of the floating electrode is always subjected to fluctuations of the order of 10 V. The average floating potential in our experiments can vary from 20 V for the electrode with high e–e emission (oxidized Al) to 200 V for the electrode with relatively low e–e emission (graphite). Changing the negative bias of the collector plate with enhanced electron secondary emission, we observed stepwise transitions from regimes of stabilization of the natural fluctuations of the electric potential to the regimes of their increase, and then to generation of high voltage and high frequency auto-oscillations. The amplitude of the auto-oscillating potential can be tens and even hundreds times higher than the average floating potential.

One of the factors that can provoke the auto-oscillations is development of instabilities in the Debye layer (DL) near the electrode [4]. The principal factor for appearance of this instability is a high yield of the secondary electron–electron emission. Thin dielectric films of various metal oxides have enhanced secondary emission. We used aluminum electrodes slightly oxidized by training in Ar discharge at low oxygen concentration. The principal feature of oxidation is a very low thickness of the oxide film. It should not be above 200 Å. Aluminum is convenient in model experiments for its oxide is similar to beryllium oxide in chemical and emissive properties. High electron emissivity was ensured also due to a group of high energy electrons (a few hundreds of eV) presented in BPD. High secondary electron–electron emission of the plasma–surface contact region leads to appearance of the negative differential resistivity (NDR) in the volt ampere characteristics (VAC) in a certain interval of the collector negative bias. NDR in the bias supply loading leads to development of the secondary-emission instability with auto-oscillations of the potential drop in DL. We call the discharges provoked in this way as auto-oscillating secondary emission discharges (ASED).

2.2. Uni-polar auto-generating RF discharges between two surfaces

Demonstration of oscillations and accompanying periphery RF discharges was performed in experiments with two collectors (Fig. 1). One of them was made of graphite and another – of aluminum. The Al electrode was irradiated through a hole in the graphite electrode. Two types of experiments

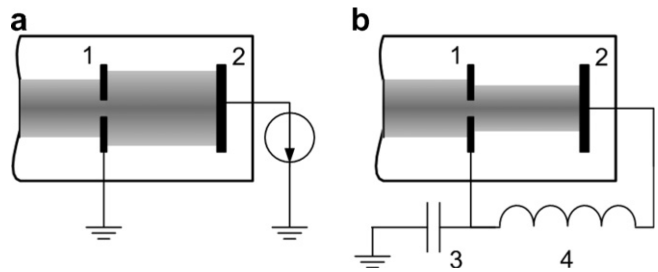

Fig. 1. Scheme of electrical connections in double electrode collector system: (a) With external bias supply, (b) floating regime. (1 and 2) Graphite and aluminum electrodes, (3 and 4) external capacitance and inductance.

were performed. In the first experiment, the graphite electrode was grounded and the aluminum electrode was under external bias potential. In the second experiment, the two electrodes were connected through an inductance, and there were no external power supplier.

In experiments with the external bias, oscillations appeared if the negative bias was in the range of the NDR (Fig. 2(a)), which is typical for ASED. The oscillations observed are of two types: so-called quasi-harmonic and relaxation. The former oscillations have the amplitude of a few hundred volts while the latter can be of a few thousand volts as described in [4]. The oscillations observed depend on the Q-factor of the effective circuit. Fig. 2 demonstrates quasi-harmonic oscillations.

Experiments with two electrically connected electrodes demonstrated that auto-oscillating instability and ASED between two electrodes can arise even in absence of external power supply (Fig. 2(b)). During bursts of auto-oscillations, the instantaneous potential of Al electrode can achieve very high negative values (hundreds and thousands of volts). These discharges without the external power supply between two surfaces, which are under the same floating potential, can be named as uni-polar auto-oscillating secondary emission discharges (UASED).

Graphite has a low secondary electron emission yield, while oxidized aluminum has a high one. In this case, the graphite becomes an acceptor of electrons from plasma, while Al becomes an emitter of secondary electrons. Therefore, a net current propagates between the electrodes through the plasma and the external circuit though the electrodes are under the same average potential relative to walls.

In conditions of excitation, we observed both stochastic and regular counter-phased oscillations of the voltage on the two electrodes as well as oscillations of the current in the external part of the circuit. One must stress again that there was no external bias applied in these experiments – the auto-oscillations were produced due to the energy of the BPD, namely of the electron component of suprathermal energies.

A typical example of the oscillating potential on the Al electrode is given in Fig. 2(b). During irradiation, the potential of the Al electrode becomes progressively negative beyond its single floating potential due to electrical connection with the graphite electrode. When its voltage reaches −200 V, high frequency (about 1 MHz) auto-oscillations start. The main harmonic frequency is determined by resonance properties of the system and can be changed by changing the external inductance between Al and C electrodes in a wide range up to 40 MHz. The oscillations take place for a short time and then stop. In the case of the external biasing, the oscillations could be very long, while without the external biasing the energy capacitance of the system is restricted and cannot support the powerful oscillations for a long time. The additional plasma generated between electrodes during the burst of oscillations in regime of UASED decays, and the process described starts again, so after a shot time necessary for obeying a proper negative potential, the oscillations burst again.

After transition to UASED regime, the discharge channel in the shadow of the main plasma became evidently wider. Fig. 3 demonstrates the radiation pattern from the BPD before (Fig. 3(a)) and after (Fig. 3(b) and (c)) transition to auto-oscillating RF discharges. For the case of the externally powered RF discharge, one can see that the discharge in the shadow region is very wide (Fig. 3(b)). For

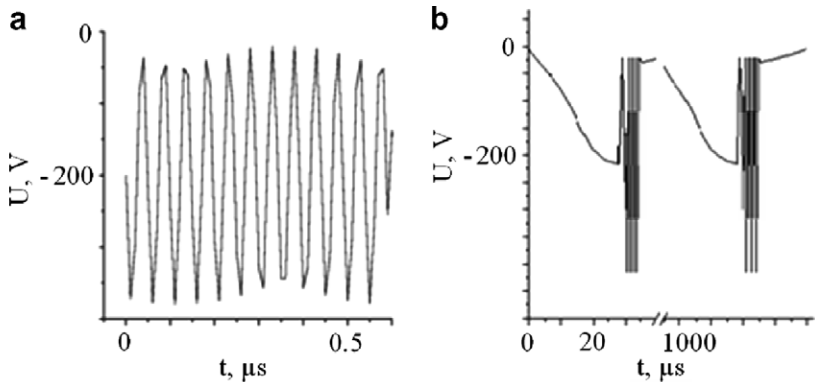

Fig. 2. Auto-oscillations of Al electrode voltage with external bias supply (a) and in floating regime (b).

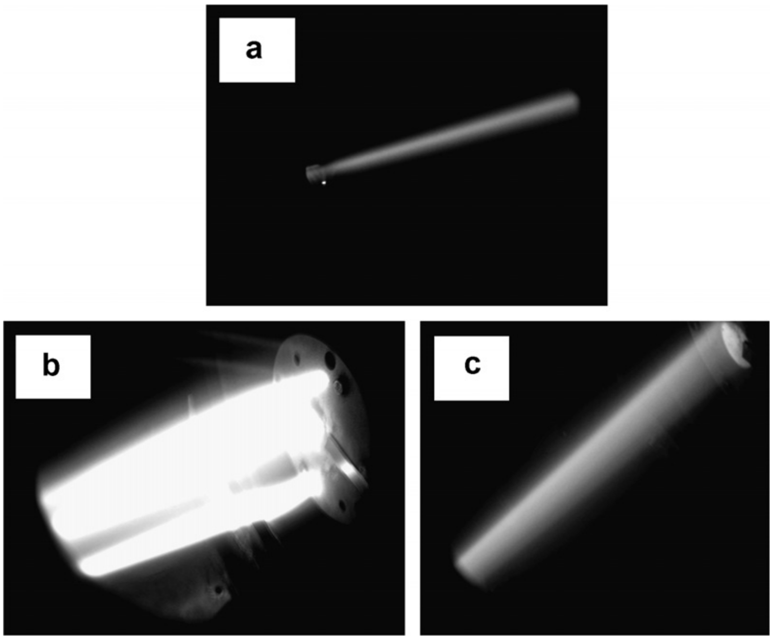

Fig. 3. Radiation from the BPD in the shadow region between two plates. The beam comes from the left through the aperture in the graphite electrode. (a) The narrow beam through the aperture before the oscillations start, (b) a wide discharge in the shadow of the carbon electrode (aluminum electrode is on the right) in conditions of ASED with external biasing, (c) a discharge in the shadow of the graphite electrode in conditions of UASED with electrically shorted electrodes under floating potential.

the case of floating electrodes, RF discharge is powered only by the capacitively stored energy and is not so wide in the shadow region (Fig. 3(c)).

The feature of the parasitic discharge is its non-uniformity. One can see that the externally powered discharge consists of several bunches. The surface of the aluminum electrode is visually non-uniform, so one can suggest that the bunches of the UASED are connected with the spots with high emissivity on the surface of the aluminum electrode.

We see oscillations in the case one electrode is attached to the wall. Observations of UASED support the suggestion that interaction of non-equilibrium plasma with the surface can lead to excitation of RF currents both in the plasma and in the surrounding walls if the electron emission properties of the contact surface are not uniform.

2.3. Side effects

High frequency discharges lead to oscillations of the potential with the amplitude up to a few kV. Therefore the surfaces are bombarded by plasma ions in a wide range of energies. Besides, the high power can be deposited on the surface leading to their heating. These effects may lead to intensive erosion of the surfaces participating in ASED.

We found in experiments that ASED is always accompanied by intensive erosion of the graphite electrode and appearance of hydrocarbons. This effect was observed by the built-in mass-spectrometer working in the intrinsic PBD magnetic field. Broadening of the discharge, such as that seen in Fig. 3, leads to increase of the transverse plasma particles transport and erosion of plasma facing components that are not touched by direct plasma flow.

2.4. Erosion and deposition in a narrow gap

To demonstrate effects in narrow gaps, a small part of the plasma facing Al collector was covered by a low emissive Mo strip 50×10 mm in size. This plate had a tight electrical contact with the Al collector being bolted at the periphery. So, a narrow gap less than 0.5 mm was formed between Mo and Al plates. After exposure to unstable auto-oscillating discharges in hydrogen, the shadowed areas of the Al and Mo plates became covered with a dark carbon film shown in Fig. 4.

The films shown in Fig. 4 can be interpreted as a-C:H films. The erosion–deposition processes in conditions of UASED can be illustrated by Fig. 5. The hot (about 700 K) graphite diaphragm interact-

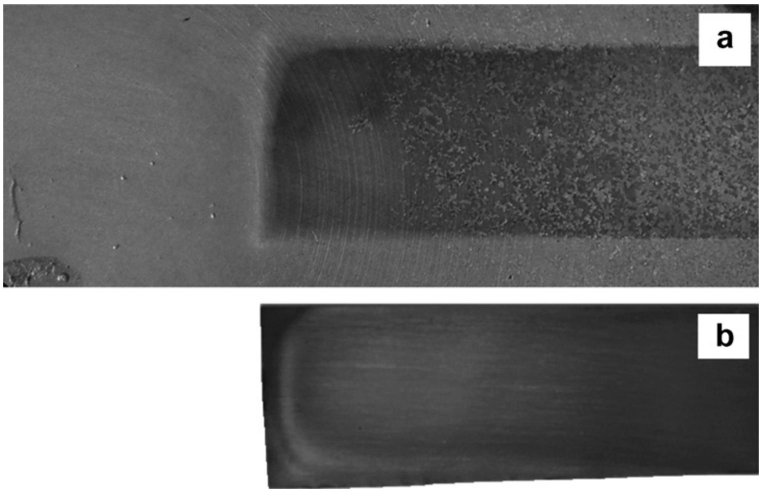

Fig. 4. The films formed on Al (a) and Mo (b) surfaces facing each other that were tightly bolted on the right end and irradiated by BPD in UASED conditions.

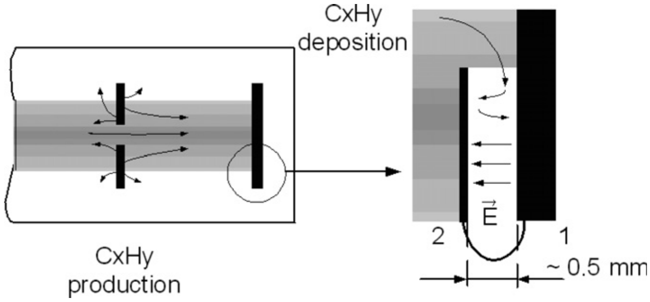

Fig. 5. The scheme of the film deposition in the narrow gap.

ing with hydrogen plasma works as the initial source of hydrocarbons with their radicals methane/methyl being the dominant [5]. Methyl is the fundamental hydrocarbon radical with very low sticking coefficient (10^{-4} for non-activated surface [6]) and can penetrate very far into remote and narrow gaps. Ionized species can be transported by plasma beam to the Al electrode. Their deposition takes place along with their erosion under hydrogen ion bombardment. The energy of ions striking the cold surface of Al electrode during development of a secondary emission instability (UASED) varies in the range of 10–1000 eV. The composition of hydrocarbons changes after their first production on graphite surface. There appear C atoms and components with unsaturated bonds (C_2H, C_2H_3), which have high sticking coefficients (close to 1). After first collisions they form depositions on the edge of the inner surface of the Mo cover plate inside the gap. On contrary, the volatile methyl can freely penetrate through the narrow gap without sorption. But during bursts of auto-oscillations, very high electric field inside the gap can stimulate polymerization of monomers due to field emission of electrons, activation of the polarization effect, and parasitic discharges.

According to our estimations, the electric field amplitude reaches 10^7 V/m. High electric fields inside the gap can activate sorption and polymerization of volatile hydrocarbons on both sides of the gap. Molybdenum is heated up to 500–600 K, and only hard a-C:H layers with low H content can survive at the edge of Mo plate. The additional factor important for polymerization of methyl radicals can be connected with an oxide film on the Al plate. It can effectively catalyze polymerization and bond the excessive hydrogen in aluminum hydroxides.

3. Extrapolation to tokamaks

Two main factors necessary for development of UASED – hot electrons in plasma periphery and thin layers with enhanced secondary emission on the surface – can be easily achieved during tokamak operation.

Development of heating systems has led to increase of the electron temperature in the peripheral plasma. Also a bifurcation transition to an improved confinement (L–H transition) characterized by a several-fold increase of the energy and the particles confinement time was observed. ELMy H-regime is considered to be the basic one for ITER. A thermal barrier is formed on the plasma boundary in this regime, so the electron temperature may rise above 1 keV. A part of these hot electrons penetrate through the barrier into SOL and then, being led by the magnetic field, strike the plasma-facing components (due to a large free path, proportional to T_e^2). The flux of hot electrons increases many times during periphery plasma instabilities, ELMs for instance. The high-energy electrons give a high secondary emission yield, especially from dielectric films (oxides, carbides, and diamond-like films).

One of the common techniques for the removing oxygen impurities from plasma is chemical bonding of oxygen on the surfaces of plasma facing components. At the same time, it is known that many oxides are dielectrics and have a high secondary emission yield (as in the case of Be). So, the main conditions for development of UASED – the presence of electrons with enhanced energy and formation of spots with high and low secondary emission on the plasma facing surface can be satisfied in tokamak periphery. One can conclude that tokamak is an ideal machine for development of parasitic RF discharges in many parts of the installation.

4. Conclusion

A model of erosion and deposition of materials in the plasma shadow (cavities, pockets, and gaps) is proposed. The model is connected with the possibility of development of the uni-polar auto-oscillating secondary emission discharge (UASED). The principal feature is in the N-shaped volt ampere characteristics VAC with the negative differential resistivity, which is connected with high secondary electron–electron emission of a plasma–surface contact region. Both the surface with high e–e emissivity ($\sigma > 1$) and the electrons of enhanced energy (a few hundreds eV) are necessary for production of high electron emission.

The UASED was modeled in the beam plasma discharge (BPD) facility. UASED was observed between two electrically connected surfaces with different electron emission.

High voltage oscillations lead to enhanced erosion of the contacting surfaces, hydrocarbon release from graphite electrode, and deposition of C:H films. The discharge broadens, transverse transport increases, so the surfaces far from the main plasma also participate in plasma–surface interaction.

UASED induces high electric fields in shadowed narrow gaps. These fields stimulate a-C:H films growth due to activation of polymerization of volatile hydrocarbons penetrating the gaps.

The inverse process of cleaning the films may be possible by RF discharges in hidden gaps and pockets.

Acknowledgements

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