2-D ELECTRON SYSTEM IN THE RF-DISCHARGE PLASMA. PART I. GENERAL OBSERVATIONS

V.L. Berezhnyj, I.V. Berezhnaya

National Science Center “Kharkov Institute of Physics and Technology”,
Institute of Plasma Physics, Kharkiv, Ukraine

E-mail: berezhnyj@kipt.kharkov.ua

The hypothesis is advanced for similarity between the space-charge layers formed by the plasma in the near-antenna region of ICRF discharges and the two-dimensional electron systems created specially for each specific realization for the studies of metals, semimetals and semiconductors.

PACS: 52.55.Fa; 52.35.B

The peculiarity of fusion-plasma RF discharges consists in the formation of space-charge layers close to the antenna surface. A simple mechanism of their formation was suggested by S.M. Levitsky [1, 2]. Under exposure to the RF field, the electrons in the gap between electrodes, *l*, move and oscillate with the amplitude $A = \mu_0\ (E_m/p\omega)$, where μ_0 is the electron mobility at p=133.3 Pa. Here it should be noted that during the closest RF field period, the electrons being at their mid-position (at $\omega t = 0,\ \pi$) at a distance of *A/2* from the electrode, reach its surface. As for the electrons being from the nearest electrode at a distance greater than the oscillation amplitude *A*, they will participate in the oscillations, but will not fail to arrive at the electrode. According to V.A. Godyak being the competent authority in the field of RF discharges, the mechanism of space charge (RF sheath) formation proposed and confirmed experimentally (see refs. [1, 2]), has become commonly accepted [3].

The torsatron Uragan-3M (U-3M) and the stellarator-torsatronUragan 2M (U-2M) are the electrodeless installations [4, 5]. Nonetheless, the rfsheath formation starts from the departure of electrons, being at a distance of ≤ *A*/2 from the antenna surface [6-9], with subsequent arrival at the mentioned surface. The RF antenna surface serves as one of the plasma capacitor plates.

The region, which is closest to the antenna, turns out to be depleted of electrons. Beyond the RF sheath, the plasma remains quasineutral throughout the entire volume. However, owing to positively-charged low-mobility ions that form the positive RF sheath, the plasma comes out to be positively charged relative to the antenna [1, 7, 10, 11]. This charge around the antenna surface can be represented as a virtual positive plasma capacitor plate [6]. The capacitive antenna-plasma component transforms the RF discharge into a hybrid inductive-capacitive discharge [6, 12]. In consequence, the RF power can come to the plasma through the inductive and capacitive channels. This capacitor makes possible the localization of a thin electron layer on the antenna surface, being due to the potential field of positive ions on the one side, and to the potential barrier on the other side, with the result that the potential well is formed. The electrons walk away alternately from one side to the other. This contributes to the increase in the oscillating parallel electron current. The central oscillating voltage rises and falls as a doubled applied frequency (2ω). In this layer, the rectification of the applied RF voltage occurs [3, 13, 14]). As this takes place, the constant electrode-to-plasma potential difference U_0 may be about 30 % higher than the applied a.c. RF voltage $U_0 \sim V_{\sim}/\pi$ [3]. Thus, the formation of a multilayer space charge in the near-antenna region is accompanied by an essential dissipation of power applied to the antenna at RF discharges [13], $P_{sh} \sim n_b c_s\, A_b V_{rf}$, where $n_b c_s$ is the plasma stream, *A* is the projection of area normal to the magnetic field. Owing to the V-I curve nonlinearity of the space-charge near-electrode layer, the radial component of discharge current may arise [10]. This means that apart from generation of the longitudinal RF-field component E_z by the antenna, in order to give effect to the starting phase of RF plasma creation [15, 16], the E_r component may also participate in the ionization due to the radial avalanche. Besides, many more other effects arise in the interaction of the interconnected ICRF-antenna-plasma chain [1-3, 7-10, 14-18]. For brevity sake, we restrict our discussion to the general conclusion that the formation of space charge layers in the near-antenna region plays an important role in the cleaning of the installation components, the initial ionization of the working gas, the plasma heating and confinement. The most undesirable effect is the RF antenna bombardment by accelerated positive ions that results in the enhanced sputtering of the surface, and hence, in the arrival of heavy metallic impurities with great *z* at the plasma confinement volume [13, 18, 19]. The attempts to attenuate or control these effects are hampered by difficulties of their direct diagnostics. In most cases, the heavy impurities are reduced through the design improvement of the antenna elements by coating them with metals difficult to sputter, or with low-*z* materials (boronizing) [13, 19-21]. Owing to electron oscillations in the locally bounded layer [13], many effects are dependent on the layer thickness *d* along the longitudinal component *E* of the applied RF field. In its turn, the *d* value is determined by the plasma parameters n_e and T_e, as well as by the amplitude *A* and the frequency *ω* of RF voltage applied to the antenna [10].

This has given impetus to a search for similar formations for the purpose of gaining additional useful information on the controllability of the effects occurring in them. The creation of two-dimensional electron systems (TDES) in the research of solids has led to striking results. This has stimulated the attempt to demonstrate the identity of the processes occurring in the near-antenna region of the RF discharge and in the TDES. The common characteristic feature of both the plasma and solids is the presence of free electrons. In a separate atom, the electrons are moving so that their energy levels have a discrete character, i.e., they get quantized. This opens ample opportunities for plasma spectroscopy. The free electron spectra of in solids (crystals) also specify their type and basic properties. As atoms group together in a solid, their electron shells get overlapped. Each energy level gives rise to level bands, i.e., the bands, the number of which equals the number of electrons in the crystal. The energy separation between the levels in the band is very small. The allowed energy bands are separated by forbidden bands. With increase in the energy, the allowed band width increases, while the forbidden band width decreases. In the crystal, the allowed bands may be filled wholly (insulator), partially (conductor) or may be perfectly free. The crystal, where an appreciable number of electrons fall within the empty band due to thermal excitation, is a semiconductor. It is evident that the type and properties of the solid are specified by the band structure, which is difficult for investigation in the bulky crystal. The problem was solved using the methods of dimensional effects [22]. The term “dimensional effect” implies the dependence of properties of the solid body on its geometrical dimensions, when at least one of the dimensions would become comparable with the characteristic physical quantity having the length dimension. It follows from this definition that the indispensable condition for manifestation of the dimensional effect is the presence of the TDES in the medium.The first theoretical work on quantum dimensional effect was performed by the KIPT scientists I.M. Lifshits and A.M. Kosevich [23]. However, the experimental realization of the dimensional quantization on the basis of the sample to be studied called for the formation of the 2D electron gas. For this purpose, the TDES is created specially for each particular realization [24]. To the effect, the crystal film was prepared, the thickness of which, d, was comparable with the de Broglie wavelengthλ_{dB}. The film is placed in the (x-y) plane normally to the electric field E. In the (x-y) plane, electrons move freely as in a bulky crystal. The energy of transverse motion along z takes on some selected values, determined by the film thickness d, i.e., it gets quantized. This results in a cardinal reconstruction of the electron spectrum. Apart from thin films and wires, it has appeared possible to create the TDES through electron localization in a certain space region, viz., the potential well having the width of about the electron wavelengthλ_{dB}. These structures represent the capacitor with metal-metal, semiconductor-metal, and semiconductor-semiconductor plates. The 2D electron gas is localized in the potential well formed by the potential barrier on the semiconductor surface on the one side, and by the space-charge electrostatic potential on the other side. Therefore, the basic structure of the TDES is muchsimilar to the RF sheath in the RF discharge. The possibility to control electrons in the TDES has made it possible to investigate the band structure of solids, to create new elements for microelectronics, and thus to provide a convenient model system for studying physical processes. In RF discharges, the plasma itself creates the space charges of particles for forming the potential well in the vicinity of the antenna surface. The present paper offers the hypothesis about the similarity of the RF-sheath in the RF discharge to the TDES in solids. The second part of the work gives the comparison between the media of existence, the conditions of creation and possibilities of controlling the processes in the formations under discussion.

REFERENCES

1. S.M. Levitsky. The space potential and electrode sputtering in the RF discharge // *ZhTF*. 1957, v. XXVII, v. 5, p. 1001-1009.
2. S.M. Levitsky. Investigation of RF discharges ignition potential in gas in the transition region of frequencies and pressures // *ZhTF*. 1957, v. XXVII, v. 5, p. 970-977.
3. V.A. Godyak, A.A. Kuzovnikov. On electrical valve-like action of RF discharges // *Fizika Plazmy*. 1975, v. 1, № 3, p. 496-503 (in Russian).
4. V.E. Moiseenko, V.L. Berezhnyj, V.N. Bondarenko, et al. RF Plasma Production and Heating Below Ion-Cyclotron Frequencies in Uragan-3M torsatrons // *Nucl. Fusion*. 2011, v. 51, 083036, p. 8.
5. I.M. Pankratov, A.A. Beletskii, V.L. Berezhnyj. Behavior of RF Discharge Plasmas in the Uragan-3M and Uragan-2M Torsatronsv// *Contrib. Plasma Phys*. 2010, v. 50, № 6-7, p. 520-528.
6. E.A. Kral’kina. The inductive RF low-pressure discharge and possibilities of plasma source optimization on its basis // *Uspekhi Fiz. Nauk*. 2008, v. 178, № 5, p. 519-540 (in Russian).
7. V.L. Berezhnyj. ICRF – volume charge-antenna edge interactions in the torsatronsU-3M and U-2M.Part 1. Formation of a volume space charge (VSC) of positive ions // *Problems of Atomic Science and Technology. Series “Plasma Physics”(22).* 2016, № 6, p. 19-21.
8. V.L. Berezhnyj. ICRF – volume charge-antenna edge interactions in the torsatrons U-3M and U-2M.Part2. VSC-RF antenna interaction // *Problems of Atomic Science and Technology. Series ”Plasma Physics”(22),* 2016, № 6, p. 22-24.
9. V.L. Berezhnyj.ICRF – volume charge-antenna edge interactions in the U-3M and U-2M torsatrons. Part 3. ICRF-VSC interaction // *Problems of Atomic Science*

and Technology. *Series “Plasma Physics”(23).* 2017, № 1, p. 10-13.

10. V.A. Godyak. A stationary low-pressure RF discharge // *Fizika Plazmy*. 1976, v. 2, № 1, p. 141-151 (in Russian).

11. E.P. Velikhov, A.S. Kovalev, A.T. Rakhimov. *Physical phenomena in the gas-discharge plasma*. Moscow: “Nauka” / Main office of Physical-Mathematical Literature, 1987, p. 60.

12. M.L. Mayoral, P.U. Lamalle, D. Van Eeser, et al. Hydrogen plasmas with ICRF inverted minority and mode conversion heating regimes in the JET tokamak // *Nucl. Fusion*. 2006, v. 46, p. 550-563.

13. I.R. Myra, D.A. D’Ippolito, D.A. Russel, et al. Nonlinear ICRF plasma interactions // *Nuclear Fusion* 2006, v. 46, № 7, p. 455-468.

14. V.L. Berezhnyj, I.V. Berezhnaya, V.S. Voitsenya, et al. Effects of RF field rectification and occeleration electron beam generation in the torsatron U-3M during plasma production // *Problems of Atomic Science and Technology*. *Series “Plasma Physics”(17)*, 2011, № 1(71), p. 26-28.

15. Yu.G. Zaleskij, P.I. Kurilko, N.I. Nazarov, V.V. Plyusnin, O.M. Shvets. Investigation of RF plasma-creation start phase in the torsatron “Uragan-3” // *Fizika Plazmy*. 1989, v. 15, № 12, p. 1424-1429 (in Russian).

16. H.I. Lysojvan, V.E. Moiseenko, O.M. Shvets, K.N. Stepanov. *ICRF-methchod for plasmas production in large stellarators.* VIII Stellarator Workshop collection of Papers. Kharkov, USSR, 1991, 27-31 May, p. 243-246.

17. V.L. Berezhnyj, S.P. Bondarenko, M.P. Vasil’ev, et al // *Behaviorof impurities during RF heating in the Uragan-3 torsatron*. IAEA-CN-50/c. 1999, v. 1, p. 599-609.

18. D.A. D’Ippolito, I.R. Myra, J.H. Rogers et al. Analisis of RF sheath interactions in TFTR// *Nuclear Fusion*. 1998, v. 38, № 10, p. 1543-1563.

19. S.J. Wukitch, B.La Bombard, Y. Lin, et al. ICRF specific impurity sources and plasma sheaths in Alcator C-Mod // *Journal of Nuclear Materials.* 2009, v. 390-391, p. 951-954.

20. Vl.V. Bobkov, R. Bilato, F. Braun, et al. ICRF antenna coupling dependence on edge plasma conditions in ASDEX Upgrade // *Nuclear Fusion*, 2006, v. 46, p. 469-475.

21. I.R. Myra, D.A. D’Ippolito, M.J. Gerver. Faraday screen sheaths and impurity production during ion cyclotron heating // *Nuclear Fusion*. 1990, v. 30, № 5, p. 845-858.

22. B.V. Tavger, V.Ya. Demikhovsky. Quantium dimensional effects in semiconductor and polycrystalline filsms // *Uspekhi Fiz. Nauk.* 1968, v. 96, v. 1, p. 61-86 (in Russian).

23. I.M. Lifshits, A.M. Kosevich. Toward a theory of magnetic susceptibility of thin metal layers at low temperatures // *DAN SSSR*, 1953, v. 91, № 4, p. 795-798.

24. A.Ya. Shik. Two-dimensional electronic systems. *Educational guidance*. St. Petersburg: “LGTU OChL: SPbGTU”, 1993, p. 75.

Article received 10.10.2018

ДВУМЕРНАЯ ЭЛЕКТРОННАЯ СИСТЕМА (ДЭС) В ПЛАЗМЕ ВЧ-РАЗРЯДА. ЧАСТЬ I. ОБЩИЕ ПОЛОЖЕНИЯ

В.Л. Бережный, И.В. Бережная

Выдвигается гипотеза об аналогичности слоев объемных зарядов, образуемых плазмой в приантенной области ICRF-разрядов и двумерных электронных систем, создаваемых специально в каждой конкретной реализации для исследования металлов, полуметаллов и полупроводников.

ДВОМІРНА ЕЛЕКТРОННА СИСТЕМА (ДЕС) У ПЛАЗМІ ВЧ-РОЗРЯДУ. ЧАСТИНА I. ЗАГАЛЬНІ ПОЛОЖЕННЯ

В.Л. Бережний, І.В. Бережна

Висувається гіпотеза про аналогічність шарів об’ємних зарядів, що створюються плазмою у приантенній області ICRF-розрядів та двомірних електронних систем, які виготовляються спеціально в кожній конкретній реалізації для дослідження металів, напівметалів та напівпровідників.