2-D ELECTRON SYSTEM IN THE RF-DISCHARGE PLASMA. PART II. SIMILARITY OF TDES IN A SOLID AND IN THE RF DISCHARGE

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Comparison studies have been carried out into structural and physical peculiarities of the two-dimensional electron system (TDES) in solids and the RF plasma. The observed similarity points to possible workability and usefulness of advances in scientific and applied investigations in solids for improving the efficiency of RF plasma heating.

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The realization of TDES calls for the presence of free electrons in the medium. This property is exhibited by metals, semimetals, semiconductors and plasma. As regards the substance structure, the plasma and solids (crystals) stand in opposition to each other. And yet, their common feature is the presence of free electrons. In U-3M and U-2M torsatrons, the plasma is created and heated only by RF methods. Therefore, the electron density n_e generally ranges between 10^8 and 10^{14} cm^{-3}. The solid is mainly represented by dielectrics (resistivity $\rho \sim 10^8...10^{13}\ \Omega\cdot$m), metals (free-electron density $n_e \sim 10^{24}$ cm^{-3}, $\rho \sim 10^{-6}...10^{-8}\ \Omega\cdot$m), semimetals ($n_e \sim 10^{18}...10^{20}$ cm^{-3}, $\rho \sim 10^{-4}...10^{-5}\ \Omega\cdot$m), and semiconductors ($n_e \sim 10^{14}...10^{18}$ cm^{-3}, $\rho \sim 10^{-5}...10^{8}\ \Omega\cdot$m). The solids varieties and their properties are determined by energy band structures. However, because of electronic energy level overlapping in the bands, their identification appears practically impossible, since instead of separate spectral energy levels, a continuous spectrum is virtually observed. Nonetheless, the studies of current-carrier energy spectra still remain dominant in the physical-property investigations of crystals as such, and semiconductors, in particular, for the needs of thriving microelectronics. To solve the problem, the method is required for sort of widening between individual energy levels in the necessary energy interval. The possibility to identify separate electronic levels that form the bands has appeared with putting to use the dimensional effects [1]. Experimentally, this means that instead of a bulk crystal, its very thin film of thickness d, being of about electron wavelength λ_{dB} (de Broglie wavelength), is used. In this case, the crystal size is in no way related to the size of the potential well, and thus, can be as large as is wished. However, for realization of the method, a number of conditions should be fulfilled. The film thickness must be sufficient to accommodate a whole number of de Broglie half-wavelengths, i.e., $d = \frac{n\cdot\lambda_{dB}}{2}$ [2]. Considering that in the case under study $\lambda_{dB} == \frac{2\cdot\pi\cdot\hbar}{|P_z|}$, we obtain $d = \frac{\pi\cdot\hbar\cdot n}{|P_z|}$ or $|P_z| = \frac{\pi\cdot\hbar\cdot n}{d}$, where n = 1, 2, 3… is the dimensional quantum number. In other words, at the so chosen film thickness d (potential well depth), the electron quasi-momentum component P_z along the z – axis takes on only specified values, i.e., it gets quantized. Since the energy of the transverse motion of electrons in the film is dependent on $|P_z|$, then it is also quantized $E_n = \frac{\pi^2\cdot\hbar^2\cdot n^2}{2m^* d^2}$, where m^* is the effective current-carrier mass in the crystal in the z direction. For metals, λ_{dB} is about 10^{-8} to 10^{-7} cm, i.e., it is comparable with the lattice constant, that involves difficulties in making the metallic films with $d \sim \lambda_{dB}$ in thickness. In semimetals and semiconductors, the effective electron mass m^* is several orders of magnitude smaller than in metals, where the effective electron mass is of the same order as the mass of the free electron ($m^* \sim m_0$). To determine the energy of the n-th level, it is necessary that the distance between the dimensional levels $\Delta E = E_{n+1} - E_n$ should be greater than their width $\delta E = \hbar/\tau$. The energy spectrum change leads to an essential change in the electron state density as a function of the electron energy $q(E)$. The $q(E)$ value determines the number of electron states in the energy range from E up to $E+\Delta E$, related to the interval value ΔE, i.e., the number of electron states in the energy unit interval. The condition $\Delta E >> \delta E = \hbar/\tau$ means that for the observation of the quantum dimensional effect it is necessary to have the samples with great time of relaxation τ, i.e., with a great free path of electrons. The stepwise behavior of the function $q(E)$ and the oscillatory behavior versus the film thickness $g(d)$ lead to changes in the basic macroscopic properties of the films compared with the properties of the bulk crystal of the same substance. It was just the oscillatory behavior of thermodynamic coefficients in metallic films that were considered in the theoretical papers [1-3]. On the basis of the theoretical studies and meeting the main rather hard conditions, the first experimental work on the bismuth (Bi) film has been made [4]. In the experiment, the TDES was represented by a Bi semimetallic film. In that TDES, the Bi effective mass component m^*_0 was estimated to be about 0.01 m_0, and the Fermi energy was comparatively low, $\varepsilon_F \sim 0.02$. The resistivity (ρ), the Hall constant (R_H) and the magnetoresistance ($\Delta\rho/\rho$) were studied as functions of the bismuth film thickness. All the measured functions showed the oscillation character, thereby pointing, in the authors' opinion, to a high probability of quantum-size effects manifestation. Their caution of the conclusions was due to possible inaccuracies of film manufacture. However, the results were confirmed by theoretical works dealing with quantum dimensional effects [5, 6]. On the other hand, the works [4-6] have predetermined the development of more perfect structures for creating the TDES. It has appeared not obligatory to restrict the sample dimensions to extremely thin thicknesses *d*. It is sufficient to localize electrons in a certain space region (potential well of width $d \sim \lambda_{dB}$ on the sample surface). Note that the sample size is in no way related to the potential well size, and therefore, can be arbitrarily large. In fact, the metallic thin film was limited by two infinitely high potential walls similarly to the case of the electron gas layer in the potential well, as during transverse motion the electrons cannot run beyond the well [1]. Generally, the semiconductor-based TDES is represented by the capacitor with metal-semiconductor plates separated by a dielectric with the dielectric constant ε. The voltage is applied to the capacitor in such a way that the metal plate should be positively charged, whereas the semiconductor plate is negatively charged. Here the electrons are trapped close to the semiconductor surface by the electrostatic field E_z, which is perpendicular to the interface surface and is created by positive charges and by the potential barrier on the semiconductor surface, thereby giving rise to the potential well [7]. The well depth (*d*) along the axis *z* is generally comparable with λ_{dB}, i.e., the motion of electrons in the *z* direction is quantized. The motion of electrons in the (*x*, *y*) plane remains free just as in the bulk sample. So, the electrons localized in the potential well on the semiconductor surface create the two-dimensional electron gas (TDEG) (Fig. 1,a). The unique possibility of controlling the surface concentration of electrons through the electric field E_z change has made it possible to create a radically new field-effect transistor (FET) on the basis of the TDES represented by the metal-dielectric-semiconductor set. Here, the “source” and “drain” contacts in the (*x*, *y*) plane play the parts of the cathode and the anode, while the control electrode (the capacitor positive plate) plays the role of the grid [8]. Owing to this property, and to the capability of working at low temperatures, the FET holds a most unique position among the elements of microelectronics. The FET experiments at low temperatures, when the FET resistance decreases by a factor of millions, and the magnetic field *H*, perpendicular to the 2d-plane, is strong, have led to a “new discovery” of the quantum Hall effect. It has appeared that at certain surface electron concentrations and magnetic field values, the Hall resistance R_H is quantized and is governed only by the ratios of fundamental physical constants and the integer *i* = 0, 1, 2…, which determines the number of levels in increasing order of their energies $R_H = \hbar/ie^2$. The quantum Hall effect discovered in the TDES is of great importance not only for the solid-state physics, but also for the physics in whole, because it allows a direct determination of the fine structure constant $\alpha = e^2 \cdot c/2\hbar$, which characterizes the interaction of charged particles with electromagnetic radiation; this being of particular importance in the fusion plasma research [9]. Similarly, the TDES can be created on the basis of heterojunctions, which represent the contact of two different semiconductors having different Fermi levels (Fig. 1,b) [10]. The free electrons from $Al_xGa_{1-x}As$ go over to the *GaAs* semiconductor, making the latter negatively charged. In consequence of electron depletion, the $Al_xGa_{1-x}As$ semiconductor becomes positively charged. The electrostatic field E_z traps the electrons in the vicinity of the *GaAs* semiconductor surface. The TDESs based on semiconductors and heterostructures are widely used in scientific research, microelectronics, communication facilities; extend FET potentials [2, 7, 8, 11, 12] in creating the frequency-tuned lasers in the infrared and submillimeter-wave regions [10, 13]. A similar TDES is created on the antenna surface by the RF discharge plasma (Fig. 2). It has been described in the survey [14]. The electrons moving in the RF field near the antenna fall on its surface. To regain quasi-neutrality, the plasma creates the layer (sheath) of positively charged ions. This is how the capacitor, being the basis of any type of the TDES, is formed. The potential field of positive ions attracts the electrons from the antenna to its surface. The secondary electron emission also takes place. So, a layer of local electrons is formed in the potential well. The latter is created by the potential barrier on the antenna surface, on the one side, and by the electrostatic field of positive ions [15], on the other side. It is evident from Figs. 1,2 that the TDESs based on semiconductors, heterostructures, and the TDES formed on the RF antenna surface have similar structures, though the first two refer to quantum effects, and the third TDES pertains to classical dimensional effects. In the semiconductor-based TDES, to control the current in a thin electron sheath, an additional source is used for creating the transverse electric field E_z.

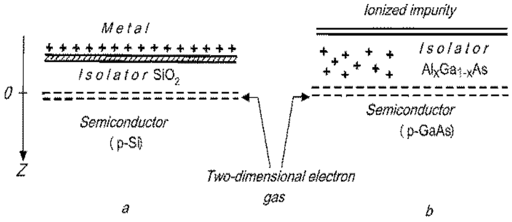

Fig. 1. a – semiconductor-based TDES;
b – heterostructure-based TDES

In plasma, the E_z is created by positive ions of the plasma itself. In all types of the TDES, the electrons oscillate and are reflected from the walls of the potential well of width *d* [3, 14]. The change in the width *d* by varying the E_z intensity causes the change in the resistivity of the sample under study.

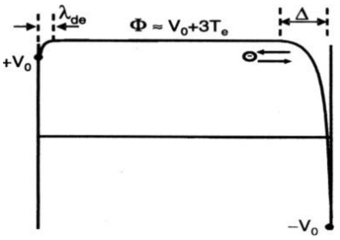

Fig. 2. Principal physics of the sheath. The RF sheath (TDES analog) is formed in the process of equalizing the rates of electron/ion losses. The resulting potential forms the potential barrier Δ *on the side of the RF antenna. On the plasma side, the potential electric field of positive ions,* E_z*, reflects electrons towards the antenna*

Unfortunately, the E_z value in the plasma is a multicomponent function of the parameters of the RF pulse and the plasma itself [16]. And here lies the problem of controlling numerous effects resulting from the ICRF – antenna – plasma interaction [18-20]. It has been reported in the survey [14] that in the near-antenna TDES, electrons oscillate in the potential well at a doubled frequency of the RF field ($2\omega_0$); here also, the rectification of a part of the applied RF voltage occurs. In effect, a considerable dissipation of RF power takes place. The authors of ref. [20] have observed the second-harmonic generation at a supply of the wave to the piezoceramic film Cds at frequencies of $f_0 \sim 13\ldots21$ MHz. In the experiment, the condition of the classical dimensional effect $d \sim 30\ldots70$ μm $>>\lambda_{dB}$ was fulfilled. That experiment has provided indirect evidence of the similarity between the semiconductor-based TDES and the TDES in the RF plasma. The generation of second- and higher-order harmonics [14] in the U-2M and U-3M [21, 22] is due to the TDES formation in the RF plasma. In comparison with the semiconductor-based structures, the TDES structure in the near-antenna region is more complicated. A priori, the RF electric field perpendicular to the antenna surface is nonuniform along the antenna conductor. This means that along the antenna conductor there appears the RF electric field component $E_{\|}$. So, the current $J_{\|}$ arises along the antenna conductor. Besides, the $E_{\|}$ is perpendicular to the confining magnetic field H_0. In its turn, this increases the $\vec{E}$ x $\vec{B}$ plasma escape from the antenna conductor. This convection as the competition with diffusion, and the antenna itself, which displays the electron sink effect, lead to the depletion of the electron density close to the antenna. This was observed experimentally in the vicinity of the RF antenna at the TFTR tokamak [14]. These effects can stimulate the excitation of a number of low-frequency instabilities, they influence the generation, transformation and propagation of both fast ad slow ICRF waves required for plasma production and heating in the U-3M and U-2M. To have optimum conditions for ICRF wave propagation, it is essential that good antenna-plasma coupling should be provided. For this purpose, the antenna must be placed close to the plasma. However, this may cause the modification of edge plasma density profiles that can change the antenna-plasma coupling. The dimensional effects may take place in the magnetic fields H, if the TDES transverse size d is comparable with the orbit size of the cyclotron electron rotation in H. For realization of the classical dimensional effect, it is necessary that the Larmor radius of electron rotation around the line of the magnetic field H should exceed by far the electron wavelength d_{dB}: $r_e = {}^{V}\!/_{\omega c} = {}^{m^{*}Vc}\!/_{cH} \gg \lambda_{dB}$. In the case of $r_e \ll \lambda_{dB}$, the quantum effects become essential. The dimensional effects are possible to occur in anisotropic solids [23] and in anisotropic plasma states [24]. So the dimensional effects can take place in solids and the RF plasma. The indispensable condition for the use of any dimensional effect is the presence of the TDES for creating the two-dimensional electron gas (TDES) (sheath). In solid-state TDES, the two-dimensional electron layer is created on the basis of semimetals or semiconductors, specifically for each experiment. The phenomenal TDES capability of controlling the current of the two-dimensional electron layer by the independent voltage source has permitted the realization of the experiments with the use of dimensional effects in both the basic and applied research. The plasma created and (or) heated by the RF methods is itself capable of forming the TDES near the antenna surfaces. The only direct source of acting on the electron sheath is the potential electric field created by space charges of positive plasma ions. Thus, the possibility of controlling the two-dimensional electron near-antenna layer (sheath) depends on both the RF pulse parameters, and the RF pulse-created plasma parameters. In this scenario, the effective results obtained with solids-based TDES would be rather useful for the ICRF experiments in the plasma.

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ДВУМЕРНАЯ ЭЛЕКТРОННАЯ СИСТЕМА (ДЭС) В ПЛАЗМЕ ВЧ-РАЗРЯДА. ЧАСТЬ II. АНАЛОГИЧНОСТЬ ДЭС В ТВЕРДОМ ТЕЛЕ И ВЧ-РАЗРЯДЕ

В.Л. Бережный, И.В. Бережная

Проведен сравнительный анализ структурных и физических особенностей ДЭС в исследованиях твердых тел и ВЧ-плазмы. Их аналогичность указывает на возможность и полезность использования научных и прикладных достижений в твердых телах для повышения эффективности ВЧ-нагрева плазмы.

ДВОМІРНА ЕЛЕКТРОННА СИСТЕМА (ДЕС) У ПЛАЗМІ ВЧ-РОЗРЯДУ. ЧАСТИНА II. АНАЛОГІЧНІСТЬ ДЕС У ТВЕРДОМУ ТІЛІ ТА ВЧ-РОЗРЯДІ

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Проведено порівняльний аналіз структурних та фізичних особливостей ДЕС у дослідженнях твердих тіл та ВЧ-плазми. Їх аналогічність вказує на можливість та корисність використання наукових та прикладних досліджень у твердих тілах для підвищення ефективності ВЧ-нагріву плазми.