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This book includes the abstracts of talks presented on MD-8 by scientists from different countries on methods of microwave plasma generation, physics of high and low pressure microwave discharges, microwave discharge modeling and diagnostics, application of microwave plasma

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I. THEORY, MODELING, AND DIAGNOSTICS

MODELLING OF MICROWAVE DISCHARGES SUSTAINED BY TRAVELLING ELECTROMAGNETIC WAVES

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Travelling electromagnetic wave can produce plasma at various geometries. In cylindrical geometry plasma can be produced inside the dielectric tube (cylindrical plasma column) as well as outside the dielectric tube, usually when at the tube axis a metal antenna is arranged (coaxial discharge configuration). In some cases plasma can be produced outside the dielectric even without any metal rod at its axis. We have studied theoretically the conditions at which plasma can be produced and the plasma properties at such configurations.

A self-consistent numerical model of surface-wave sustained argon plasma is applied to investigate the electron energy distribution function (EEDF), rate coefficients of the elementary processes in the discharge, levels population dynamics, as well as all plasma characteristics at various gas pressures and plasma radii. The model describes both the gas discharge kinetics and the wave propagation along the axially inhomogeneous plasma. It is based on steady-state Boltzmann equation coupled with collisional-radiative model for argon discharge solved together with Maxwell's equations.

Because of the plasma axial inhomogenity all processes and plasma characteristics are changing along the column. The axial distributions of plasma density, excited atoms number densities, electron energy distribution function (EEDF) and mean electron energy, electron–neutral collision frequency for momentum transfer, mean power for sustaining and electron–ion pair in the discharge, gas temperature, the partial distribution of gain and loss processes in population of excited states, and other plasma characteristics are obtained varying the pressure p and the discharge tube radius R. The theoretical investigation shows that the relative part of the different processes changes not only with the pressure but also along the plasma column at given operating conditions.

PLASMA DYNAMICS DURING MICROWAVE BREAKDONW

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Microwave breakdown in air at atmospheric pressure can lead to the formation of self-organized filamentary structures that appear as moving toward the source. Such structures have been observed in Russia in the 1980s (see, eg, [1,2]), and, more recently, at MIT, with fast imaging camera [3,4].

We present simulation results based on a simple model where Maxwell's equations are solved together with a diffusion-ionization-recombination equation for the quasi-neutral plasma density [5-8]. An effective diffusion coefficient [7] is used, accounting for the transition between free electron diffusion at the plasma front and ambipolar diffusion in the plasma bulk. The simulations of microwave breakdown in open air can satisfactorily reproduce [5,6] the MIT experiments (obtained with a 110 GHz gyrotron). We also present results for an isolated microwave streamer produced in a mirror configuration [8]. The simulations show that the electric field in the streamer head is modulated in time because of resonance effects associated with the filament length.

Finally, we will briefly discuss the effect of gas heating on the microwave filament dynamics and on plasma formation for under-critical incident fields.

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COUPLING MODES OF MICROWAVE PLASMA SOURCES WITH LOCALISED POWER ABSORPTION

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One major problem that arises in the realization of the microwave plasma devices is the coupling efficiency of the power delivered from microwave generator to the plasma. An ideal applicator must be able to convert the whole power of the propagating mode from the feed line into another propagating mode in the discharge, with a zero reflected power. To address this requirement, an impedance matching network is generally inserted into the circuit and thus, the field applicator with its tuner may act as a mode converter and impedance transformer, respectively.

The accurate knowledge of plasma impedance can permit to directly design the microwave applicators acting as impedance converter and thereby minimize the impedance matcher role using it only to fine-adjust the system impedance. Some examples will be presented from microwave plasma sources recently developed where coaxial microwave applicators were specially designed to be adapted for specific operating ranges. In each nominal range, both power transmitted $(P_i\text{-}P_r)/P_i$ and power absorbed by the plasma $P_a\,/(P_i\text{-}P_r)$ are close to 100% (fully resistive coupling) without any auxiliary impedance matching.

Moreover, with their specific terminal configuration, these plasma sources allow the extension of the operating range, namely from less than 1 mTorr up to few Torrs, and from ~1 W up to several hundred W. This permitted to investigate a wide range of plasma parameters, *i.e.* ν/ω, ω_{pe}/ω and ω_{ce}/ω, corresponding to various electrical conductivities and therefore plasma impedances. Beside the continuous transition from ECR (under magnetic field) to the collisional absorption observed beyond 50 mTorr, the plasma impedance measurements have revealed several coupling modes: capacitive (imaginary part of plasma impedance $X < 0$) or inductive ($X > 0$) coupling, according to the operating conditions. Less attention is generally paid to the reactive part of the plasma impedance, but its knowledge can present general interest for both fundamental research and specific applications [1,2].

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MODELING OF MODERATE PRESSURE MICROWAVE PLASMA-ASSISTED CHEMICAL VAPOR DEPOSITION REACTORS

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Microwave plasma-assisted chemical vapor deposition (PACVD) reactors have been used extensively for the growth of diamond films. The design geometric features of these reactors vary to enable control and shaping of the electromagnetic fields and plasma discharge. In particular, the design and tuning of various geometric parameters is known to affect not only the electromagnetic field structure, but also the plasma shape during operation. In the past, empirical experience has oftлл en guided decisions for changing these physical parameters during design and operation. A more detailed numerical study of these effects related to the geometry and the interaction of the microwave fields and plasma discharge is undertaken in this study. This study may also lead to more efficient reactor designs and ultimately faster deposition rates.

A systematic numerical study of the effect of reactor design and geometry tuning of hydrogen-based plasmas in Microwave PACVD reactors will be presented. The primary tool used during this study is a self-consistent, multi-physics simulation coupling an electromagnetics model with a reacting plasma flow model. The general operating conditions studied include pressures from 100-300 Torr, frequency of 2.45 GHz, and microwave powers from 1-3 kW. The electromagnetic fields are first solved over the entire reactor using a complex-valued conductivity profile supplied by the plasma flow model. The absorbed power profile is then supplied to the plasma flow model, where the plasma flow velocities, chemical reaction rates, and energy exchange terms are solved. The two models are coupled to produce a single, multi-physics 2-D (r-z) solution reached via an iterative procedure.

Variations in the microwave PACVD reactor are simulated and compared to selected experimental operating conditions. Particular attention will be given to the reactor operation at higher pressures of 150-300 Torr where higher rate diamond deposition occurs.

3-D MODELING OF SUBCRITICAL MW DISCHARGES OF HIGH PRESSURE

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Microwave (MW) discharges of high pressure are able to propagate into region where electromagnetic field is smaller than critical one. This ability is explained by so named the streamer effect. The electric field amplitude increase at tip of thin discharge channel provides the local ionization before tip and further development of the streamer channels. It results the growing of discharge mainly against of MW radiation as complicated net of the streamer channels [1]. The direct modeling of this strongly nonlinear process with net of thin channels by full system of Maxwell and Navier-Stokes equations can't be practically realized. (It is known one precedent of such modeling applied to MW discharge with $\lambda/4$ periodical structure in a pulse linear polarized radiation of 2cm wavelength at median pressure, "fish skeleton"; this unique study has demanded supercomputer use during approximately two weeks).

For study of the streamer discharge development the simplified model was designed and successfully used [2, 3]. The model is based on integral equation for describing of current distribution in arbitrary dislocated thin channels with arbitrary distributed electrical line conductivity in external MW radiation. It is well known Pocklington equation [4], designed for wire antenna system, modified for 3-D geometry and finite electrical conductivity. The integral equation is assisted by differential equations for channel radius and line conductivity.

The samples of the model use are presented: loops creation, far propagation, a snake instability of pinched MW discharge.

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NUMERICAL ANALYSIS OF IONIZATION FRONT FORMATION IN MICROWAVE PROPULSION USING FDTD METHOD

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Microwave beaming rocket gains propulsive energy with no fuel by irradiation of high power microwave transmitted from a distant ground base. An ionization front of the induced plasma absorbs the microwave and travels at a supersonic speed as sustaining a shock wave. These processes have been investigated experimentally by some authors so far, and they found that the ionization front has filamentary structures [1-3]. Such structures are formed at the order of the atmospheric pressure but disappear at 0.2 atm or less [1]. The mechanism of the filamentary structure formation is, therefore, a key issue for predicting the shock formation and the resultant thrust in the microwave beaming rocket.

Simple model indicates that local enhancement of the microwave intensity just ahead of a discharge spot is responsible for the formation of the structure [2]. However, the quantitative assessment is insufficient to explain the velocity of ionization front and its dependence on the ambient pressure. In the present paper, we have developed a two-dimensional simulation code which can describe microwave propagation and focusing. The numerical model is based on finite-difference time domain (FDTD) method for solving Maxwell equations coupled with a simple ionization model.

We assumed that the incident microwave is focused by a parabola mirror. In numerical simulation of microwave focusing, the ionization front is formed in succession due to enhancement of electric field around preformed discharged region and propagates toward the direction of the microwave source. The subsequent discharged region discretely appears at a quarter of microwave wavelength from the former discharged region. The simulation results show that the incident microwave is reflected due to the high electron number density, and a localized strong electric field is formed. Moreover, propagation speed of an ionization front depends on ambient pressure and incident microwave intensity. This tendency agrees with the past experimental results [3].

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THE POWER ABSORBED PER ELECTRON IN SURFACE-WAVE DISCHARGES: ITS CONTRIBUTION TO THE MODELLING OF ELECTRIC-FIELD DISCHARGES IN GENERAL AND A MEANS OF APPRAISING THEIR EFFICIENCY AS FUNCTIONS OF OPERATING CONDITIONS

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Discharges sustained by the electric field of an electromagnetic (EM) surface wave (SW) provide the most flexible plasma columns ever in terms of operating conditions, while keeping the same EM wave mode throughout. This allows pursuing strict parametric studies as functions of EM field frequency (few MHz to GHz), discharge tube diameter (1 mm to at least 300 mm) and gas pressure (few mtorr to at least 10 times atmospheric pressure), with the additional possibility of subjecting the SW discharge to a static magnetic field: in such an investigation, all operating conditions can be kept constant, except the one which is varied.

The major interest of introducing the power absorbed per electron, θ_a, for the characterization of HF plasmas comes from its easy experimental access; θ_a is simply given by the ratio between the absorbed power and the number of electrons at the measured volume location in the discharge. In contrast, the maintenance electric field intensity, which is one of the basic parameters used to characterize DC discharges, is extremely difficult to determine in HF plasmas, as any probe will affect the EM field. The use of the power θ_a is, therefore, a major asset for direct comparison between experiments and models. This quantity can also be utilized as a means of assessing the efficiency of a discharge and finding its minimum value by tuning the operating conditions. As a matter of fact, studies of SW discharges have led to the development of a general model valid for any electrodeless plasma sustained by EM waves, the so-called high frequency (HF) plasmas, whatever the means used for coupling HF power to plasma. It comes out that, under given operating conditions, the value of θ_a should be the same, for instance, for both ECR and helicon plasmas, although the way that their HF power is transferred to the discharge is totally different.

This presentation will review the essential features of the power absorbed per electron and show the deep insight into the discharge mechanisms brought about from its use as a reference parameter, for example in revealing similarity laws and revisiting the ECR mechanism.

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LASER SCATTERING DIAGNOSTICS ON SURFACE WAVE DISCHARGES: ACHIEVING SPATIAL AND TEMPORAL CHARACTERIZATION.

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Over the past few years a new branch of diagnostics of surface wave discharges based on laser scattering techniques has been introduced. These techniques, mainly Thomson and Rayleigh scattering (TS and RyS), provide precise and direct measurements of important plasma parameters like electron density and temperature and gas temperature (n_e, T_e and T_g). With these advanced methods the surface wave discharges can be studied in a different and theory-independent way, validating results from previously established characterizations. Simultaneously, due to their temporal and spatial resolution, the laser techniques provide new insight in surface wave plasmas, fundamental for the full understanding of these discharges and comparison with modeling.

In this contribution we present a review over the different laser experiments performed over the past few years in our group. The whole study is focused on achieving a complete temporal and spatial characterization of surfatron plasmas at intermediate pressures (1 mbar – 90 mbar).

The first step was the determination of the axial dependence of the plasma columns of n_e and T_e with TS measurements [1]. This axial profile "picture" has been completed now with the T_g measurements along the columns with RyS [2] and with the characterization of the very end of the of the discharge with TS [3]. Simultaneously, the radial profile of n_e and T_e has been measured with TS showing its dependence and contraction with pressure [4]. Finally, with the help of time resolved TS measurements, the temporal evolution of n_e and T_e has been determined during the switch on/off phases of the discharges [5].

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RESONANCES IN HIGH FREQUENCY CCP DISCHARGES

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It is well known that surface waves can propagate along plasma-sheath – metal interface in the low pressure CCP discharge [1]. These waves have been discovered in research of antenna properties in plasma environment [2]. Now these waves are found in ICP plasma in vicinity of large RF electrode with applied two frequency (2 and 60 MHz) voltage [3]. The theory of these waves was developed in works [4], [5]. In real CCP discharge surface waves can extend both along an electrode with a substrate, and along an active electrode. Except these waves, there are also the evanescent waves excited near to a point of HF voltage input, penetrating into plasma on skin depth.

In the given work analytical expressions for CCP discharge impedance taking into account excitation of even and odd surface waves, and also evanescent waves are found. The well-known plasma-sheath geometrical resonance corresponds to excitation of evanescent waves. Surface waves strongly decay at these conditions. When electrons density grows, skin depth falls and role of evanescent waves in plasma decreases. Quite the contrary the length of surface waves and energy transferred by them grows.

At high plasma density discharge impedance is almost completely defined by surface waves. The relationship between amplitudes of even and odd surface waves is defined by geometry of the of excitation device.

Space charge sheath is described by nonlinear phenomenological model. Specified approach allows to calculate discharge impedance and explains possibilities ambiguity of plasma characteristics, connected with electrodynamic resonances and chemical processes in plasma. The role of HF field harmonics generation of on sheath nonlinearity is considered.

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A 2D MODEL FOR COAXIAL SURFACE WAVE DISCHARGES

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Surface wave sustained discharges have attracted much attention in industry and academia because of their broad range of operating conditions. Well known configurations are the cylindrical plasma columns generated by surfatron or surfaguide launchers. This study, however, is devoted to the coaxial structure in which a rod antenna, positioned along the axis of the setup, couples the electromagnetic (EM) energy into the plasma. Air and a quartz tube surround the antenna and separate it from the plasma. This configuration can be regarded as a coaxial waveguide in which the rod is the inner conductor whereas the plasma plays the role of the outer conductor. The plasma and wave properties of coaxial surface wave discharges significantly differs from those created by other cylindrical structures. Compared to surfatron, in addition to the advantage of a greater plasma volume, a coaxial plasma also provides the possibility of having surfaces remotely.

To study this relatively new plasma configuration, we coupled an EM module with a non-LTE model to construct a Grand model [1,2]. This Grand model, designed for $Ar/H_2/SiH_4$ mixtures, describes the coaxial surface wave discharge in a self consistently manner.

In this contribution, we present a two dimensional model to investigate the effect of changing plasma control parameters. The results are compared with those for surfatron at similar conditions. To conclude, we compare the model results with those of measurements.

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TWO DIMENSIONAL MODELLING OF MICROWAVE INDUCED PLASMAS USING PLASIMO

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We present the Plasimo modelling platform [1] as a tool to study microwave induced plasmas (MIPs). In the past, a non-local-thermal-equilibrium model (non-LTE) was used to model a pinched cascaded arc and a MIP for fibre production [1]. We improved the electromagnetic (EM) model for microwave propagation [1,2]: the geometry is now created from the input-file. In [2] we already showed it as a tool to study and optimize the EM distribution in an axial injection torch. After this, we coupled the EM-model with the non-LTE model to create a flexible tool for studying the EM-plasma interaction in MIPs. Currently the following applications of the model are available and under development:

(1) Surfatron source (argon, and pressure from 660 to 8800 Pa). We present the model and compare the results with experiments in [3].
(2) Optimization of plasma confinement in a MIP. Using two chokes, we confined the EM-waves and thus the plasma "inside" the cavity, similar to our previous study about the MIP for optical fibre production.
(3) Coaxial surface wave discharge.
(4) Waveguide surfatron at atmospheric pressure. The model is available for argon and helium as filling gas.

We will show the characteristics and limitations of the model and a set of representative results (e.g. for the surfatron and the EM-plasma confinement).

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COMPARISON OF GAS COMPOSITION EFFECT ON PARAMETERS OF DC GLOW AND MICROWAVE DISCHARGES IN MIXTURES OF HELIUM WITH NITROGEN

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Emission spectroscopy is used to investigate effect of gas composition on macro and microscopic parameters (radiative spectral distribution, translational temperature, rotational temperature, electronically – vibrationally – rotational energy distribution functions in the electronic excited $C^3\Pi_u$ and $B^3\Pi_g$ - states of the nitrogen molecules, and as well as $B^2\Sigma_u^+$ - state of the nitrogen ion molecules) of DC glow discharge (pressure of 7.6 Torr, discharge current of 70 mA and 90 mA, percentages of N_2 4.5%$\div$35% and He 95.5%$\div$64.5%) and the strongly inhomogeneous microwave discharge generated near the end of the electrode antenna (frequency of 2.45 GHz, pressure 4.8 Torr, incident microwave power of 108 W, percentages of N_2 1.6%$\div$50% and He 98.4%$\div$50%).

New approach of processing and modeling of plasma emission spectra was developed for reconstruction of nonequilibrium energy distributions of excited hydrogen, helium atoms and nitrogen molecules in the case of spectral overlapping of the atomic lines and molecular bands.

It was shown that assumption on Boltzmann distribution of rotational levels give good agreement of modeled and measured intensities of emission bands of $N_2(C^3\Pi_u - B^3\Pi_g)$, $N_2(B^3\Pi_g - A^3\Sigma^+_u)$ and $N^+_2(B^2\Sigma^+_u - X^2\Sigma^+_g)$. Dependences of intensities of bands of $N_2(B^3\Pi_g - A^3\Sigma^+_u)$ and $N^+_2(B^2\Sigma^+_u - X^2\Sigma^+_g)$ on the gas composition are different in both discharges.

Vibrational distributions of $C^3\Pi_u$-state slightly differ from the Boltzmann distribution in both discharges and does not depend on the composition of gas mixture. Vibrational distributions of $B^3\Pi_g$-state (v_B=3$\div$12) in both discharges differ markedly from the Boltzmann distribution and slightly depend on the composition of the mixture. Different temperatures, corresponding electronically – vibrationally – rotational levels and translational degrees of freedom of nitrogen molecule in both discharges are placed in order:
$T_v(B^3\Pi_g)>T_v(C^3\Pi_u)>T_v(B^2\Sigma^+_u)\geq T_{rot}(C^3\Pi_u)= T_{rot}(B^3\Pi_g)=T_g$.

This study was supported by grant RFBR № 12-08-91052 NCNI_a.

PROBING EXCITATION KINETICS IN MICROWAVE PLASMAS BY LASER INDUCED FLUORESCENCE AND COLLISIONAL RADIATIVE MODELS

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Excitation and desexcitation of neutral/charged species in plasmas can be characterized by different time-scales depending on "external" parameters such as the pressure or the electron density. One of the goals in plasma diagnostics and modeling is the determination of the reaction channels leading to the production of specific species of interest for applications. These excitation paths can be weighted by their effective production frequency.

The perturbation of a steady-state plasma by a nanosecond photon pulse tuned to an optical transition of a specie allows to probe the relaxation kinetics of the latter. An intermediate pressure microwave plasma belonging to the class of surface wave discharges (SWDs) was probed by nanosecond, time-dependent laser (collisional) induced fluorescence L(C)IF [1]. In the same conditions, the electron density and temperature (n_e, T_e) were measured by Thomson scattering (TS) to determine the local, steady-state properties of the plasma for Argon and diverse mixtures such as Nitrogen or Hydrogen. A time-dependent collisional radiative model (CRM) was developed for Argon to investigate the perturbation of the Argon excitation system subsequent to the laser pulse. The results are compared with the LCIF measurements.

The CRM allows to dig into the excitation kinetics within the laser pulse as well as after the laser pulse. The values of (n_e, T_e) being measured by TS and used as input in the CRM, allow to check also for the cross sections inside the CRM as well as to discriminate excitation channels due to charged species or neutral species. These results were also obtained while doing LCIF parametric studies of the plasma as a function of the electron density and pressure. Excitation transfer channels between argon excited states and atomic hydrogen were highlighted as well as with N_2.

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LOW-TEMPERATURE SYNTHESIS OF CARBON NANOTUBES AND GRAPHENE SHEETS USING MICROWAVE PLASMA

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Carbon nanotubes (CNTs) and graphene possess extraordinary combinations of optical, mechanical electronic and other properties [1,2] that makes it a potential candidate for different applications [2,3]. However, to apply it in the real devices it is necessary to develop methods to synthesize aligned CNTs arrays or large-scale graphene sheets with high rate of growth on any substrate directly, for instance. There are several ways to produce carbon nanomaterials (CNMs) [2,3], but one most promising methods to realize a low-temperature, rapid and large-scale synthesis of CNMs is the plasma-enhanced chemical vapor deposition (PECVD). This method can be applied not only CNTs production [4,5], but also for graphene synthesis [6].

In this study we propose to use microwave PECVD to realize growth of CNTs and few-layered graphene-liked films directly onto polymer substrates at relatively low temperature of 250 ~ 280 °C. Graphene-encapsulated Ni nanoparticles [7] have been used as the catalytic material for CNMs growing in the atmosphere of gas flow mixtures of ammonia and methane. The investigation of the effects of substrates and bias voltage on the structure of CNMs has been carried out in this study.

It has been demonstrated an ability to control the growing structure of the carbon nanomaterials by applying the bias voltage and by changing the type of substrate. The low-temperature growth of few-layered graphene sheets onto the polymer substrates has been also demonstrated. The details of the experimental results will be presented and discussed at the conference.

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ELECTRODYNAMIC CHARACTERISTICS OF THE PLASMA LAYERS AT ATMOSPHERIC PRESSURE IN THE MICROWAVE SPECTRUM

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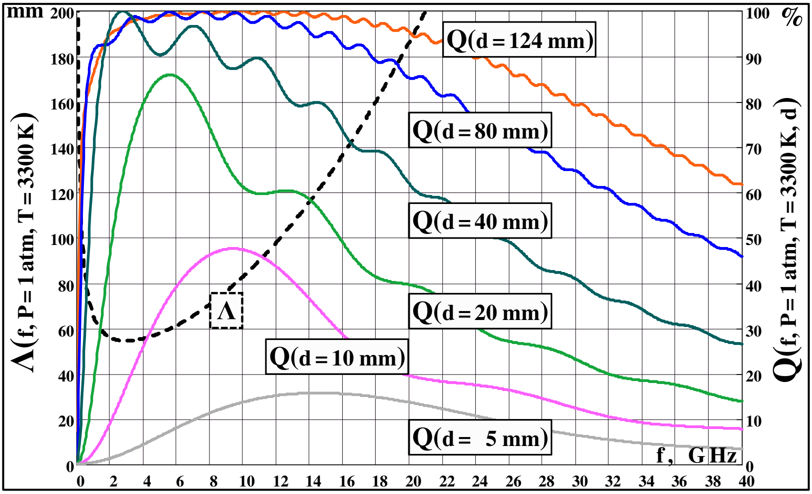
The quantitative description of a plasma layer interaction at atmospheric pressure with an electromagnetic field of the microwave range is executed. For the plasma layer localized near to a metal (mirror) surface with the set thickness *d*, temperature *T* and pressure *P* the broadband spectrum **Q**(**f**,*P*,*T*,*d*) for



absorption coefficient of the microwave radiations has been received.

At pressure *P* equal to one atmosphere the parameters (*d* =124 mm, *T* =3300 K) of a plasma layer are optimized for the maximum of screening effect achievement in the set range (2 – 20 GHz) of the microwave radiations frequencies **f** = **ω**/2π. At propagation to half–space occupied with plasma, depth Λ (f, P, T) for 90 % of microwave radiations absorption looks like a curve with a minimum. The optimal thickness of a screening layer $d(\mathbf{f_c},P,T) \approx 3\Lambda(\mathbf{f_c},P,T)/2$, where $\mathbf{f_c}$ – the central frequency in area ($\mathbf{f_{min}}$ – $\mathbf{f_{max}}$) for 95 % of microwave radiations absorption. Performance of these researches also was stimulated by necessity of oscillograms processing which have been received in laboratory by means of detecting on a remembering oscillograph of the microwave radiations reflected from plasma formation at atmospheric pressure.

MICROWAVE MULTIPACTOR DISCHARGE ON A DIELECTRIC: THEORY, EXPERIMENT, AND 2D COMPUTER SIMULATIONS

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The coefficient κ of microwave power absorption by a single-surface multipactor discharge (MD) on a dielectric is studied analytically and numerically as a function of the incident microwave power. Using the traditionally employed Vaughan's empirical formula for the secondary emission yield $\delta(\varepsilon)$, the following asymptotic expression for κ is derived analytically for electron oscillation energies ε_{osc} much higher than the first crossover energy ε_1:

$$\kappa \approx (\pi/2)^{1/2}(v_{Te}/c)\ln(\varepsilon_{osc}/\varepsilon_1),$$

where v_{Te} is the thermal velocity of secondary electrons.

It is shown with the help of 1D3V numerical simulations that taking into account electron reflections from the dielectric surface substantially increases the coefficient of microwave power absorption. The analytical and numerical results are compared with experimental data.

A 2D3V particle-in-cell code for simulation of an MD on a dielectric in a plane-parallel metal waveguide has been developed. The code solves the equations of motion of electrons in the microwave field and the self-consistent field of electron space charge with allowance for secondary electron emission (SEE) from the dielectric surface and waveguide walls, finite temperature of secondary electrons, and elastic and inelastic electron reflections.

It is shown that the threshold for the onset of an MD on a dielectric placed in a waveguide increases as compared to the case of an unbounded dielectric surface due to electron losses on the waveguide walls. It is found that, depending on the amplitude of the microwave field and the SEE characteristics of the waveguide walls, the MD can operate in two different modes. In the first mode, the MD develops only on the dielectric surface, in which case the dielectric is charged positively. In the second mode, which occurs at microwave intensities exceeding the threshold for the onset of a two-surface MD between the waveguide walls, both the single-surface MD on the dielectric and the two-surface MD between the waveguide walls operate simultaneously. In this case, the region occupied by the two-surface MD rapidly expands along the waveguide axis and the dielectric acquires a negative potential with respect to the waveguide walls.

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INFLUENCE OF DC VOLTAGE ON CHARACTERISTICS OF MICROWAVE PLASMA CATHODE IN NITROGEN

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Generation and study of non-self-sustained discharges is one of important problems of plasma physics. Study of plasma cathodes is a part of these problems. It was shown that non-equilibrium electrode microwave discharge (EMD) can be used as plasma cathode for non-self-sustained DC discharge [1]. DC plasma can be generated near the surface of large dimension electrode if DC voltage is applied in non-symmetric electrode system between the small (microwave powered plasma cathode) and large area electrodes. This property can be used for design of methods of treatment of internal surface of large chambers.

This paper presents results of experimental study of influence of external DC field on the structure and properties of EMD in nitrogen at pressures 1-5 Torr. The discharge chamber was the stainless steel cylinder with diameter of 15 cm (the experimental setup was described in detail in [1]). The electrode-antenna was inserted in the chamber through the vacuum junction in the cup of the chamber. The electrode was isolated from the chamber. Plasma was ignited near the tip of antenna. The incident power was <180 W (2.45 GHz). DC voltage of the electrode relatively the chamber was varied between -300 and +500 V. Emission spectra of EMD was analyzed with spectrometer Avaspec-2048, Electron optic camera K-008 was used for visualization of the discharge. Spectra from the near electrode region were analyzed.

DC voltage–current characteristics of EMD were measured. Method of relative intensities of the second positive and first negative system of nitrogen was used for study of dependencies of microwave field in near electrode region on pressure, microwave power, DC voltage and distance from the electrode. The vibrational distributions of nitrogen molecules in the $C^3\Pi_u$-state are slightly changed with DC voltage and changed with distance from the electrode. DC voltage changes the spatial distributions intensities of nitrogen bands in the near electrode region, dimension of EMD and its shape.

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SURFACE WAVE MICROWAVE PLASMAS PRODUCED IN A COAXIAL STRUCTURE AT LOW PRESSURE

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Most of the theoretical and experimental works on gas discharges sustained by high-frequency traveling waves deal with surface wave propagating in cylindrical structures, in which the plasma column is sustained by the electromagnetic wave traveling mainly along the interface between the plasma and the surrounding dielectric tube [1]. Surface-wave discharges can be also maintained with a tubular structure, where the plasma is produced between an inner and outer radius [2]. In this structure, the tubes can be dielectric or conductor ones [3]. When an inner central conductor is added, tubular plasma in a coaxial structure is obtained.If the tubular plasmas present two plasma-dielectric interfaces, two azimuthal surface-wave plasma modes exist associated to each boundary in a certain sense [4], [5].

This work shows the experimental characterization of the surface waves producing a microwave argon plasma column at low pressures in a coaxial structure. The coaxial structure makes the plasma and the wave properties significantly different from those obtained without a central conductor. In fact, due to the electric field components, the coaxial propagating structure may not need a conventional wave launcher to excite a surface wave. In our case, the wave excitation can be achieved by making the coaxial structure to be the continuation of the power feeding coaxial cable. The radial, azimuthal and axial profiles of the electric field are investigated under different experimental conditions to characterize the surface wave propagation.

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II. MICROWAVE PLASMA GENERATION

MICROWAVE PLASMA REACTOR FOR CVD DIAMOND SYNTHESIS

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Since the demonstration of microwave plasma assisted chemical vapor deposition (MPACVD) of diamond by Matsumoto et. al. [1] microwave plasma processing reactor technologies have evolved into an variety of mature commercially available technologies. One such technology, the microwave cavity plasma reactor (MCPR), was adapted to MPACVD diamond synthesis applications in 1986 and since then the technology has further evolved into a group of diamond synthesis machines that are capable of efficiently depositing ultra-nanocrystalline (UNCD), polycrystalline diamond (PCD) and single crystalline (SCD) materials over 0.5 - 300 torr pressure regime. Uniform diamond synthesis is achieved over 15-20 cm diameters and SCD synthesis can be achieved with growth rates of 15-70 microns/h.

Since its application to diamond synthesis the MCPR has evolved into several design variations : (1) low pressure (a few milli-torr to a few tens of torr) to high pressure (> 100 -350 torr) operation, (2) operation with a floating substrate holder, (3) operation with a water cooled or heated substrate holder, (4) high pressure operation (100-350 Torr), and reactor scale up by (5) varying the excitation frequency; i.e. 915MHz versus 2.45GHz excitation. The basic design concept of the MCPR will be briefly reviewed and then each of the structural modifications that address the above mentioned (1) – (5) design variations will be briefly described. Recently developed reactor designs for high pressure diamond synthesis will be described [2,3]. Experimentally measured discharge behavior, i.e. size, location, shape and absorbed power density versus pressure, substrate position and geometry, input power and methane concentration will be presented. Then a general understanding of reactor performance versus the multi-dimensional experimental operating space, i.e. an operating field map for a reactor design, will be presented. Methods of CVD process control based on the knowledge of the operating field map are described and examples of high rate multi-carat single crystal diamond synthesis will be presented.

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SURFACE WAVE DRIVEN AIR-WATER PLASMAS

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There exists growing interest in the potential applications of microwave plasmas at atmospheric pressure since such plasmas may enable lower facility and process costs for a variety of plasma processing techniques currently performed under vacuum conditions. In this respect, waveguide-based atmospheric plasma sources driven by surface waves (SWs) are an attractive alternative to classical sources, since they are compact, electrodeless, economical, and easy to operate.

In the present work we investigate both theoretically and experimentally a microwave driven air-water plasma as a source of active species of practical interest such as $O(^3P)$ ground state atoms, UV radiation, plasma-generated NO(X), etc. A theoretical model based on a self-consistent treatment of particle kinetics, gas dynamics, gas thermal balance, and wave electrodynamics is used to analyze the performance of this plasma source. The model includes coupled equations for the plasma bulk describing the kinetics of free electrons and of excited electronic states of molecules and atoms [$N_2(A)$, $N_2(B)$, $N_2(a')$, $N_2(a)$, $N_2(C)$, $N_2(a'')$, $N(^2D)$, $N(^2P)$, $O_2(a)$, $O_2(b)$, $O(^1D)$, $O(^1S)$], the chemical kinetics involving neutral molecules and ground state atoms [N_2, O_2, N, O, O_3, NO, N_2O, NO_2, NO_3, N_2O_5, H_2O, H, H_2, OH, HO_2, H_2O_2, NH_3, NH_2, NH, HNO, HNO_2, HNO_3], the kinetics of positive [N_2^+, N_4^+, O^+, O_2^+, O_4^+, NO^+, NO_2^+, N_2O^+, H_2O^+, H_3O^+, H_2^+, H_3^+, HN_2^+, NH_3^+, NH_4^+] and negative $[O^-, O_2^-, O_3^-, H^-, OH^-, NO_2^-, NO_3^-]$ ions, the gas thermal balance and the equation of mass conservation for the fluid as a whole. The wave dispersion and power balance equations are further incorporated into the system of equations. This model describes both the SW driven discharge zone and its flowing afterglow. The predicted plasma-generated NO(X), $O(^3P)$, $O_2(a^1\Delta)$ concentrations, and the intensities of atomic oxygen lines and NO(γ) band radiation along the source are presented and discussed as a function of external parameters. The relative concentrations of NO(X), HNO_2, NO_2 species in the exhaust gas stream of the source have been measured by mass analysis and FT-IR and compared with the model predictions. Emission spectroscopy has been used to detect the plasma spectra emitted in the 250−850 nm range. The oxygen atomic lines at 777.4 nm, 844 nm and 630 nm, and the NO(γ) band radiation in the range 230−260 nm have been detected. Potential biomedical applications of this source such as NO-therapy and plasma decontamination are addressed.

FREELY LOCALIZED AND SURFACE MICROWAVE DISCHARGES

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In the review the researches executed at Faculty of Physics of the Moscow State University, and devoted to studying of the microwave discharges created both in motionless air, and in supersonic air-hydrocarbon streams, are considered. The basic properties of two types of microwave discharges are examined. The volumetric freely localized microwave discharge created by the focused beam of electromagnetic energy in the fixed place of free space is the first type of the discharge. The second type is a surface microwave discharge created by a surface wave on the dielectric antenna. Discharges were created inside a metal chamber of 1 m in diameter and of 3 m in length in a wide range of air pressure $p = 10^{-3}$ – 760 Torr. Pulse microwaves generators of centimetric waves were used: $\lambda = 2.4$ cm, 4.3 cm, 10 cm and 12.24 cm. Duration of pulses could change from 1 up to 150 μs for the first generator, from 5 μs up to 1 s for the second one, and pulse duration for the third one is $\tau = 3$ μs. The forth generator works in continuous regime. Parameters of generators allowed changing of a power stream density brought to the discharges from 10^1 up to 10^5 W/cm^2. For discharge initiation at atmospheric air pressure various initiators were used: metal-dielectric contact, low-current spark discharge, laser spark. Prominent feature of the microwave discharges is their propagation in the direction of a radiation source, at this the more power brought to the discharges, the faster discharges are moved. Space-temporal evolution of key parameters of the discharges was investigated: intensity of an electric field, electron density and temperature, vibrational and translational temperatures, discharge propagation speed, gas heating rate, hydro- and gas-dynamical perturbation in zone of discharge existence, and so on. For management of key parameters of the discharge the mode of programmable regime is offered and investigated by us. This regime allowed to locate the discharge and permanently to support it in the fixed place of free space. The microwave discharge may find applications in such fields as super- and hypersonic plasma aerodynamics, flow control near the surface of a body moving in dense layers of atmosphere, reduction of surface friction, optimization of ignition and combustion stabilization of supersonic gaseous and liquid fuel flows. Microwave discharges may also be used to advantage in development of new plasma sources for micro- and nana-electronics (plasma treatment of surfaces, etching, and film deposition), etc.

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EXPERIMENTAL CHARACTERIZATION OF SILICA PLASMOIDS EXCITED BY LOCALIZED MICROWAVES

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The plasmoids studied in this paper are obtained by directing localized microwave power (<1kW at 2.45 GHz) into a solid substrate (e.g. silicon) hence creating a hotspot from which the plasmoid is blown up to the air atmosphere within the microwave cavity [1]. The paper reviews the characteristics of such microwave-excited plasmoids (fireballs) measured by synchrotron small-angle X-ray diffraction (SAXS) and by scanning-electron microscope (SEM) [2-4], and presents new experimental results obtained by Langmuir probe, microwave scattering, and optical spectroscopy. Microwave spontaneous emission is detected at various frequencies during the fireball evolution, including the second harmonic of the microwave-excitation frequency. Plasma characteristics of these plasmoids (the electron density and temperature) are estimated, and their dusty-plasma features are discussed. Their resemblance to the natural ball-lightning [1] is reviewed, and their potential applications (such as a direct means for conversion of solids to powders [3] and igniters for thermite reactions [4]) are discussed.

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NONLINEAR PHENOMENA INHERENT IN MICROWAVE DISCHARGE PHYSICS AS A BASIS OF A NEW PLASMATRONS DEVICE

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Investigations of fundamental problems of microwave gas discharges (MD) made it possible to create a new microwave plasma sources designed and suitable for physical laboratory research as well as for some applications.

The following physical phenomena, revealed and investigated in the last decades provided the basis for these plasma sources (microwave plasmatrons):

- Low threshold MD (sparks) at a metal-dielectric interface [1];
- Thermal-ionization instability of self-non-sustained MD attaining strongly nonlinear phase [2-3];
- "Plasma resonance" phenomenon consist in the totality of nonlinear processes, occurring where the plasma density of nonmagnetized plasma approaches the critical value $n_{ec} = m(\omega^2 + \nu_{eff}^2)/4\pi e^2$ on its essentially nonuniform profile (here, ν_{eff} is the effective frequency of electron-neutral collisions, ω is cyclic frequency of microwave radiation) [4].

Three type of microwave gas-discharge plasma sources based on the list phenomena have been elaborated, investigated and applied for some technologies:

- Coaxial microwave plasmatron ;
- "Microwave Arc" and
- "Biresonant" plasma source .

Results of experiments for studying the characteristics of plasma generated by these plasmatrons are described. Role of the above mentioned fundamental peculiarities of microwave discharges are revealed. Field of applications of a new microwave plasma sources is analyzed.

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INVESTIGATING A COAXIAL MICROWAVE PLASMA

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In this work we present a microwave plasma device intended for thin film deposition. The plasma is a surface wave sustained discharge that operates at low pressure p<1 mbar in a coaxial configuration stabilized by a central quartz tube enclosing a microwave antenna. In this configuration the plasma is the outer conductor in a coaxial transmission line.

At very low pressure, or high electron energy losses, the surface wave discharge turns into a mw-radiation coil plasma. That means the coaxial structure does not determine the shape any longer. At higher pressure (above 20 mbar in Ar) the discharge is confined to the central tube, while it shows a variety of contraction-related phenomena.

The ignition condition is analyzed in terms of input power with respect to the underlying electron particle balance and electron-wave interaction. Moreover we studied by basic diagnostics of the emitted continuum and line radiation the electron gas properties. Absolute calibrated continuum radiation in an Ar-plasma allows determining the electron density, while absolute calibrated line radiation in combination with a collisional radiative model determines the electron density [1]. This combination of techniques was extended to molecular loaded plasmas. Finally molecular radiation of H_2 could be used to determine rotational temperatures.

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ELECTROMAGNETIC VIBRATOR NEAR METAL SURFACE AS INITIATOR OF SUBCRITICAL MICROWAVE DISCHARGES

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Development of distributed regular systems of microwave-discharged plasma regions generated in weak electromagnetic fields of a remote low-power MW radiation source is of great interest from the point of view of a variety of applications such as plasma aerodynamics, plasma stimulated combustion, plasma chemistry, etc. Thus, last years new boundary-layer control method based on creation near a model surface of localized zones of energy release are actively studied [1,2]. In this respect one should point works [3,4] where authors offered and investigated principally new-type of liner electromagnetic vibrators located in close vicinity of a metal screen-reflector. This design gave exciting possibility to solve two basic electrodynamic problems: (i) generate MW discharges in very low electric fields (down to 100 V/cm and less) of a low-power quasioptical electromagnetic beam, and (ii) overcome the obstacle of strong electromagnetic interaction of parallel vibrators in system, excitation of a multi-mode field structure and, thereby, production of non-uniform distribution of induced fields and densities of electromagnetic energy.

The results of long-term theoretical and experimental investigations of regular multi-systems of initiators of MW discharges based on their different designs are presented in this report. Influence of various parameters both of a single initiator and of an array of initiators (including their shapes, dimensions and materials) on characteristics of induced local electromagnetic fields and plasma formations is considered in detail.

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GENERATION OF A LASER-PLASMA ION FLOW IN A MICROWAVE CAVITY

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The possibility of obtaining an additional flow of laser plasma ions to the near-boundary surface is being experimentally investigated by passing microwave-range electric current through the plasma.

Electric current leads to redistribution of the space charge and formation of near-electrode zones, with voltage drop much greater than the plasma temperature. Therefore, one should expect (as in the gas discharge) that the energy of ions going to the surface will be the same as the near-electrode voltage drop. However, in the case of gas discharge plasma as the external source frequency increases, the energy of ions going to the surface decreases, so that in the microwave frequency range the effect of plasma-surface interaction is not observed. With increasing frequency the oscillation amplitude of electrons also decreases, and in the microwave range it becomes smaller than the Debye length. The situation is different in dense laser plasma (10^{15}-10^{17}cm^{-3}) for an area of several GHz. The electrons passing through the screening layer manage to leave the bulk, charging the plasma and increasing the positive space charge layer that forms an ion flow to the surface. Nevertheless, such investigations have not been performed yet.

To inject microwave energy into the plasma we use a toroidal cavity resonator in which laser plasma is initiated in the area of toroidal resonator capacitor. A 2.47 GHz magnetron, which is switched on synchronously with the plasma-initiating laser pulse, is used to create microwave oscillations. Control of the magnetron power supply makes it possible to regulate the delay (with respect to the laser pulse leading edge beginning with 0.1 μs) and duration (from 0.5 μs and higher) of microwave pulses. The operation frequency of the pulse-periodic laser-plasma setup [1] is in the range from 1 to 100 kHz. The microwave generator has a pulsed power of 5 kW, and a mean power of 1.5 kW. A circulator (0.3/26 dB) is used for stable operation of the magnetron with respect to the reflected wave in the microwave channel. The passed and reflected waves, as well as the field in the cavity, are recorded in the experiment. The created near-surface electric field is estimated using measurements of the Stark broadening of ion lines.

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NEW MICROWAVE PLASMA SOURCE IN WATER

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Investigations concerned with the fundamental problem of microwave gas discharges, which carried out at the General Physics Institute of RAS (GPI RAS), made it possible to create a new microwave plasma source which is suitable for physical laboratory research as well as for some applications

Three types of microwave gas discharge plasma sources have been elaborated, investigated and applied to some technological problems at the GPI RAS: [1-3] The new type of microwave plasma source is shown schematically in Fig.1.

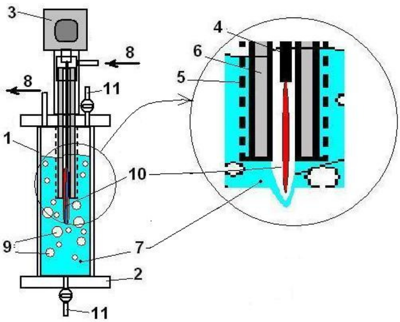

Fig.1. 1-Organic glass cylindrical tube, 2-end flanges, 3-magnetron (N=850 W, f=2.45 GHz), 4-inner electrode, 5-outer electrode, 6-quartz tube around the inner electrode, 7-liquid (water),8-gas inlet/outlet, 9-gas babbles, 10-plasma jet, 11- water inlet/outlet.

The design of the plasma source allows for operation in liquid. The water is expelled from the quartz tube by the admitted gas, which makes it possible to generate a plasma jet. There are two operating regimes depending on the gas flow rate. At large values of the gas flow rate, the plasma jet is formed totally from the injected gas. When the gas flow rate is decreased, the plasma jet is formed from a mixture of the gas with water vapor.Results of experiments for studying the characteristics of plasmatron is described. Field of applications of a new microwave plasma source is analyzed.

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III. MICROWAVE PLASMA APPLICATION

PRETREATMENT OF BIOMASS BY ATMOSPHERIC PRESSURE MICROWAVE PLASMAS

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Nowadays, increasing attention and effort are focused on the production of renewable fuels, especially bio-ethanol from lignocellulosic biomass. This process generally involves hydrolysis of the cellulose to produce simple sugars. Sugarcane biomass consists of cellulose, hemicelluloses and lignin, which are packed together in the cell wall. To reach a fermentable condition, the biomass requires relatively harsh pretreatment processes. Some important objectives of the pretreatment of biomass are to break the lignin-hemicellulose complex, increase the porosity of the biomass and disrupt or loosen-up the crystalline structure of cellulose.

In this work, 2.45 GHz microwave plasma torches operating at atmospheric pressure in Ar-steam-air mixtures and in pure air plasmas have been applied for sugarcane bagasse pretreatment [1]. Sugarcane baggase, crushed to a size of 0.5 mm, is supplied by *Usina da Pedra*, *Brazil*. The samples of dry biomass (~2 g) have been exposed to the afterglow plasma jet at different distances from the discharge end (d = 2 – 10 cm) and were treated for different exposure times (t = 2 – 20 min). Scanning Electron Microscopy (SEM) has been applied to analyze the morphological changes of the treated samples. The results demonstrate that prolonging the exposure time increases the morphological changes of the surface. The porosity of the sample tends to increase with the delivered microwave power and the total gas flow. The exhaust gas streams have been analyzed by mass spectrometry and Fourier-Transform Infrared Spectroscopy (FT-IR). Optical emission spectroscopy has been applied to identify the main active species and determine the gas temperature axial profile. The results obtained demonstrate significant surface modification due to the plasma etching effect leading to the destruction of the lignin layer.

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MICROWAVE DISCHARGE IN INTERSECTING MILLIMETER WAVE BEAMS AND ITS APPLICATIONS

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The paper reviews the studies of a new type of the microwave discharge produced in gases by millimeter-wave radiation in wave beams. Such a discharge is characterized by high plasma density, whereas wave beams allow one to control the form and size of plasma formations maintained both in free space and near surfaces of various materials. The paper presents the results of studying dense plasmas in microwave discharges, which are maintained in crossed beams of electromagnetic waves in free space by radiation of gyrotron, i.e., high-power source of microwave millimeter-wave radiation. The results of using such plasmas for advancing the technique of chemical deposition of diamond films from the gas phase are discussed. Facilities based on millimeter-wave gyrotrons are compared with conventional setups based on decimeter-wave magnetrons and used in plasma technologies. The presentation demonstrates the potentials of a plasma CVD reactor based on the 15 kW/28 GHz gyrotron as an example.

APPLICATION OF THE ECR PLASMA IN MICRO- AND NANOELECTRONICS

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In this work we describe some results of the cold plasma application for different nanotechnology samples manufacturing. Microwave plasma under electron cyclotron resonance conditions (ECR) appears a lot of advantages in comparison with others plasmas and could be applied for different precise technological processes. Cold plasma systems have become a very important tool for the nanotechnology processing including semiconductors, thin films and the production of polymers, the modification of materials, isotopes separation and others. The technology is used in all industries that require advanced materials, surface treating and other processing.

There are basically three types of cold plasma systems in use these are capacitance driven discharge, inductively driven discharge and the electron cyclotron resonance (ECR) discharge. Of the three, the ECR is the most advanced system and it probably has the best future ahead of it. ECR systems are important for these reasons: 1) the 2.45 GHz frequency produces the highest fraction of ionized (>0.1) sand excited species; 2) no high voltage sheat is present since the ECR accecelerates the electrons to where ionization and excitation takes place; 3) the ECR region is adjusted by the axial magnetic field of the source. This allows remote location of the plasma from the target eliminating particles and high energy bombardment; 4) Multipole magnetic field filters are used as mirrors to keep the plasma off the chamber walls.

These characteristics allow better control of the chemistry parameters, eliminating of contaminants and more stable operation. In the semiconductor field these units have been used deposition, etching, and epitaxial growth. Such wide area of application demands the different configurations of the ECR plasma sources and technological set up.

Experiments were made in plasma streams produces by the different design of the ECR plasma sources attached to a stainless steel chamber. Impedance of the microwave transmission line was controlled by tuner based on vector-reflection-coefficient measurement. Two adjustable magnetic coils surrounded the source chamber forming a Helmholtz pair.

In this paper we described some recent results of the application of the ECR plasma for nanotechnology processing, including microwave high power wide-band-gap devices with the T-shape gate, microbridges of the bolometric matrix manufacturing, sensors located directly on silicon readout ICs.

CONVERSION OF SILICON TETRACHLORIDE IN MICROWAVE PLASMA

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Due to the increased interest to development of new technologies of photovoltaic, the main task is the investigation of the mechanisms of silicon deposition from its halogenides under different types of discharge.

In this work the processes of plasma chemical conversion of silicon tetrachloride into silicon are investigated as well as other products of reaction under microwave discharge with frequency of 2.45 GHz at reduced and atmospheric pressures. The experiments were carried out at input power of 900 Wt. with pressure in reactor of 50 and 760 torr.

It is shown that the conversion degree of silicon tetrachloride is 95%. During the increase in energy contribution the increase in silicon yield up to 90% is observed. The yield of hexachlordisilane (Si_2Cl_6) and of polysilanechlorides decreases with the increase in energy contribution. Introduction of reagents in afterglow zone leads to intensive polymerization of chlorosilanes with the yield up to 20%.

Investigation of the conversion process of silicon tetrachloride under atmospheric pressure was conducted in reactor with plasma source in the form of torch discharge in the point of metal electrode. This design of reactor makes it possible to generate the torch discharge at atmospheric pressure using helium or hydrogen as the plasma-forming gas. Experiments have shown that with such organization of process the formation of polysilane chlorides also takes place. Addition of helium into plasma-forming gas leads to more stable combustion of discharge and to greater yield of polychlorosilanes of 40%.

The obtained results make it possible to assume the main plasma chemical reactions taking place in the zone of plasma chemical discharge.

STABILIZATION OF COMBUSTION OF HIGH-SPEED HYDROCARBON-AIR STREAMS UNDER CONDITIONS OF THE COMBINED MICROWAVE DISCHARGE

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Ignition and combustion of high-speed air-hydrocarbons streams under condition of programmable discharge [1] were investigated. Stabilization of external combustion of high-speed propane-air, alcohol-air and alcohol-propane-air streams was experimentally realized [2, 3]. Installation includes the vacuum chamber; receivers of a high pressure of air, propane and alcohol; system for creation of a supersonic stream; magnetron generator; synchronization system and diagnostic equipment. As a source of a microwave energy serves the pulse magnetron generator ($\lambda = 2.4$ cm; $W_p < 100$ kW; $\tau_p = 5–150$ μs; period to pulse duration ratio $Q = 1000$). The air mass consumption could be varied from 10 to 125 g/s, propane – from 1 up to 7 g/s, and alcohol – from 0.5 up to 1.5 g/s. Pressure of motionless air in the vacuum chamber – from 40 up to 760 Torr. It was shown, that in conditions of the combined discharge in a subsonic stream there is a full combustion of liquid and gaseous hydrocarbons. In conditions of supersonic streams completeness of fuel combustion changes from 100 to 80 % depending on a stream speed. At alcohol combustion the thermal stream grows in 7 times and at propane combustion – in 15 times in comparison with a heat stream from the discharge in air. Electron density, measured on distance of 10 cm from electrodes downwards on a stream, is less than 10^9 cm^{-3} at creation of the discharge in air stream, reaches of $2{\cdot}10^{11}$ cm^{-3} at alcohol combustion, and is equal $3{\cdot}10^{11}$ cm^{-3} at propane combustion. The flame temperature in the field of the discharge existence changes from 2000 up to 2500 K, and outside of the discharge on distance of 20 cm from electrodes is about 1800 K gradually decreasing downwards on a stream. The received results confirm efficiency of use of the combined microwave discharge in plasma aerodynamics.

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THERMITE IGNITION BY LOCALIZED MICROWAVES

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This paper presents an ignition technique for pure thermite powders by low-power microwaves (<100 W) [1]. The microwave energy is supplied locally to the powder to create a confined hotspot within the powder. Due to the thermal-runaway instability, the hotspot temperature exceeds the ignition temperature of the thermite mixture hence a self-propagating combustion is initiated in the entire powder volume. A miniature solid-state microwave-drill device [2] feeds an open-end coaxial applicator inserted into the thermite powder as a local igniter in the experimental setup. Fe_3O_4-Al thermite powder ignition and its consequent flame ejection are observed within ~3 seconds at 2.1-GHz, <100-W microwave injection. The experimental results agree with the theoretical model presented. Practical aspects and potential applications of this mechanism, such as rust conversion, self-propagating high-temperature synthesis (SHS), energy production, and propulsion, are discussed.

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DIAMOND FILM DEPOSITION BY MICROWAVE PLASMA TORCH AT ATMOSPHERIC PRESSURE

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The microwave torch discharge is used for diamond film deposition that is carried out by the continuous power of 1kW magnetron of a home oven at the frequency 2,45 GHz. Gas jet on a mixture of technical gases: argon and hydrogen with pure methane at atmosphere pressure (in relation 1:0,2:0,003) were used for the process. The polycrystal diamond film deposition is realised upon the dielectric (SiO_2), metal (Mo) and composite (WC-Co) substrates with the growth rate 2÷15 μm/h [1].

The high-quality monocrystal layer of the diamond on a synthetic HPHT diamond crystal was grown up with the growth rate ~5μm/h under higher contents of methane in relative to hydrogen i.e. 1:0,2:0,05 [2].

The diamond growth is accompanied a bright torch optic emission in blue-green part of its spectrum. By means of the intensities rate of spectral line C_2 (carbon) radiations compared with H_α (hydrogen) radiations it is possible to define that the chosen mode of diamond deposition is optimum, what in our condition it turned out to be ~1. The methane excess leads to formation increased density of the radical C_2, but owing to high concentration of absorbed power in the torch ($>10^3$ W/cm^3.) this does not stimulate growth a graphite phase on substrates. This allows to consider that radical C_2, serves also as building material of the diamond lattice.

Positive results of diamond deposition are attained for the cutting tools made from hard composite (WC-Co) with aim increase of their toughness and lifetime.

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HYDROGEN REDUCTION OF SILICON TETRAFLUORIDE IN PLASMA SUSTAINED BY DIFFERENT ELECTRIC DISCHARGES

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The deposition processes of silicon from the (SiF_4 + H_2) mixture in form of nanocrystalline films and polycrystal flakes with characteristic linear size of 3-5mm in inductively-coupled RF-discharge (13,56 MHz) as well as in form of nanosize amorphous particles in the microwave impulse surface MW discharge (2,45 GHz) have been studied. In experiments using the 13,56 MHz discharge the optimization of the technological process parameters has been carried out. The dependence of the yield of the silicon on the pressure, reagents ratio and energy input has been studied. The maximum silicon yield at P=0,2 Torr for the the reagents ratio H_2/SiF_4=1:6 was observed. The possibility of silicon deposition with conversion degree of 57% has been shown. In the optical emission spectra of plasma at these conditions the intense emission at 440 nm assigned to SiF species has been observed.

In the the experiments using 2,45 GHz discharge the possibility of obtaining of silicon powder at higher pressure in the reactor equal to 300-700 Torr has been shown. In the corresponding optical emission spectra in the range of 250-650 nm a number of intensive emission lines have been registered. The lines at 250nm, 260nm, 290nm, 522nm have been assigned to excited Si species and at 335, 440nm –to excited SiF. fragments. The emission at 390 refers probably to the mixture Si + SiF.

Based on obtained results it could be proposed that the formation of SiF fragment is the most probable intermediate for the pathway of silicon deposition.

SILICA FIBER OPTIC PROBES FOR THE LUMINESCENT CANCER DIAGNOSTICS PRODUCED BY THE MICROWAVE DISCHARGE AT A LOW PRESSURE

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Plasma chemical methods of the fiber preform production are the most advantages in the modern technology of optical fibers.

In order to increase the efficiency of the plasmochemical deposition of the silica glass doped by fluorine we proposed MWD excitation device operating in the H_{10}-mode (f=2,45 GHz, P=2,0 kW) [1].

It is known that under performing of photodynamic diagnostics (PDD) of tumours, it is necessary to radiate relatively large surfaces of bio-object tissues. The higher light-diode numerical aperture (NA), the more light radiation modes are spread along the fiber and the larger surface area will be affected by radiation. The number of modes in the fibers grows much faster than liniearly as the NA increases for a fixed core size and operating wavelength. Small gains NA can nave great benefits. In FIRE RAS by microwave plasmochemical deposition method at a low pressure (PCVD), quartz preforms of fiber light-guides composed of SiO_2+F/SiO_2 (SiO_2 — core, SiO_2+F — reflecting cladding) with increased value of NA up to 0,35 were developed. The drawing of the optical fibers from the obtained preforms was carried out by known technology with graphite furnace application.

On the basis of the obtained light-guides, fiber optic probes, containing in its design central optical fiber composed of SiO_2+F/SiO_2 with core diameter 200 μm and NA~0,32 for luminescence excitation, as well as 12 periphery fibers of the similar composition and geometry for luminescence detection, were developed.

The further probes approbation in the bio-object study showed its good efficiency. The questions of plasmochemical process parameters and silica glass layer deposition are also discussed.

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PLASMA GENERATED BY MICROWAVE IRRADIATION INNER CARBON ABSORBENTS PORES FOR HIGH DISPERSED CATALYST PREPARATION AND TOXIC COMPOUNDS DEGRADATION

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In this work the results relate to research of microwave irradiation (MWI) influence on substrates conversion followed by adsorption into carbon adsorbents pores are presented. We studied microwave irradiation action on the sorbents with using home installation set-up equipped with magnetron (2450 MHz) and flow reactor-resonator located in waveguide. Carbon adsorbents were prepared on based of natural coal and renewable biomass (campfire flax; rice husks; bone of fruit).

The theoretical analysis of black body model taking into account dielectric constant, particle size, wavelength and penetration depth of electromagnetic field in a particle, showed satisfactory agreement between calculated dynamics of heating and experimental data. Under microwave action carbon adsorbents heated up rapidly with plasma formation. The time of exposition around 20 sec is enough to reach 850-900^{0}C at I = 200 μA and V = 4,5 - 5 KV.

Inorganic natural impurities in the coal adsorbents as well as nanoparticles of iron gamma-oxide forming directly on the adsorbents surface significantly increase heating rate. It was shown, that size of the pores also affects significantly on heating speed and plasma appearance: the higher $V_{macropores}/V_{micropores}$ ratio the faster grains heating up speed. Macro pores may be considered as pseudo-capacitors, in which volume bulk carriers of charge emerged that led to disruption processes initiation and subsequent plasma arising. So micro pores may be considered as surface irregularities make for amplification of MWI absorption according to Fowler- Nordheim effect.

Experiments with MWI were carried out into two directions:1- iron catalyst formation for oxidation of hydrogen sulfide to sulfur reaction; 2- fast degradation of toxic phosphorus-containing compounds and tar oil. Particles of γ- Fe_2O_3 with size of 4-6 nm were formed under MWI at 500^{0}C during 15 min of exposition on the carbon adsorbent containing preliminary adsorbed $Fe(acac)_3$ complex. Convective heating of the same support led to 10-15 nm iron oxide clusters during 5-8 h of heating at the same temperature.

Complete degradation of 20-30 wt.% phosphorous substrates and tar oil preliminary absorbed by coal sorbents under microwave irradiation was reached at 300-600^{o}C during 10-15 min.

CONTROL OF ELECTROMAGNETIC BAND GAP DEVICES BY DISCHARGE PLASMAS

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Different electromagnetic band gap (EBG) structures have received growing attention in recent years. In the various EBG materials, most of them are realized by artificial metallic structures such as using wires to produce effective negative permittivity. Glow discharge plasmas have high potentials as effective control elements in these devices [1]. In this report we present the results of the microwave propagation through the both the waveguide band-pass filters and EBG structures formed by metallic rods in combination with the plasma columns.

Two microwave band-pass filters were designed using the waveguides at dimensions of 23 × 10 mm^2 and 90 × 10 mm^2. Regular structures in waveguides are formed by metallic rods in combination with the discharge lamps (GSh-5) located perpendicular to the wide walls. For first case the transmittance attenuation up to 40/50 dB at the frequency band of 7.5 GHz is demonstrated. For second, possibility to control the transmission level in the range from 0 to -25 dB by changing of the GSh-5 discharge current from 0 to 70 mA was demonstrated. There is a good agreement between experimental results and the simulation by HFSS Ansoft commercial software.

Another series of experiments were carried out with a space triangular EBG structure [1] formed by a square network of metallic rods and modified for the frequency of 8.8 GHz. Using the GSh-5 plasma columns as defect or defect compensator in the EBG interface the microwave propagation at direction of 45° are observed. The signal level in this direction can be changed on about 10 dB at the discharge current variation up to 120 mA. The triangular EBG structure was tested at high microwave pulse power of about 50 kW.

Electron densities in the atmospheric pressure glow discharges [2] can reach 10^{15} cm^{-3}. In the experiments it was attempted to use these discharges as a defect compensators and control elements of the microwave band devices.

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CERTAIN PECULIARITIES OF ELECTRON DYNAMICS AND HEATING UNDER MICROWAVE RADIATION

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Using concepts of statistical physics a simple approach to describe electron transfer and heating in substance under the force of electric field is developed [1]. This approach enables to obtain electron drift velocity (V) and heating energy (ε) as a function of electric field strength (E). Two substantial properties of electron forced transfer and heating, earlier not taken into account, are revealed and demonstrated for gas-like matter of atoms (with mass M), where electrons (with mass m) are scattered elastically and isotropic (since $m<<M$).

It is shown that relaxation time (τ_P) of electron transfer momentum ($P_E=mV$) is not equal to electron mean free-path time (τ), as usually assumed, but is much more. As found the value of $\tau_P/\tau \equiv Z$ varies in the range Z=16÷4 with ε grows at E increased. Obtained value Z=16 for weakly heated electrons means that drift velocity of such electrons, calculated at assumption $\tau_P=\tau$, is underestimated by 16 times. It is also established that dynamics of electron forced transfer must be described by effective mass, which in matter considered is equal to M/Z. This fact means that usually used integral relation of V value with electron velocity distribution function should be reduced by M/Zm times. This result gives that velocity distribution function of strongly heated electrons at high E is significantly anisotropic despite used assumption of its very small anisotropy.

Obtained results let first explain observed distinctive $V(E)$ dependence in rare gases and “anomalously” fast electron transfer in tokamaks and at Bohm diffusion, indicating the consistence of theoretical approach developed.

In report the applicability of established properties of electron stationary forced transfer and heating to electron dynamics upon microwave radiation are considered in view of relation between τ^{-1} and radiation frequency. Also, the important peculiarity of electron dynamics due to influence of microwave cosmic radiation, which determine electron “wave” behavior, is specially note.

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POSSIBILITY OF APPLICATION OF MW DISCHARGES ON A DIELECTRIC GRID EXCITED IN THE FIELD OF A QUASIOPTICAL ELECTROMAGNETIC BEAM FOR PLASMA-ASSISTED COMBUSTION

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At present for solution of a number of aerodynamic and combustion problems various plasma technological approaches are considered. In this report possibility of application of microwave (MW) discharge generated on a dielectric net in the combustion zone of a channel of a ramjet engine is analyzed in detail.

By this time wide accumulated experience of research of pulse initiated subcritical MW discharges with spatially developed streamer volumetric structure initiated in the field of a quasioptical MW beam demonstrated their exciting possibility to ignite high-speed combustible gas mixtures, to stabilize their combustion area in space and increase gas burning rate [1]. The speed of discharge front propagation from the discharge initiator toward the MW radiation source also significantly increases.

Previous experimental works on creation of such discharge on a dielectric plate surface have shown that their stream channels “run” only along this dielectric surface [2, 3]. New experiments on generation of similar MW discharges on a wire-dielectric net highlighted that even in this case streamer channels also propagate only along dielectric fiber surface.

This unique property and characteristics of microwave discharges on dielectric nets demand detailed research. However already today there are all bases to raise the question about application of this-type discharges in the combustion chamber of the modern ramjet engine. At that probably the need of braking of air flow at the engine channel inlet will disappear, the fuel burning efficiency will increase and its combustion zone length will decrease.

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IV. POSTERS

EOS, PROBE AND X-RAY MEASUREMENTS MIRROR CONFINED LOW PRESSURE ECR-PLASMA

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Electron cyclotron resonance (ECR) plasma is widely used for different applications due to its attractive features that high plasma density can be obtained at low pressures. A resonant energy coupling between the wave and the electrons occurs whenever electrons cross a particular magnetic surface where the cyclotron frequency is equal to the wave frequency. This leads to an increase in the velocity component perpendicular to the magnetic lines and the heated electrons are confined in mirror magnetic trap. The argon plasma (within the range 1 10^{-5} – 1 10^{-4} Torr) was created by launching a 2.45 GHz HF-wave (700-2500 W) equal to the cyclotron frequency at 0.0875 T, under mirror magnetic configuration (R - 1.6, L - 12 cm). The details of the experimental apparatus have been described in [1]. We investigate behavior of main plasma parameters under change of discharge mode's which influence strong on generated under gyromagnetic autoresonance relativistic plasmoids. For the measurements of the electron temperatures and densities of bulk-plasma (cold component) comparative measurements with Langmuir probe, and with optical emission spectroscopy OES and TRG methods was used [2, 3]. Investigation of properties of the hot component fulfilled by X-ray spectrometry and imaging techniques (pinhole X-ray CCD camera). In particular, we take notice of the effects of the magnetic field strength under stable mirror configuration, pressure, and input HF-power on plasma parameters i.e. temperature of electron's components and their densities. Experimental investigation showed that the electrons of produced plasma can be grouped into three populations, i.e. the cold, warm and hot ones, and parameters each of them strongly depends on above mentioned discharge modes. As a result, it was found out that the increasing of magnetic field's strength was valid due to the both effects of plasma confinement and temperature anisotropy.

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MICROWAVE AUTORESONANCE PULSE-PERIODIC PLASMA ACCELERATOR

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Nowadays various methods of the relativistic plasma generation are known. However, in the majority of them the energy price of accelerated particles is enormously high. For numerous applications: non-destructive control methods, different technologies, a number of biological and genetic research, medical purposes there is a need in compact sources of high-energy particles and X-radiation with a spectral energy range 10-1000 keV**.** Along with, power consumption must be temperate and the source of radiation must be electrically safe.

A possibility of relativistic plasma generation under conditions of gyromagnetic autoresonance (GA) heating of microwave plasma was shown first in [1]. The maximum energy, is limited only by radiation losses and its average kinetic energy (in keV) is defined by the magnitude of the magnetic field and it does not depend considerably on microwave field intensity: $W(t)=511[B_{max}/B_0 - 1]$.

Specificity of the report consists in physical principles of the device operation based on GA effects and the results obtained by simulation (particle-in-cell method) and experimentally of the most productive and the most effective operating conditions of the device [2].

Numeric modeling and experimentally obtained results showed the possibility of generation stable relativistic plasmoids with controlled parameters (power and angular distribution of bremsstrahlung radiation. Fulfilled investigations allowed us to analyze the dependence of electron's trapping in GA-regime, hot-plasma localization and its energetic spectrum on working modes of installation to tune the proposed source in order to generate bremsstrahlung with a priory given output parameters in quite broad limits.

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INVESTIGATION OF THE PUMP BACKSCATTERING IN UPPER HYBRID RESONANCE

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As was recently shown, anomalous reflection of electromagnetic waves that are caused by the parametric decay instabilities (PDI) of induced scattering, is accompanying the HF-heating of plasma in magnetic confinement [1]. The PDI may lead to anomalous backscattering [2], redistribution of the heating power and acceleration of ions.

In this report the results of model experiments on interaction of ECR frequency range microwave pump with inhomogeneous plasma are presented. The experiments were carried out on the linear plasma device “Granit” [3], where magnetic field varying from more than 0.3 T at the magnetic system end to less than 0.05 T in the center was formed. Using the waveguide 72 x 34 mm^2 a microwave power at frequency f_0 = 2.1 -3.5 GHz is launched. The microwave electric field is perpendicular to the external magnetic field in the quartz tube which passes through the holes in narrow walls of the waveguide.

As it was shown, the upper hybrid resonance (UHR) exists in plasma for a wave at frequency f_0=2.35 GHz for magnetic fields in the range of 0.053-0.085 T. The value of the electron density at the lower magnetic field boundary was estimated to be $n_e \sim 4.4 \times 10^{10}$ cm^{-3}. At the incident wave power less than 2 W, the spectra of scattering on the fluctuations in the UHR region were registered. The spectra dependences on the magnitude of external magnetic field, incident wave frequency and its power were determined.

The absorption dynamics for the microwave pulses (1-10 μs) was investigated at power up to 150 W. With help of the registration of the light emission distribution it was shown that the region of maximum microwave power absorption is shifted from the center of the plasma column to it’s periphery when the magnetic field is changed from 0.05 T to 0.085 T. In the spectra of scattering the low-frequency oscillations were observed, which may be associated with excitation of parametric instability in the UHR region.

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MICROWAVE HEATING OF CERAMIC PLATE TAKING INTO CONSIDERATION THE CERAMIC RADIATION

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Mathematical model of ceramic plate heating in a microwave was developed taking into account the ceramic radiation [1-3].

There is calculation of microwave heating of the plate with Al_2O_3, thickness of which is R_c = 15 mm in chamber of R = 50 mm with air pressure cooled walls: Q_n = 80 kW/m^2, *f= 30 GHz*.
Energy attenuation of the plate essentially changes the heating regime due to the heat radiation of the ceramics and to achieve, for example, temperature of 2000 K, it is require to increase the input power of electromagnetic field in 17 times (Q_n = 700 kW/m^2, Q_d ~ 100 kW/m^2). The predetermined temperature of the plate is achieved within 1.65 hour, i.e. 11 times faster than without consideration of the heat radiation. The flat plate couldn't be heated up to 2000 K if the values of the electromagnetic field would be lower.

During ceramic plate heating in «adiabatic» box the process time is shortened in 1.5 times (t_{max} = 11.8 hours, Q_n=80 kW/m^2, *f=30 GHz*), as compared with heating in cooled chamber walls. In areas of change in resonant dependence of η there is a sharp rise in temperature of ceramics.

Conclusion

It shows that the heat radiation from the ceramic surface significantly influence the regime of plate heating in microwave.

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DESIGN AND PERFORMANCES OF TOP-TO-TAIL MICROWAVE PLASMA SOURCES

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The microwave plasma sources presented are derived from multi-dipolar [1,2] and matrix plasma [3] concepts, where individual plasma sources are used together to achieve uniform plasmas via their distribution over two-dimensional (planar sources) or tri-dimensional (volume plasma) networks. Each kind of these elementary sources operates in distinct pressure ranges, namely from ~1 to 10 mTorr in argon plasma for multi-dipolar and beyond 100 mTorr for matrix configuration. To overcome this limitation and, particularly, to cover the 10-100 mTorr pressure range, a new plasma source has been designed. Based on coaxial microwave applicator ended by top-to-tail magnetic configuration, this kind of source allows highly extended operating conditions in terms of pressure range (from less than 10^{-3} up to few Torr) and microwave power (from ~1 up to several hundred W). Indeed, the resonant ECR absorption, particularly efficient at low pressure, continuously transits to the collisional absorption when the effect of the magnetic field is progressively annihilated by collisions at higher pressure.The microwave applicators serve as impedance transformers between the standard transmission line and the plasma, and, for the design chosen as example, effective coupling is ensured in the low-pressure, low-power range. Without any impedance matcher, the applicator is able to transmit more than 80% of microwave power over up to 2 decades of pressure, from 10^{-3} up to 10^{-1} Torr. An auxiliary impedance matcher was also used in order to ensure energy efficiency of the plasma source close to 100 % over a wide pressure and power range.

The performances of plasma sources in terms of energy efficiency and current density will be presented as a function of pressure (up to few Torr) and input microwave power. The experimental results concern an elementary plasma source as well as 12 and 24 plasma sources implemented on a plasma chamber according to one or two rings.

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CERA-RX (C) – DEPENDENCE OF X-RAY INTENSITY ON ECR DISCHARGE CONDITIONS

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X-ray ECR (2.45 GHz) plasma source CERA-RX [1] has been created on the basis of the coaxial resonator and can operate in pulse as well as in continuous regimes. This source forms X-ray azimuth symmetric flow in radial direction. For creation of the directed radiation of a narrow spectral range (characteristic radiation) the axial electrode of the resonator in the central part has been added by the cylindrical, radial directed electrode-target (CERA-RX (C)). The electrode-target material defines energy of generated quanta of radiation. Energetic spectrum of electrons interacting with the target is defined by dimension of the target and the magnitudes of the static magnetic and the microwave fields.

By computer simulation it has been established:

1. Dependences of power spectra of electrons landed on an electrode-target on the magnitude of the magnetic field and the intensity of the microwave source.
2. Presence of the pulsating electric field due to electrons landing on an electrode-target with the frequency is equal to that of a microwave field.
3. Dependence of intensity of characteristic radiation (copper) on intensity of the microwave field and the magnitude of the magnetic field.
4. Influence of the pulsating electric field created by the electrons landed on an electrode-target on X-ray intensity.

The results of experimental researches are in good conformity with computer simulation and show essential influence of the high-frequency pulsations of the electric field of constant phase interval with microwave oscillation on ECR heating and X-ray radiation in CERA-RX (C). Thus unlike earlier study of the influence of the pulsating electric field on ECR heating [2], in an investigated case auto-synchronization of interaction process has been realized.

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MODELLING OF MICROWAVE DISCHARGES IN COAXIAL GEOMETRY

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Microwave discharges sustained by travelling electromagnetic waves are investigated in the past decades both theoretically and experimentally. The coaxial structure is relatively new type of plasma source, which was proposed recently [1,2]. In the coaxial structure the plasma is produced outside the dielectric tube in a low-pressure dielectric or metal chamber. Usually a metal rod is arranged at the dielectric tube axis. The basic relations in our model are the local dispersion relation [3] and the wave energy balance equation. The plasma is both radially and axially inhomogeneous, so the local dispersion relation gives the dependence between the normalized plasma density and the dimensionless wave number, so called phase diagrams. The axial profiles of normalize plasma density, wave power and electric field components are obtained at various configurations and geometry factors.

We have investigated the coaxial structures which consist of a metal rode at the dielectric tube axis with (a) and without (b) surrounding metal tube. The behavior of the phase diagrams, wave field components and plasma density distribution are compared in different configurations depending on geometrical factors.

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MICROWAVE DISCHARGE IN LIQUID *n*-HEPTANE.

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Recent study showed that in-liquid microwave discharge can be used for decomposition of *n*-dodecane [1]. The system of quarter-wave-length antennas were used to ignite the discharge in liquid and microwave oven was used as source of microwave power.

This paper presents first results on decomposition of *n*-heptane by in-liquid microwave discharge. Experimental setup consists of the metal chamber connected through rectangular waveguides with 3 magnetrons (3x500 W, 2.45 GHz). The waveguides have different orientation relatively each other to prevent damage of one magnetron by radiation of another one. Experiments were run with use of one magnetron. The antenna unit was used for discharge ignition. The antenna unit consists of 3 half-wave-length antennas (1.5. mm diam. copper wire) placed parallel to the metal sheet (see e.g. [2]). Antennas were mounted on Teflon holder at distance of 1 cm over the metal sheet. The length of antennas was chosen taking into account the dielectric constant of *n*-heptane (ε=1.92). The antenna unit was placed on the bottom of heat resistant glass reactor partly filled with heptanes. Antennas were completely emerged in heptanes. Gas volume over the level of liquid was evacuated by Ar. Microwave discharge exists on both tips of each antenna.

First experiments showed that that microwave discharge is an efficient tool for *n*-heptane decomposition with generation of hydrogen and soot. The composition of liquid heptanes was not changed after plasma treatment.

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AVERAGED RELATIVISTIC MOTION OF THE CHARGED PARTICLE IN THE WAVE GUIDE

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Relativistic motion of the charged particle in the field of wave of arbitrary H_{mn} mode propagating along the axis of rectangular wave guide is considered [1].

By the method of Bogoliubov the averaged equations for the smoothed dynamic variables of the particle under the sufficiently general conditions of injection into the wave guide are obtained. Additional periodical terms of the first and second approximation to the averaged dynamical variables are calculated. The components of the vector of the ponderomotive (averaged) force, acting on the particle, are found.

The parameter of expansion is the ratio of the amplitude of oscillatory velocity of the particle in the field of wave to the light speed. Averaging over the fast phase of wave is performed.

It is shown that the averaged force, acting on the relativistic particle in the direction of the wave propagation, in general, is absent in accordance with results of [2]. At the same time under the definite choice of the parameters of injection of the particle into wave the particle experiences action of the ponderomotive force in the direction of the wave propagation. In this case obtained general expression for the ponderomotive force is in accordance with the result [3]. Therefore, performed calculations are demonstrated that the averaged action of the wave of the H_{mn} mode on the relativistic particle essentially depends on the parameters of injection of the particle into wave.

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INVESTIGATION OF GAS GISCHARGE PLASMA MAINTAINED IN CROSSED MILLIMETER WAVE BEAMS

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Gas discharge plasma covering a large area substrate surface can be generated in intersecting millimeter wave beams [1]. High power density in plasma of this discharge can be obtained. CVD reactor for diamond films deposition based on microwave discharge in intersecting wave beams was manufactured [2]. Investigation of plasma parameters allows to achieve better understanding of plasma chemical processes in the reactor and optimize its operation. The aim of this work was the investigation of plasma created and maintained in crossed beams of millimeter wave band in two schemes of experiments. In one set of experiments microwave discharge was generated in two crossed beams. In another set of experiments four intersecting beams were used. In both cases plasma parameters in argon, hydrogen, and methane gas mixture in the CVD reactor based on gyrotron with frequency of 30 GHz were studied. In the performed experiments for both beam configurations total incident power was in range from 4 to 10 kW and the gas pressure was 150-400 Torr. The ratio CH_4/H_2 was 2% and the ratio $H_2/(Ar+H_2)$ varied from 25% to 50%. Atomic hydrogen, argon and C_2 emission lines were measured by Jobin Yvon FHR-1000 spectrometer. Gas kinetic temperature and electron concentration and their dependence on external parameters – incident microwave power, operating pressure and gas mixture composition were studied by method of optical emission spectroscopy [3]. The gas kinetic temperature was obtained from spectrum of C_2 Swan rotational distribution. To obtain electron concentration the effect of Stark broadening of Balmer series of atomic hydrogen emission lines was used. Dependences of gas temperature and electron concentration on microwave power and pressure of gas mixture were discussed.

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MODEL OF THE POSITIVE COLUMN OF A Cs-Xe DC DISCHARGE AFFECTED BY A MICROWAVE PULSE

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Papers [1, 2] analyze applications of the plasma slab of the positive column(PC) of a DC discharge in the mixture of cesium-vapor and xenon (Cs-Xe discharge) as a nonlinear medium for microwave (MW) phase conjugation and as a two-dimensional sensor for imaging of microwaves. To study of the physical basics of these techniques, we modeled the dynamics of the kinetic and electrical parameters of the homogeneous PC of a Cs-Xe discharge affected by a long Ka-band microwave pulse. Calculations were done for the xenon pressure 30 and 45 Torr, discharge current density equal to 100 mA/cm^2, and density of Cs atoms ranged from 2 10^{12} to 1.5 10^{13} cm^{-3}. Time history of the potential electric field, the electron temperature and electron density, densities of atomic and molecular ions, cesium and xenon atoms in the ground and excited states were computed. It was shown that for microwave intensity W less than 2 W/cm^2 the electron temperature in the PC rises in direct proportion to W. The increase of the electron temperature is approximately 0.2 eV for W= 1 W/cm^2. It was shown that time history of the electron density variation induced by a long microwave pulse with a short leading edge can be approximated by exponential law. Characteristic time of the electron density variation decreases with the increase of microwave intensity: for W = 0.1 W/cm^2 this time is of the order of 1 ms and for W = 1 W/cm^2 it is of the order 0.1 ms. For W < 0.5 W/cm^2 steady state densities of the electrons and the main ions Cs^+ increase with W. The densities reach saturation for W > 0.5 W/cm^2, which is caused by the full ionization of Cs atoms in the PC plasma. For W > 4 W/cm^2 the electron density increases again with rise of W because impact of ionization of xenon becomes significant. The efficient ionization of xenon is the main cause of the ionization instability of the homogeneous PC plasma and its microwave breakdown. The results of our modeling are in a good agreement with the results of the experiments [1, 3].

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MICROWAVE PLASMA TORCH AT ATMOSPHERIC PRESSURE: THERMAL TRANSFER

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Among the microwave plasma torches, the axial injection torch (TIA) [1] has been used for several years to create chemically active species, in applications such as gas analysis, surface processing and gaseous waste treatments. We study the energy transferred from the plasma created by the torch at atmospheric pressure, which finds its interest for instance in the heating of helium in a dirigible balloon to achieve its rise in altitude. The TIA allows the coupling of microwave energy (2.45 GHz) to a gas injected axially through an antenna-nozzle system. The TIA produces non equilibrium plasma with high luminosity and a maximum of charged particle density at the nozzle's exit [2]. Our study involves both experiment and modeling of this torch in order to understand the distribution of the electromagnetic field, the flow of the gas / plasma system and the plasma-to-gas heat transfer.

Optical emission spectroscopy measurements allowed determining the gas temperature for different experimental conditions (flow, power), by fitting the N_2 ro-vibrational spectra obtained from air, using the SPECAIR software. The measurement of the electron density was performed based on the Stark broadening of the H_β line. Experiments have a double objective: to obtain input data for the numerical model and to validate its results. Modeling uses two modules of the COMSOL Multiphysics software: (i) a 3D electromagnetic module, which solves Maxwell's equations, (ii) a 2D hydrodynamic module [3], which solves Navier-Stokes' equations taking into account the plasma ions. A plasma module, which solves the fluid equations for electrons and ions, is in development.

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AIR PLASMA AT ATMOSPHERIC PRESSURE FOR APPLICATION IN PLASMA-PHOTONIC CRYSTAL.

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In this paper we investigate the possibility of a plasma photonic crystals to control the flow of powerful microwave radiation. Experimentally proved in principle possible to control the microwave radiation with the help of an air plasma at atmospheric pressure. The theoretical justification of the possibility of creating a plasma photonic crystal-based plasma at atmospheric pressure with the desired characteristics, the experimental data to create a plasma at atmospheric pressure, as well as an assessment of its basic characteristics.

Photonic crystals are widely known as a structure with many unique properties exhibited by, in particular, in optical physics. In this study we investigated (theoretically and experimentally) one-and two-dimensional photonic crystals plasma (PFC) for the reflection and/or absorption of microwave radiation. At present time there are several models of PFC, which allow to calculate their properties, but they appear different values of one of the main plasma parameter - the coefficient of absorption (or reflection). In this paper, a series of experiments to evaluate this parameter. For this purpose built Fabry-Perot resonator at the wavelength range 8.11 GHz, in which a plasma at atmospheric pressure with a temperature of ~ 3400K, and measured the change in signal VSWR. The obtained experimental evaluation of the dielectric constant, or rather its imaginary part has been used in the theoretical model for the calculation of the reflection spectra (absorption) 2D PFC. Calculations show that these spectra are very dependent on the efficiency of absorption of the scattered electromagnetic waves in plasma. In addition, the calculation becomes clear that the possible implementation of flow control of microwave radiation with the help of structured 2D PFC.

MICROWAVE TORCH AS A MEANS OF SYNTHESIS GAS PRODUCTION

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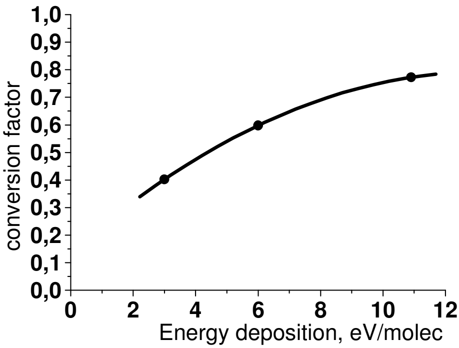
Production of a $CO+H_2$ synthesis gas by processing a flow of the working gas (methane CH_4 and carbon dioxide CO_2 in equal amounts) in a coaxial microwave torch has been investigated. The working gas was ejected through a nozzle situated at the end of the inner shortened electrode of the coaxial line. The construction of such a plasmatron and its action are described in detail in [1,2]. In previous investigations, the microwave torch proved to be highly efficient for various plasmochemical applications, such as methane destruction [3], nitric oxide production in air, etc.

The concentration of products at the outlet from the reactor was measured with the help of a Specord 80 infrared spectrograph. Besides the remaining CH_4 and CO_2, the presence of only carbon oxide CO was detected, whereas the concentration of the formed hydrogen H_2 was not measured. The experiments were carried out at gas flow rates of CH_4 + CO_2 mixture equal to 1.1, 2 and 4 l/min. The microwave power was 800 W.

If the assumption is made that the methane decomposition occurs mainly by the reaction $CH_4+CO_2 \rightarrow 2CO+2H_2$, then the conversion can be shown to be related to the output mixture composition by the equation

$$\alpha = (1 - C_{CH4})/(1 + C_{CH4}) = (1 - C_{CO2})/(1 + C_{CO2}) = C_{CO}/(2 - C_{CO}) = C_{H2}/(2 - C_{H2})$$

where C_i is the measured relative concentration of the corresponding gas component. Substitution of the experimentally measured values in this equation yields α with dispersion not exceeding 10%. As illustrated in the figure, the conversion may be as high as 80%. A minimum energy cost for production of a pair of molecules the synthesis gas $CO+H_2$ is estimated as 7.5 eV/molec.



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SPECTROSCOPY AND 2D MODELING OF NON-UNIFORM MICROWAVE DISCHARGE IN NITROGEN AND NITROGEN-HYDROGEN MIXTUREs

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The influence of small hydrogen admixture on strongly non-uniform nitrogen microwave discharge is studied by optical emission spectroscopy and 2D modeling. Experiments were performed with EMD source, described in detail elsewhere [1], at pressure of 1 Torr. The spatial intensity distributions of the H_{α} line and N_2 (2^+ and 1^+ system) and N_2^+ (1^- system) molecular bands are determined for different incident microwave power and hydrogen admixtures. By means of collisional-radiative (CR) model, electric field strength in nitrogen discharge is evaluated from the intensity ratio of 2^+ and 1^- system of nitrogen bands. A self-consistent 2D model, incorporated in commercially available package COMSOL [2], is used to determine spatial distributions of nitrogen molecules in $C^3\Pi_u$ state, microwave field strength, electron density and concentrations of N_2^+, N_4^+ in pure nitrogen and in nitrogen-hydrogen mixtures. In nitrogen-hydrogen mixtures the concentration of N_2H^+ ions is determined also. The results of 2D modeling are in agreement with experimental results and prove that the influence of hydrogen to discharge is related to the fast conversion reactions of nitrogen ions (N_2^+, N_4^+) to N_2H^+ ion [3]. These reactions are responsible for the change of transport properties of ion plasma component, which leads to the modification of microwave field strength in plasma, and consequently, to the alternation of all plasma parameters.

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TWO DIMENSIONAL MODEL OF MICROWAVE INDUCED Ar PLASMA FOR FIBRE PRODUCTION

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In industry, microwave induced plasmas (MIPs) are employed for the purpose of deposition. One example is the deposition on the inner wall of quartz tubes, which is the first step in the production of optical fibres. The setup consists on an electromagnetic cavity similar to the surfatron source [2] that is covering the quartz tube. In the tube, there is a flowing gas, e.g. $SiCl_4$ and O_2. The cavity includes two chokes designed to confine the electromagnetic (EM) waves and the plasma.

In this contribution, we present modeling results of such a setup in two dimensions using the Plasimo modeling platform [1]. In this initial study, we have considered an argon plasma. For the description of the MIP, the non-local-thermal-equilibrium (non-LTE) model solves particle, momentum and energy balance equations of certain species in conjunction with the EM-model for wave propagation and absorption [2].

The confinement of the EM-waves depends on the choke depth and its optimum value depends on the plasma quantities (e.g. electron density and collision frequency of momentum transfer). This implies that the coupling between the plasma and the EM-waves must be treated self-consistently, as realized in this study.

As a proof-of-concept of the model, we present the power response of an argon plasma as a function of the choke depth. From this curve, we can determine the optimum depth. Additionally, we show the corresponding distributions for the EM-fields, electron temperature and electron density for various points of the power response curve.

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NANOSTRUCTURE MICROWAVE PLASMA FORMATION OF OPTOELECTRONIC DEVICES

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Nanostructure formation in optoelectronic devices led to improvement in efficiency. We improved efficiency in silicon photovoltaic cells and InGaN/GaN-based light-emitting diodes (LED) by nanostructure formation. That is one and two dimensional gratings on top surface [1] with 100 nm width and thick of strip-line rulings and different gap. It creates spatially homogeneous distribution of current density in p-n junction area of LED and resonantly transparent for light in case of metal grating top p-electrode. The etched strip-line rulings on silicon photovoltaic cells reduce light reflection from silicon surface.

We used precision electron cyclotron resonance (ECR) plasma dry etching for getting gratings. For nanostructure formation Si_3N_4 film on Si or GaN by ECR plasma-enhanced chemical vapor deposition etch in accordance with photo resist mask [2, 3]. ECR plasma application allows to minimum radiative damages near-surface structure region, etching with precision to some nanometers depending on sample material and making better roughness parameters.

The results of making and measured device characteristics are presented in our stand report.

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INVESTIGATION OF FAST-ELECTRON COMPONENT IN ECR-PLASMA CONFINED IN STRONGLY NON-UNIFORM MAGNETIC FIELD

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The investigation of a fast electron group in the microwave plasma confined by the magnetic field of the two ring coils with opposite currents is presented. Stabilization possibility of the plasma convective instability in such a magnetic configuration is a result of zero field regions presence. Herewith the plasma pressure should be smoother than the critical profile being defined by magnetic configuration [1].

Earlier it was experimentally observed that ECR-plasma being localized inside the magnetic trap with a sharp density decreasing towards the periphery was restricted by the magnetic separatrix. The background pressure profile measured by Langmuir probes conforms with the convectively-stable critical one [2].

The x-ray measurement performed by using the pinhole camera and the collimation system gave an opportunity to define both the spatial localization of the ECR hot-electron fraction and their energy spectrum which have had two effective temperatures 2 keV and 6 keV and the x-ray maximal energy higher than 25 keV [3]. However, these studies have not taken into account the contribution by fast electrons group into the total pressure.

This paper presents the results of experiments to determine the dynamics of the fast electrons group appearance being registered during the X-ray radiation. At the same time the fast electrons contribution into plasma pressure by measuring the magnetic field changes while the plasma appearance has been recorded.

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INFLUENCE OF SMALL ADDITIONS OF NEON ON THE CHARACTERISTICS OF STRONGLY NON-UNIFORM MICROWAVE DISCHARGE IN NITROGEN.

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Recent study showed that strong non-uniformity of discharge leads to occurrence of new phenomena. It was shown that contrary to the plasma of quasi-homogeneous discharges small additions of argon to nitrogen in the electrode microwave discharge (EMD) results in strong influence on the plasma parameters [1]. This paper presents results of experimental study of influence of small additions of neon on the properties of nitrogen EMD.

Experimental setup for generation and study of EMD described in details elsewhere [1, 2] was used in this investigation. The incident power of continuous microwaves was <180 W (2.45 GHz), total gas pressure in the chamber varied between 1 and 10 Torrs, neon concentration was 0-5%. Emission spectra of EMD was analyzed with spectrometer Avaspec-2048, electron optic camera К-008 was used for visualization of the discharge. Spectra from the near electrode region and spherical part of EMD were analyzed.

It was shown that at pressure 1 Torr addition of neon leads to decrease of intensities of emission of the second positive system of nitrogen in near electrode region of EMD. No influence was observed in the spherical part of EMD at any pressures. At pressure 5 Torr influence of neon was not observed in all parts of EMD. Results of 2D modeling at pressure 1 Torr agree with experimental results.

Mechanism of influence of neon on parameters of strongly non-uniform discharge at low pressure can be similar to that proposed in в [1]: influence is caused by relation of kinetics and topology of the discharge. Absence of such influence at high pressures can be explained by depletion of the electron energy distribution function in the high energy region. This leads to decrease of influence of excited and ionized neon atoms on plasma kinetics because of high threshold energies of these processes.

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STRUCTURE OF SURFACE LAYER OF HYDROGEN MICROWAVE PLASMA IN DC FIELD

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It was shown earlier that non-equilibrium electrode microwave discharge (EMD) can be used as plasma cathode for non-self-sustained DC discharge [1]. This paper presents results of experimental study of influence of external DC field on properties of EMD in hydrogen at pressures 1-5 Torr. The structure of thin near electrode layer of microwave plasma with thickness of 1 mm was the main topic of this study. Surface plasma plays the key role in different processes: plasma modification of surfaces, etching, deposition of coatings, crystals growth, etc. So results of this study are important both for study of microwave plasma cathode and for understanding the physical processes in surface plasma.

The discharge chamber was the stainless steel cylinder with diameter of 15 cm (the experimental setup was described in detail in [1]). The electrode-antenna was inserted in the chamber through the vacuum junction in the cup of the chamber. The electrode was isolated from the chamber. Plasma was ignited near the tip of antenna. The incident power was below180 W (2.45 GHz). DC voltage between the electrode and the chamber was varied between -300 and +500 V. Spatially resolved emission spectra of EMD (resolution was of 100 microns) was analyzed with spectrometer Avaspec-2048 equipped by the optical fiber. Electron optic camera K-008 was used for visualization of the discharge.

DC voltage–current characteristics of EMD were measured. Method of relative intensities of H_α and H_β Balmer series assuming the coronal model (dissociative excitation by electron impact and radiative decay) was used for study of dependencies of microwave field in near electrode region on pressure, microwave power, DC voltage and distance from the electrode. The energy distributions of H atoms were defined from emission of H_α, H_β and H_γ lines. are slightly changed with DC voltage and changed with distance from the electrode. DC voltage changes the spatial distributions intensities of nitrogen bands in the near electrode region, dimension of EMD and its shape.

This study was supported in part by the Russian Foundation for Basic Research (grant no. 11-02-00075).

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2D and 3D MODELING OF THE EMD: SEARCH FOR OPTIMAL SIZES OF ELEMENTS OF THE WORKING CHAMBER; CHARACTERISTICS OF H_2 AND N_2 MICROWAVE DISCHARGES

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The electrode microwave discharge (EMD) is a time-constant ball-like plasma formed in different gases at the tip of the internal electrode-antenna, along which the electromagnetic energy enters the chamber. Such discharges in hydrogen, nitrogen, argon and their mixtures has been observed and studied experimentally in the range of pressures 1-10 Torr [1, 2].

The structure of microwave fields settled inside the working chamber influences greatly on the properties of the sustained discharge. Then the choice of optimal length and position of the electrode-antenna tip relative to given chamber geometry and observation windows brings to the best matching of the EMD (i.e. obtaining the highest microwave fields at the tip and lowest microwave energy leakages through the windows at fixed level of microwave power).

For the specified experimental chamber the self-consistent 3D simulation of discharges in H_2 and N_2 at 1 Torr is carried out [3]. Spatial characteristics of their basic components are presented. The stable mean electric field does not differ strongly from the field in the same chamber without plasma. The layer of supercritical plasma is several millimeters. The profile of electron density in the layer self-consistently forms so that the resonant strengthening of the field in the areas where the plasma density is close to critical is practically compensated due to collisional absorption. The results of simulations in H_2 and N_2 qualitatively conform with the experimental results. It is shown that 3D-simulation allows us to analyze the discharge chamber details that cannot be taken into account in the 2D-model, and hence to improve forecasting qualities of the model.

All simulations are performed using the program COMSOL 3.5a [4].

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MODELLING OF MICROWAVE DISCHARGE SUSTAINED BY TRAVELLING ELECTROMAGNETIC WAVE AT ATMOSPHERIC PRESSURE

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Argon plasma column sustained by travelling electromagnetic surface wave is theoretically studied by means of a self-consistent model. This model consists of both electrodynamics of wave propagation and kinetics of the electrons and the heavy particles. Basis of the model are Boltzmann's equation, particles balance equations and Maxwell's equations. The model is applied to plasma torch (plasma–vacuum configuration) and plasma column in a dielectric tube at atmospheric pressure. Because of the high pressure it is necessary to account for the effect of electron and heavy particles interactions on the wave propagation. Therefore the electron–neutral collision frequency in the expression for the plasma permittivity is considered. Using the full expression for the plasma permittivity a complex dispersion equation is obtained. Its solution gives dependences, usually presented through phase and attenuation diagrams. The wave energy balance equation solved together with the electron energy balance equation provides a link between electrodynamics and kinetics. The self-consistent model built up in this way gives the axial distribution of electrons, ions, excited atoms, electron mean energy, and wave characteristics.

The self-consistent model of plasma sustained by traveling electromagnetic wave at atmospheric pressure allows us to study the influence of the discharge conditions (plasma radius, dielectric tube thickness) and some key plasma parameters (electron–neutral collusion frequency and the mean power for sustaining an electron-ion pair) on the phase and attenuation diagrams, plasma density and temperature, and the length of the plasma torch and plasma column in a dielectric tube.

MICROWAVE INUCED BREAKDOWN SPECTROSCOPY FOR MATERIAL IDENTIFICATION

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The paper presents a technique for identification of solid materials by localized microwaves [1]. A small hotspot (~1-mm^3) created by thermal-runaway instability on the material surface [2] is further radiated by the localized microwaves hence ejecting a plasma plume [3]. Its atomic emission spectrum is detected and analyzed by an optical spectrometer for element identification, as in the known laser-induced breakdown spectroscopy (LIBS) technique. The conceptual feasibility of the microwave-induced breakdown spectroscopy (MIBS) as a low-cost substitute for the LIBS is demonstrated by experimental results. The proposed MIBS technique for material identification might be preferable in scenarios that permit direct contact with the identified material and its slight destruction.

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GALLIUM NITRIDE AND DIAMOND LIKE CARBON FILMS DEPOSITED BY ECR PLASMA

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Gallium Nitride films was deposited on silicon and sapphire substrates by ECR plasma deposition. Diamond Like Carbon films was deposited on silicon substrates by ECR plasma deposition. We studied dependence of the growth rate and film GaN structure from microwave power W, DC self-bias U_{bias}, substrate temperature T, chamber pressure P, flow R ratio of nitrogen (N_2) to the flow trimethylgallium (TMG). Also we explored dependence of the rate of growth and composition of the Diamond Like Carbon films from dc self-bias U_{bias}, substrate temperature T, chamber pressure P, hydrogen (H_2) flow ratio of methane (CH_4) and argon (Ar).

At growth Diamond Like Carbon the substrate temperature varied from 50 to 550ºC.

A significant advantage of ECR plasma stimulated deposition method is the possibility diminution the substrate temperature compared with other methods. So the method of stimulated epitaxy ECR plasma can diminution the temperature of the substrate during the growth of GaN up to 700ºC, therefore extremely important to study the transition regime of the amorphous layer GaN growth to the polycrystal layer GaN growth mode at higher temperatures. Then study of the growth regime transition of a polycrystal layer to layer is textured. Finally, the optimization of plasma parameters in order to achieve the minimum temperature of the substrate for entry into regime of epitaxy.

Another important challenge is to optimize the parameters of any of the methods to achieve a minimum concentration of impurity atoms in deposition layers.

FTIR spectroscopy and TEM were used for express analysis of layers structure and chemical composition.. DLC films were characterized by spectral ellipsometer.

THE APPLICATION OF ECR PLASMA IN THE PROCESSING PROCEDURES OF MEMS AND NEMS SYSTEMS.

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Micro dimensions of the devices of micro and nanoelectromechanical systems (NEMS and MEMS) provided the application of the main microelectronic processing procedures for its producing. This article concerns the planar process of producing of microelectronic devices by means of consequent interchange of the plasma deposition films processes and plasma etching processes, photo and electro lithography.

ECR plasma processing has a wide range of advantages regarding the other methods of plasma obtaining [1]. The high plasma density (up to $10^{13}sm^{-3}$ at microwave power (500÷1000 W), the low working pressure (10^{-2}Pa), the low energy of particles (20÷30 eV) make it possible to reach the high rates of etching or deposition at the lowest radiation damages of surficial region structures. The low temperature of the wafer at the etching and deposition processes provides the performance of the processing procedures which are impossible to use at the application of other known methods[2]. Ions energy is controlled with the change of the bias voltage (-30 ÷ -160 V) via the application of RF field (13,56 MHz). It allows to control the rate and the anisotropy of etching. Multichannel system of gas supply and also the possibility of wafer holder temperature controlling permits to etch and deposit different materials in the single vacuum process.

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MICROWAVE PLASMA TORCH AT ATMOSPHERIC PRESSURE FOR APPLICATION TASKS

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Microwave plasma discharges are the future of new energy efficient microwave technologies. Microwave high-pressure plasma is used in the promising areas of science, such as: hydrogen energy, plasmochemistry, space technology, light sources based on microwave discharge, etc. Microwave plasma torch operating at atmospheric pressure with microwave power supply 600 watts for application tasks has been designed [1].

Resonator chamber for discharge ignition created. The optimal resonator for plasma torches is cylindrical cavity with rod systems. On the resonator axis the cylindrical rod with the rounded edges is placed. Such cavity had high electric field strength at discharge zone and high Q-factor. Microwave discharge is born in the quartz tube placed between rode and face wall of the resonator. Parameter of the electric field on axis in the pin region reached value of ξ_e=9,4 $(\mathrm{Ohm})^{0,5}$/cm, Q=3300, the resonant frequency f_0 = 2450 MHz. Experimental studies and setting up of microwave plasma torch at power 600 watts were performed. As a result of work of microwave plasma torch plasma with height 35 mm was formed and visually observed under the cavity. Energy characteristics of microwave plasma torch were also measured. Examination has shown that efficiency of microwave plasma torch had more than 60 % and bactericidal factors of microwave plasma had described. Experimental studies of influence of plasma torch plume on dried suspensions cl.sporogenes (related spore: cells = 1:5) were performed. Result of influence consists at reduction of cells and spores on 2-4 orders [2].

Microwave plasma torch at atmospheric pressure with power supply 600 watts for food industry was designed. Prospects for microwave plasma application for aseptic processing of packaging in the food industry have been shown.

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SPECTROSCOPIC INVESTIGATION OF THE ELLECTRONICAL – VIBRATIONAL – ROTATIONAL DISTRIBUTION FUNCTIONS IN THE DC GLOW DISCHARGE AND MICROWAVE DISCHARGE IN MIXTURES OF HYDROGEN WITH NITROGEN

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Emission spectroscopy is used to investigate of gas composition effect on macro and microscopic parameters radiative spectral distribution, translational and rotational temperatures, electronically – vibrationally – rotational energy level distribution functions in the electronic excited states of the nitrogen and hydrogen molecules, and as well as atomic hydrogen of DC glow discharge (pressure of 4 Torr, discharge current of 70 mA) and the strongly inhomogeneous microwave discharge generated near the end of the electrode antenna (frequency of 2.45 GHz, pressure 4 Torr, incident microwave power of 100 W) in mixtures of hydrogen with nitrogen (percentages of N_2 98.2%÷85.8% and H_2 1.8%÷14.2%).

A new approach is developed for modeling and processing of the nonequilibrium plasma emission spectra. It allows for evaluating population densities of atomic hydrogen, nitrogen ion and nitrogen molecules in the excited states at their significant deviation from Boltzmann's distribution in the case of spectral overlapping of the atomic lines and molecular bands.

This work was partly supported by grant RFBR no 12-08-91052 NCNI_a, no. 11-02-00075.

COMPARISON OF THE ELECTRONICAL – VIBRATIONAL – ROTATIONAL DISTRIBUTION FUNCTIONS OF NITROGEN MOLECULE DETECTED BY EMISSION AND CARS SPECTROSCOPY IN THE DC GLOW AND MICROWAVE DISCHARGES IN NITROGEN AT MEDIUM PRESSURE

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The spectral distribution of radiation, translational temperature, the population densities on the electronically – vibrationally – rotational levels of $X^1\Sigma_g^+$ state, $C^3\Pi_u$ state and, especially, $B^3\Pi_g$ state of the nitrogen molecule, and as well as $B^2\Sigma_u^+$ of the nitrogen ion molecule are measured using the methods of coherent anti – Stokes Raman spectroscopy (CARS) and emission spectroscopy in the strongly inhomogeneous microwave discharge generated near the end of the electrode antenna (frequency of 2.45 GHz, pressure 15 Torr, incident microwave power of 100 W) and DC glow discharge (pressure of 15÷25 Torr, discharge current of 30÷90 mA). A new approach is developed for modeling and processing of low - temperature plasma emission spectra in the case of spectral overlapping of the atomic lines and molecular bands.

In the both discharges, the spectral distribution of radiation is consists of the emission bands of $N_2(C^3\Pi_u$ - $B^3\Pi_g)$, $N_2(B^3\Pi_g$ - $A^3\Sigma^+{}_u)$, $N^+{}_2(B^2\Sigma^+{}_u$ – $X^2\Sigma^+{}_g)$, $OH(A^2\Sigma^+$-$X^2\Pi)$, β – system $NO(B^2\Pi$-$X^2\Pi)$ and γ – system $NO(A^2\Sigma^+$-$X^2\Pi)$. The population density distributions of the nitrogen molecules on the vibrationally – rotational levels in the ground $X^2\Sigma^+{}_g$ - state, as well as, on electronically - vibrationally – rotational levels of $C^3\Pi_u$ and $B^3\Pi_g$ – states are in good agreement with one's calculated by Boltzmann's formula. The values of the rotational temperatures (700÷1300 K) determined by processing of emission spectra are in good agreement with one's using CARS. Under our experimental conditions, the translational and rotational temperatures coincide. The population density distributions of nitrogen molecules on vibrational levels in the electronic excited $C^3\Pi_u$ – state coincide with the Boltzmann's distributions in both types of discharges. The vibrational distribution functions of nitrogen molecules in the electronic excited $B^3\Pi_g$ – state are significantly different from the Boltzmann distributions. The structures of the distributions are slightly depended on the conditions of DC glow and microwave discharges.

Work was partially supported by grant RFBR № 12-08-91052 NCNI_a.

X-BAND LATTICE PLASMA REFLECTOR IN AFTERGLOW OF PULSED DC-DISCHARGE

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Highly ionized gas plasma behaves as noteworthy conductor capable to substitute metal [1-3]. A unidirectional grating made from glow discharge tubes forms a plasma reflector which deflects microwave beam launched from a waveguide horn (*E*- field vector is in parallel to the tube axes). Compact fluorescent lamps with argon-mercury filling were used as the discharge tubes. Afterglow discharge with long-lived plasma was studied in order to avoid plasma noise exciting under discharge current action that could generate difficulties for antenna in the receive mode.

By optical spectroscopy and radio-physics techniques it was shown that life time of dense afterglow Ar-Hg plasma $n > 10^{12}$ cm^{-3}, created in discharge tubes at pressure Ar ~ 4 Torr + Hg ~10^{-3}÷10^{-2} Torr by powerful pulse discharge, t ~20 μs with current ~50 A has duration ~10^{-2} s.

Afterglow plasma consists of ions, atoms with long-living excited states, which take part in inelastic processes releasing fast electrons. Among them there are the chemi-ionization and de-excitation electron–atom collisions. The molecular argon ions and metastabile atoms have a great importance in the processes. Owing to dissociative recombination of Ar_2^+ ions and electrons, Ar atoms come to excitation according to scheme:

$$Ar_2^+ + e \rightarrow Ar + Ar^*(14{,}43\ \text{эВ}).$$

It was shown that Ar^+ ions in afterglow plasma are also excited up to peak level nearest to the second ionization potential 27,63 эВ that was explained by molecular ions collisions with argon metastable atoms for instance:

$$Ar_2^+\ (14{,}43\ \text{эВ}) + Ar_m^*(\ 11{,}55\ \text{эВ}) \rightarrow Ar^{+*}\ (25{,}98\ \text{эВ}) + Ar + Ar.$$

Afterglow plasma was found to exist in a latent state double long on the radiowave reflection measurements than on its optical radiation ones.

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For notes

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