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An Experimental Apparatus with Microwave Electron-Cyclotron-Resonance Plasma

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Absract—An experimental plasma apparatus operating on the basis of microwave discharge running under electron cyclotron resonance is described. The apparatus consists of a 150-mm-diameter plasma source, a plasmochemical reactor, and an automated diagnostic system. The magnetic field of the plasma source is produced with a system of twelve permanent magnets and three electromagnets. The field of electromagnets is highly uniform and has a small gradient. A PC- and CAMAC-equipment-based diagnostic system makes it possible to perform probe and spectral measurements of plasma parameters and record the operating parameters of the apparatus. The parameters obtained in the discharge for the saturation ion current density at a distance of 62 cm from the source for a microwave power of ≤1 kW and pressure of ≤1 mtorr are 6 and 12 mA/cm^2 with a nonuniformity of 5% over diameters of 15 and 10 cm, respectively.

A plasmochemical reactor with microwave ionization and electron-cyclotron heating is designed for obtaining thin films and for etching semiconductor structures. This type of apparatus has certain advantages over conventional plasma sources used in microelectronic techniques. The absence of a hot-filament cathode provides a long-duration operation with chemically active gases. There is the possibility of producing a low-pressure high-density plasma (10^{11}–10^{13} cm^{-3}) and of achieving the ionization of a high degree (up to 10%). A low (10–50 eV) and controllable ion energy allows one to vary the rate and anisotropy of etching without disturbing the substrate structure. A high spatial homogeneity of plasma makes it possible to treat 150–200-mm-diameter substrates.

The apparatus under consideration includes a magnetic system consisting of solenoidal and permanent magnets and permits a variation of the spatial distribution of plasma concentration over a wide range.

A schematic diagram of the setup is shown in Fig. 1. The vacuum chamber consists of two units: (*1*) microwave-plasma source and (*2*) plasmochemical reactor for running technological processes. The plasma source is a 150-mm-diameter cylindrical resonator 250 mm long with a quartz glass as an end face and open on the opposite side. The housing of the plasmochemical reactor is 350 mm in diameter, 650 mm long, and has six lateral pipe connections with vacuum seals. Substrate holder *3* is insulated from the vacuum chamber; therefore, both direct and alternating voltages with a frequency of 13.56 MHz can be fed from power supply *26* to the substrate. The vacuum chamber made from the Kh18N10T (Cr18Ni10Ti) sheet stainless steel 2 mm thick is a dismountable construction the separate parts of which are assembled using rubber-sealed flanges. The flanges of the entrance quartz window and the plasma source are cooled with running water.

A 50 l/s roughing VN-4 pump and two 500 l/s VMN-500 (Luch Factory, Kostroma) turbo-molecular pumps connected in parallel, evacuate the vacuum chamber. Pressure is measured with VIT-2 and VI-14 ionization gages. The evacuation rate is controlled by an electromotor-driven valve. The residual pressure in the chamber is below ≤1 μtorr. The gas feed system has two identical gas pipe-lines that can be used together or independently. The working gas from cylinder *4*, after passing through an RDM-1 pressure controller *5* and RRG-1 mass flow controller *6*, enters the vacuum chamber near the quartz entrance window and, if necessary, near the substrate. The operating pressure is 0.05–10 mtorr, and the gas flow rate is 1–100 cm^3/min.

The microwave system is constructed with account of the requirements discussed in the literature [1]. An M-105 magnetron *7* whose air-cooled heat sinks are replaced by water-cooled tubes wound around the magnetron body is used as a microwave oscillator with a frequency of 2.45 GHz. This improves the thermal regime of the installation during a long-duration continuous operation and provides its use with an output power of up to 1 kW (rated power is 650 W) without an appreciable decrease in reliability. Microwave power is transmitted from the oscillator to the plasma source along a rectangular waveguide with a cross section of 90 × 45 mm (TE_{10} mode). A water-cooled circulator with a matched load *8*, a microwave wattmeter *9*, and a three-stub matching plunger type transformer *10* are installed in the waveguide transmission-line. An impedance transformer is used to minimize the reflected power in various operating modes of the apparatus. A smooth microwave junction *11* serves to conjugate the rectangular waveguide line with the plasma source, the body

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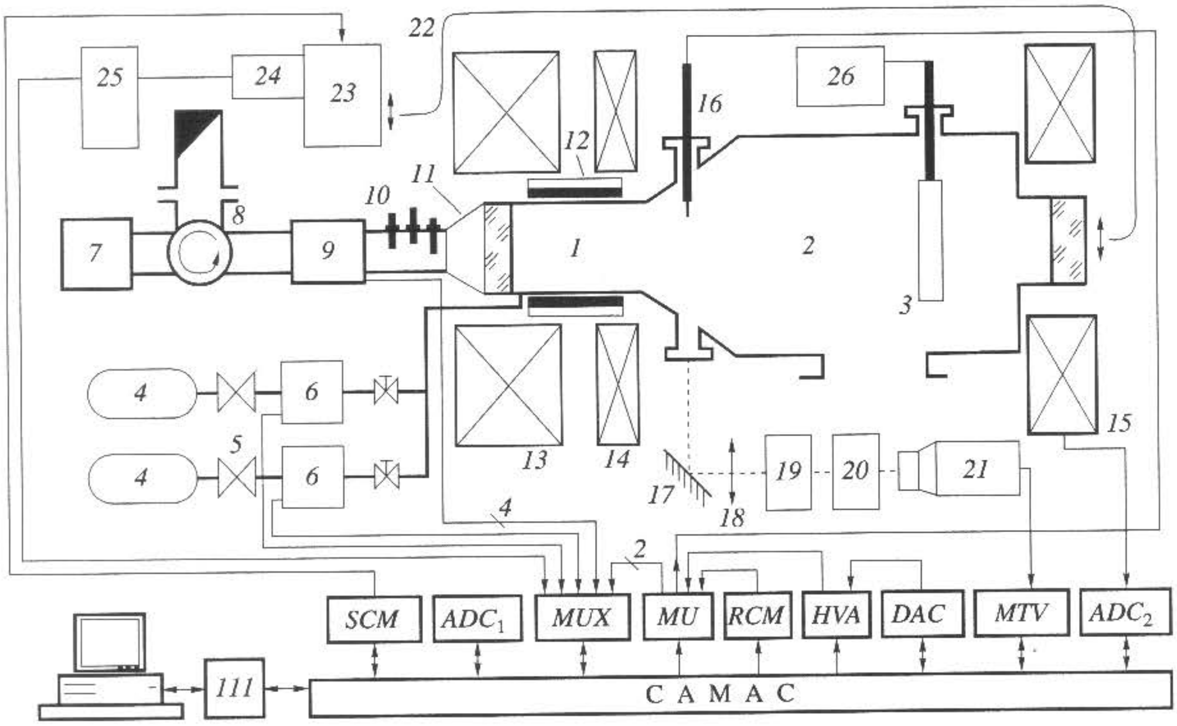

Fig. 1. Schematic diagram of the apparatus: *(1)* plasma source, *(2)* plasmochemical reactor, *(3)* substrate holder, *(4)* gas vessels, *(5)* pressure controllers, *(6)* gas flow rate controllers, *(7)* magnetron, *(8)* circulator with a load, *(9)* wattmeter, *(10)* impedance transformer, *(11)* TE_{10}–TE_{11} microwave junction, *(12)* permanent magnets, *(13–15)* electromagnets, *(16)* electrostatic probe, *(17)* mirror, *(18)* positive lens, *(19)* Fabry–Perot interferometer, *(20)* monochromator, *(21)* TV camera, *(22)* light guide, *(23)* monochromator, *(24)* photomultiplier, *(25)* amplifier, *(26)* power supply, *(HVA)* high-voltage amplifier, *(MU)* measuring unit, *(MUX)* analog multiplexer, *(ADC)* analog-to-digital converter, *(DAC)* digital-to-analog converter, *(RCM)* relay control module, *(SCM)* stepper control module.

of which is actually a round waveguide with the TE_{11} fundamental mode. Microwave power enters the plasma source through a 150-mm-diameter quartz window which is 23 mm thick.

A modified KIE-5 commercial controllable high-voltage source (produced by the Luch factory, Kostroma) is used to power the magnetron. To reduce the maximum output voltage from 9 to 4.5 kV, two of four sections in the secondary winding of the power transformer are switched off. An additional control element is introduced to the control circuit. A pulsed voltage regulator (3.15 V and 14 A) is included in the filament supply circuit. It operates as an 18-A current regulator with a load resistance below the rated one. The use of this regulator not only raises the stability of the magnetron operating mode, but also restricts the filament current at a safe level at the moment the magnetron is switched, thus significantly increasing its working life. The regulator, its rectifier, and filter are placed in the high-frequency unit along with the magnetron and filament transformer. Operation of the microwave system revealed that, according to probe measurements, the ~3% voltage ripple at the magnetron anode with a frequency of 300 Hz (full-wave three-phase rectifier circuit) results in 30% variations in the plasma concentration with the same frequency. Probably, nonlinear processes of microwave absorption in plasma can account for this effect. It is difficult to conclude how this affects the long-duration processes of etching and deposition, but in this case, the plasma diagnostics is extremely impeded. To decrease the anode voltage ripple and, consequently, the variation of the magnetron power, a capacitance of 50 μF was introduced to the output filter circuit. As a result, the voltage ripple decreased down to <0.2%, and the variation of the plasma concentration at the supply-line frequency reduced to an indistinguishable level (here, we do not consider high-frequency oscillations related to plasma instabilities).

The results of recent publications clearly show that the most important parameters of the ECR plasma that primarily determine technological characteristics of this type of installations significantly depend on the spatial configuration of the magnetic field [2–4]. The position with respect to the substrate and shape of an equimagnetic surface of 875 G that determines the ECR zone for the frequency $f = 2.45$ GHz (so-called, ECR layer) affect the radial homogeneity of plasma concentration and of ion saturation current density as well. The magnetic field gradient determines the form of the energy distribution functions for ions and angular distributions of the mean kinetic energy of directional ion motion. The latter circumstance is crucial for high-precision etching of large-sized substrates, when, in addition to a high rate, a high anisotropy and spatial uniformity of the process are necessary. Thus, a variable configuration of the magnetic field created in the apparatus is a tool to form the plasma parameters needed or desirable for a certain technique.

The magnetic field in our apparatus is formed by a system consisting of three solenoidal electromagnets *13–15*. Figure 2 shows the field configuration calculated with a computer for a current of 240 A. A radial nonuniformity of the induction is 4% over a diameter of 150 mm. The middle of the first magnet *13* with the largest number of turns (120) is positioned in the section of the entrance quartz window. The second magnet *14* with 40 turns is positioned in the plasma source output section. The field produced by these two magnets has a maximum (1080 and 1350 G at currents of 240 and 300 A through the windings, respectively) at the internal surface of the entrance window. The magnetic surface of 875 G determining the position of the ECR layer lies at a distance of 10 or 12 cm, respectively, from this window.

The second magnet reduces the longitudinal field gradient to 20–40 G/cm in the region of the 875-G magnetic surface and makes this surface plane–parallel with respect to the window. This contributes to obtaining a radius-homogeneous plasma (especially when the substrate is in the immediate vicinity of the ECR zone) [3]. The region in the plasma source, where the magnetic field exceeds the resonance field, i.e., $B > B_{ce} = 875$ G, is the propagation zone for a whistler-type electromagnetic wave, which is subsequently absorbed in this region [5, 6]. The whistler-heated region formed near the entrance window makes it possible to attain higher plasma density than critical in this type of apparatus (7.4×10^{10} cm^{-3} for the frequency $f = 2.45$ GHz) and, moreover, to achieve better matching between the microwave transmission-line and the plasma source.

The third magnet *15* with 80 turns is mounted behind the plasmochemical reactor. Although its effect on the plasma-source field is small, its magnetic field decreases the field gradient in the reactor region. First, this provides the conservation of the mean energy of translatory motion of ions in this region at a fairly low level of 10–15 eV. Second, this prevents the plasma electrons from escaping onto the reactor walls, thus permitting us to obtain a high concentration at considerable distances from the source. This is especially important in cases where, in order to prevent a substrate with a high-precision structure from the negative action of fast electrons and UV radiation, it is placed at a distance of several tens of centimeters from the ECR zone.

The electromagnets are assembled of identical windings with an inner and outer diameter of 225 and 530 mm, respectively, and 40 mm thick. They are wound with a copper bus of a 20×4-mm^2 cross section and have 40 turns each. Glass textolite sheets measuring $2 \times 20 \times 20$ mm are used for turn-to-turn insulation.

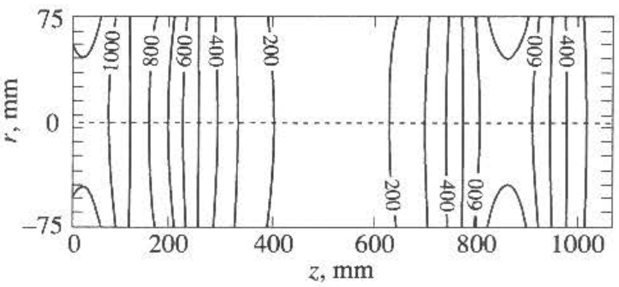

Fig. 2. Configuration of the magnetic field formed by the system of electromagnets at a current of 240 A.

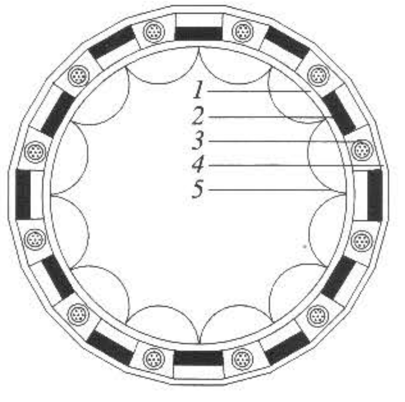

Fig. 3. Arrangement of the permanent magnets: (*1*) wall of the plasma source, (*2*) permanent magnets, (*3*) cooling system tubes, (*4*) magnetic circuit, (*5*) lines of magnetic induction.

Along with the use of fans, this insulation provides acceptable air cooling. The electromagnets are mounted in frames and can move in the longitudinal direction, making it possible to vary the magnetic field distribution within a small range. To vary this distribution within a wide range, shunts (a copper bus with taps) are connected in parallel to the second and third magnets. All of the windings of the electromagnets are connected in series and energized by a controlled dc current source of 100–300 A with a ripple of ≤1%. The current is controlled with a three-phase magnetic amplifier included in the primary winding circuit of the step-down transformer.

In addition to the electromagnets, a system of 12 permanent Sm–Co magnets *12* is used. These magnets, in the form of posts measuring $15 \times 20 \times 120$ mm (Fig. 3), are arranged symmetrically on the outside surface of plasma source *1* between the water-cooled tubes *3* and surrounded by a plate-shaped magnetic circuit *4*. Each magnetic post is an assembly of 18 plates measuring $20 \times 20 \times 5$ mm with similar poles in the longitudinal direction (Fig. 1). The magnets with alternating poles are arranged azimuthally. Thus, we can work with the magnetic field created only by the electromagnets, only by permanent magnets, or with the hybrid field as well.

All measurements are performed with a measuring and computing system based on a PC/AT-286 computer and CAMAC equipment. Basic plasma parameters, such as electron and ion concentration, saturation ion current, plasma potential, floating potential, temperature, and electron energy distribution function are determined from probe measurements of current-voltage characteristics (CVC) [7]. In addition to the plasma parameters, the following data are recorded in each experiment: the flow rate of the working gas; the incident, reflected, and transmitted microwave radiation; and the current in the first electromagnet.

The Langmuir electrostatic probes introduced into the plasma through the sealed unions on the body of the vacuum chamber are used. The first two probes are disposed at the distances $z_1 = 30$ cm (output source section) and $z_2 = 60$ cm (substrate section), respectively, from the entrance window and move in the radial direction. The third probe is introduced through the union at the end face and moves in the axial direction. Probes are made of a 5-mm-diameter shielding copper tube inside which runs a tungsten wire (0.35-mm diam) coated with a ceramic insulator. The part of the probe protruding into plasma is 10 mm long. A quartz tube is slipped over the copper one in order to prevent contamination of the plasma with copper. To decrease the effect of the magnetic field, the working parts of the probes are oriented perpendicular to the induction lines.

C–V characteristics are measured in the following way (see Fig. 1). A linearly changing voltage from a 2TsAP-10 *DAC* is fed to a high-voltage amplifier (HVA) with a maximum range of output voltages from –80 to +80 V at an output current of up to 500 mA and an output voltage build-up rate of 10 V/μs. The voltage from the *HVA* output is delivered to probe *16* via the measuring unit (*MU*). The latter includes commutatable voltage dividers, current-measuring resistors, and two measuring amplifiers and generates two voltages. One of the voltages is proportional to the probe current and the other is proportional to the probe voltage. These signals arrive at a type 752 analog multiplexer *MUX* and then at an ATsP-12 ADC_1. Because the probe currents differ by more than an order of magnitude when recording the ion and electron CVC branches, it is necessary to control the sensitivity of the current-measuring amplifier during recording. This is accomplished by a program signal via a RUR-1 relay control module (*RCM*). The maximum number of pairs of points in the probe CVC is 320. They are recorded for a time shorter than 2 s, thus allowing us to carry out measurements in chemically active media under the condition of the formation of solid precipitations. The software for probe measurements incorporates built-in graphics, which provides a prompt evaluation of data obtained and rejection of defective results. The program for CVC processing provides data antialiasing with splines and calculates the first and second derivatives for determining the plasma potential and energy distribution function for electrons respectively. It also makes it possible to seek characteristic points of a CVC and its derivatives in interactive graphics mode.

To measure the flow rate of working gases, signals from electronic flow-rate controllers *6* are applied to the analog multiplexer and then arrive at the ADC_1. A measuring shunt (500 A and 75 mV) connected in series to the electromagnets registers their current. An analog signal from the shunt arrives at a type 70 ADC_2. The latter has a galvanic input isolation and program-switched ranges, which make it very convenient for measurements in high-power circuits. Wattmeter *9* (produced by the NIIFTRI Research and Production Association) is a waveguide segment with a cross section of 90 × 45 mm with wire bolometers set along the narrow wall at a certain distance from each other. Along with thermocompensating bolometers, they are connected in four bridge circuits, and each of them has an amplifier. Analog signals from these amplifiers arrive at the multiplexer and ADC_1. The incident, reflected, and transmitted microwave power is computed from these values.

In spectral measurements of plasma, its radiation is transmitted to the input of an MDR-12 monochromator via a quartz waveguide *22* and recorded by a FEU-100 photomultiplier *23*, whose output signal arrives at the ADC_1 via an U5-9 amplifier *25* and the multiplexer. A stepper control module (*SCM*) provides the operation of the stepper that turns the diffraction grating of the monochromator. Temperature of ions and neutrals is recorded on the basis of the Doppler broadening of spectral lines. For this purpose, optical radiation of plasma is led out through one of the sight unions and, using mirror *17*, is guided to the optical system. The latter consists of a positive lens *18*, monochromator or interference light filter *20*, and the Fabry–Perot interferometer *19*, at the exit of which a KTP-85 TV camera *21* is installed. This camera is a component of a PTU-64 industrial TV apparatus (Volna Research and Production Association, Novgorod). An LI-702-3 image vidicon with a built-in electron–optical intensifier is used in this camera. Therefore, it can operate at a low illuminance down to 0.25 lx. The television signal from the TV camera arrives at a VIDEO-8 module (Elektropribor Production Association, Cheboksary) (*MTV*) that, on a command of the control program, stores an exposure as an array of 256 × 256 × 8 b for 20 ms. Its buffer memory is designed for writing four image exposures. The software for interferogram processing has a graphic component and allows us to determine the temperatures of ions and neutrals from the profile of spectral lines recorded. In our experiments, the temperatures of neutrals and ions were within 1000–2000 and 2000–7000 K, respectively.

The distribution of the ion current density is one of the most important parameters in this type of apparatus, because in many cases, only ions play a determining

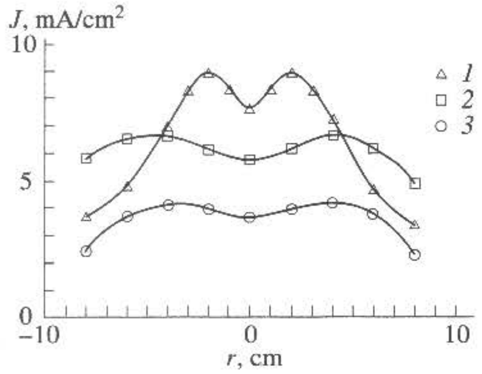

Fig. 4. Radial distribution of the saturation ion current density at the source output for two values of the magnetic field and incident power: (*1*) 900 G and 600 W, (*2*) 1100 G and 600 W, and (*3*) 1100 G and 400 W. Argon, $p = 0.32$ mtorr, and $z = 30$ cm.

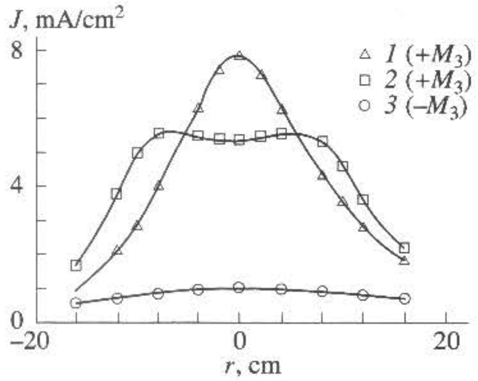

Fig. 5. Radial distribution of the saturation ion current density at the distance $z = 62$ cm from the input window for two values of the magnetic field: (*1*) 900 G and (*2* and *3*) 1100 G; the third electromagnet ($+M_3$) operates or ($-M_3$) does not operate.

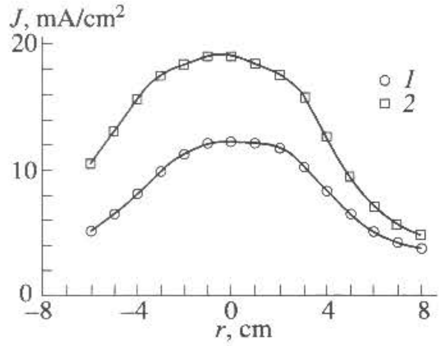

Fig. 6. Radial distribution of the saturation ion current density at the source output for pressures of (*1*) 0.5 and (*2*) 1.0 mtorr. The magnetic field of the electromagnets is $B_W = 945$ G. The permanent magnets are present. Krypton, $P = 900$ W, and $z = 30$ cm.

role in the reactions occurring on a substrate. Figure 4 presents radial distributions of the saturation ion current density at a distance $z = 30$ cm from the window as a function of the magnetic field of the electromagnets with the Sm–Co permanent magnets removed (numerical values B_W on the internal surface of the entrance window are always indicated) and on incident power. The curves show that at the magnetic field $B_W = 900$ G, the discharge is strongly radially inhomogeneous. It manifests itself as a core with a bright near-axial region. Under this condition, the ECR layer is localized in the immediate vicinity of the entrance window, and intense plasma heating takes place in its central region, which is characterized with the maximum electric wave field for the TE_{11} mode. As the magnetic field rises up to $B_W = 1100$ G, the discharge becomes more homogeneous, but we observe a dip in the ion current density, i.e., a decrease in the plasma concentration by ~10% in the near-axial region. This corresponds to the position of the ECR layer at a distance of about 10 cm from the window and to the presence of a whistler-heated region between the window and ECR layer. Figure 5 shows similar radial distributions corresponding to $z = 62$ cm. Here the decrease in the plasma concentration mentioned above is much less pronounced. Curves in Fig. 5 also illustrate a positive effect of the third magnet mounted at the exit of the plasmochemical reactor. We see that without this magnet the saturation ion current density becomes several times smaller as a result of plasma drift to the walls.

Adding permanent magnets to the system leads to a twofold increase in the plasma density (saturation ion current density is 15 mA/cm³), but its homogeneity simultaneously decreases (Fig. 6).

This experimental apparatus is intended for use in systematic studies in the field of plasma techniques for microelectronics [8].

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