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High-Current Low-Pressure Quasi-Stationary Discharge in a Magnetic Field: Experimental Research

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Abstract – The possibility of realizing several types of high-power quasi-stationary low-pressure discharge in a magnetic field was shown. Two noncontracted discharge regimes in crossed **E** and **H** fields were studied. These discharges had much higher cathode current densities than those of other known discharge types. Their parameter ranges were determined, and their operating regimes were investigated. The voltage for the high-voltage form discharge ranged from 450 to 1000 V; the discharge current amounted to 250 A, and cathode current density reached 25 A/cm^2. A low-voltage discharge form was first observed: voltage ranged from 75 to 120 V; discharge current amounted to 1800 A, and cathode current density reached 75 A/cm^2; lifetime was about 1.5 ms. The ion density was 1.5×10^{15} cm^{-3} in argon discharges and amounted to 5×10^{14} cm^{-3} in He–H$_2$-mixture discharges, while the electron temperature was about 3 - 8 eV. The properties of both discharge types are expected to open up new fields of application in technology.

1. INTRODUCTION

Low-pressure discharges in a magnetic field attract much attention due to their wide use in technological magnetron devices, closed-electron-drift plasma accelerators, and, as plasma emitters in electron or ion injectors.

Stationary regimes of the discharges in planar magnetrons of technological use are characterized by $p \simeq 10^{-4}$ - 5×10^{-2} torr operating pressure and 300 - 1000 G magnetic field at the cathode surface [1, 2]. Their AV characteristic is described by the formula $I_d = kU_d^n$, where I_d is the discharge current, and U_d is the discharge voltage. The quantities k and n depend on the device geometry, working gas type and pressure, and magnetic field strength. The condition $n > 1$ holds, if the cathode current density j_c does not exceed 0.03 A/cm^2. In this case the discharge voltage amounts to 400 - 600 V, the plasma density n_i ranges from 10^8 to 10^{11} cm^{-3}, and electron temperature T_e reaches 20 eV. If the current density is higher, a transition of the discharge into the arc regime is observed.

Because of the need for greater discharge power and plasma density, pulse or quasi-stationary regimes appear to be of interest. Some experiments on magnetron systems of various geometry showed that discharge regimes which do not transit to arcs can be obtained even at high currents. For example, a superdense glow discharge, realized in a device of "reversed-magnetron" type of coaxial geometry, exhibited the following parameters: about 70 A discharge current I_d, 400 V discharge voltage U_d, 60 μs pulse duration, and 10^{12} cm^{-3} plasma density n_i [3]. A pulse duration decrease down to 100 μs, which was performed in a planar magnetron discharge in Ar, N$_2$, or H$_2$ at 10^{-3} - 5×10^{-2} torr pressures and 1.0 - 3.0 kG magnetic field strength, permitted a 1000 A current value to be obtained in the noncontracted regime, at 300 - 500 V discharge voltage, with about 50 J of total energy deposition [4]. In both examples, the discharge current-voltage characteristic increased and then became constant with the increase in the discharge currents. A further increase in the discharge currents caused the discharges to transit to the arc regimes, with voltage not higher than 50 V under those conditions.

Our previous experiments demonstrated the possibility of realizing several stable discharge regimes in devices with closed electron drift [5 - 7]. Among these regimes which differed from the arcs, was an intermediate low-voltage regime ($U_d \simeq 100$ V, $I_d \le 1.5$ kA) of longer than 1-ms pulse duration (hereafter called a "high-current diffuse regime").

The main purpose of this work was to study experimentally a high-power noncontracted quasi-stationary discharge in crossed fields of various geometry and to determine their parameter ranges. We investigated the discharge regimes in various gas mixtures at 10^{-3} - 10 torr, $B_0 \le 1000$ G, and pulse durations exceeding 1 ms. Such regimes can be useful in generating large-volume dense plasmas and intense flows of charged particles. Furthermore, we consider qualitatively the mechanism of low-voltage high-current discharge formation.

2. EXPERIMENT

To study the high-current forms of the discharge, we used two types of devices: a planar magnetron and a system with specifically shaped hollow electrodes.

The planar magnetron (Fig. 1) involved a plane cathode 120 mm in diameter and a ring-shaped anode

160 mm in diameter. The electrodes were immersed in a magnetic field of annular permanent magnets. Magnetic circuits were used to vary the size of the region of the large magnetic-field radial component and magnetic field inhomogeneity degree. To control the magnetic field strength at the cathode surface, we displaced the magnetic system along the axis z (Fig. 1) and used two types of permanent magnets made of $SmCo_5$ and NdFeB. The discharge had an annular shape and was adjacent to the cathode. The maximum of the magnetic field radial component B_r at the cathode surface was 800 G for the $SmCo_5$ magnet or 1200 G for the NdFeB magnet. The cathodes we used were made of Cu, Mo, Ti, Al, or stainless steel. The cathode was placed on a cooled surface. The anodes were made of aluminum or stainless steel.

The system with shaped electrodes involved two hollow axisymmetrical electrodes 120 mm in diameter, separated by about 10 mm, and immersed in a cusp-shaped magnetic field produced by oppositely directed multilayer coils. The discharge volume bounded by the electrodes was about 10^3 cm^3. The ratio of the maximal magnetic field at the axis of symmetry $B_{\max}(z, 0)$ to the maximal magnetic field at the plane of symmetry $B_{\max}(0, r)$ was about 3. The values of $B_{\max}$ were controlled by coil current variation to range from 0 to 1000 G. The electrode shapes followed the magnetic line profile, which enabled the electric field to be perpendicular to the magnetic field along the cathode surface. Such a field configuration allowed us to combine a high-current magnetron discharge with a hollow-cathode discharge.

The gas from the discharge volume was pumped out; minimal residual gas pressure was about 8×10^{-6} torr.

It was possible to form the high-current quasi-stationary regime by applying a square voltage pulse to the discharge gap which was filled up with either neutral or pre-ionized gas. Estimates were made to determine both the quasi-stationary plasma density and its building-up time [5, 7]. The necessary pre-ionized plasma density n_i turned out to be 10^7 - 10^9 cm^{-3} for argon. In addition, the estimates determined the shape and parameters of the voltage pulse. The pre-ionization could be provided by RF discharge, anomalous glow or magnetron discharge, etc.

Figure 2 presents a simplified scheme of the discharge supply system. The supply unit involved a pulsed discharge supply unit and a system for pre-ionization. The quasi-stationary discharge-supply unit consisted of a long line of $W = 5.5$ kJ maximal energy content, a switch, and a matching unit. The pre-ionization system provided direct current up to 0.3 A and voltage up to 3 kV.

The frequency parameters of the pulsed supply unit were chosen in accordance with the increase in time of the quasi-stationary plasma density formation and the times of the ionization instability and ionization-overheating instability development. Designing the unit, we took into account the dependences which had been obtained in [8] of ionization relaxation on pre-ionization parameters, pressure, and pulse voltage amplitude. In addition, we allowed for the fact that the development time for the ionization-overheating instability was about 10^{-3} - 3×10^{-3} s in the pressure range up to 0.5 torr [9]. Thus, the supply unit was made providing square voltage and current pulses with raise times (leading edge) of 5 - 60 μs and durations of as much as 1.5 ms. Short-circuit current amplitude was up to 3 kA; no-load voltage was as much as 2.4 kV.

For pre-ionization, we used a stationary magnetron discharge; the discharge current ranged up to 300 mA. We measured the discharge current-voltage characteristics (CVC) in a 10^{-3} - 10 torr pressure range and plasma parameters of the discharge at the symmetry center of the shaped-electrode system using a probe technique. We found out that only the regimes with magnetic field strength not lower than 400 G provided the initial plasma density in the 10^9 - 10^{11} cm^{-3} range. This initial density was sufficient for plasma density to grow when the square voltage pulse was applied to the gap. So we chose these regimes as pre-ionization regimes.

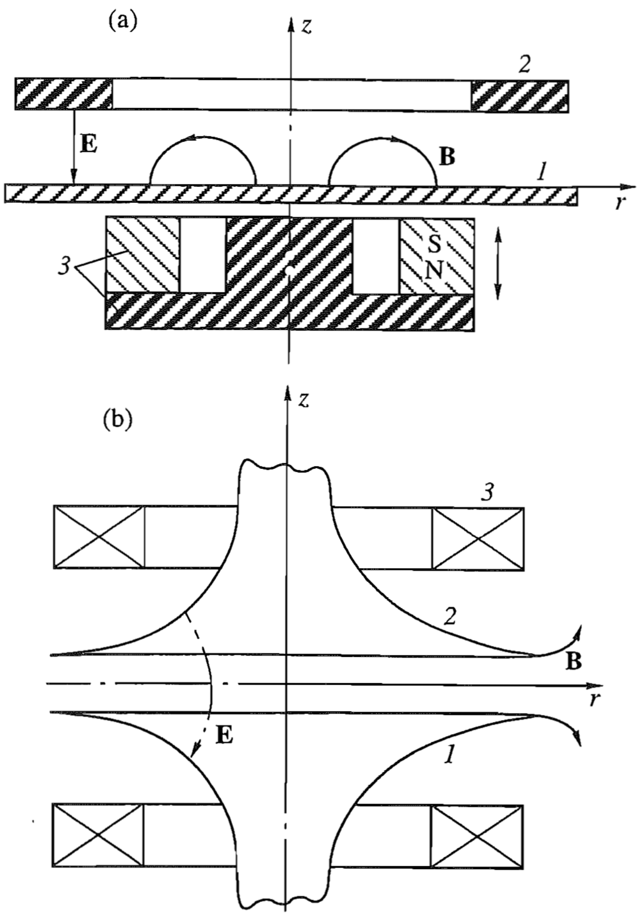

Fig. 1. Discharge device configurations: (a) planar magnetron; (b) shaped-electrode configuration. (*1*) Cathode; (*2*) anode; (*3*) magnetic system.

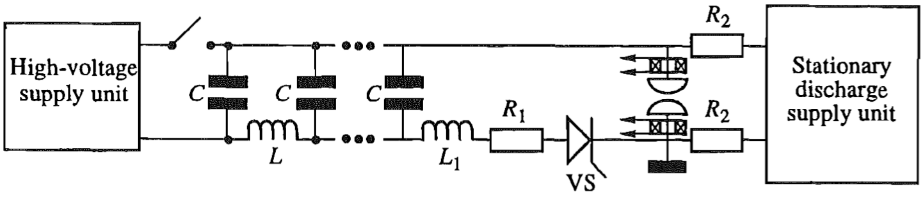

Fig. 2. Discharge supply unit.

3. QUASI-STATIONARY DISCHARGE REGIMES

We studied the high-current discharge in wide ranges of discharge current (from 5 A to 1.8 kA) and operating pressure (from 10^{-3} to 10 torr) using various gases (Ar, N_2, SF_6, He, and H_2) or their mixtures of various composition (argon percentage in Ar–N_2 and Ar–SF_6 composition ranged from 10 to 90%; He : H_2 = 1 : 1). We investigated the planar-magnetron and cusped-mirror configurations varying the magnetic field strength. We obtained current-voltage characteristics of the discharge, time-integrated photographs of the discharge glow, and probe characteristics of the discharge plasma. We detected the particle flux from the plasma and measured their intensities. As a result, we found out that a variety of regimes differing in discharge voltage, current range, and discharge space structure occurred.

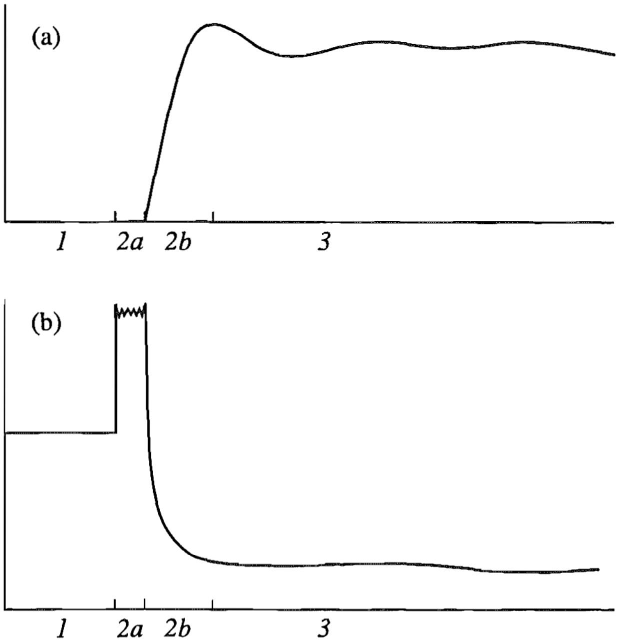

Fig. 3. Oscillograms of (a) current and (b) voltage of the quasi-stationary discharge (50 μs per div., 180 A per div., 180 V per div.).

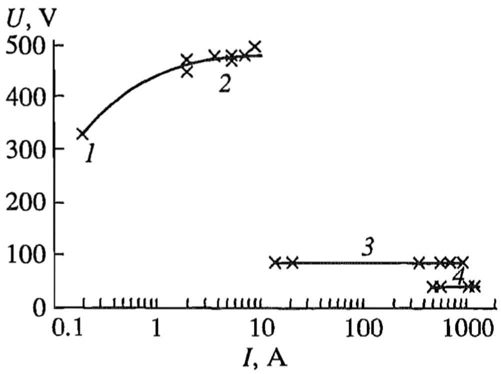

Fig. 4. Current-voltage characteristic of the quasi-stationary discharge with shaped electrodes in argon, $p = 0.1$ torr; $B =$ 0.4 kG.

Figure 3 shows typical voltage and current oscillograms of the quasi-stationary discharge. Part *1* in the voltage oscillogram represents the voltage of the stationary discharge (pre-ionization stage). Part *2a* displays the square voltage pulse application to the gap. At this stage, the plasma density grows and reaches its quasi-stationary value (part *2b*); the discharge current also grows, and then both the discharge current and voltage attain their quasi-stationary values (part *3*). The time it takes for the plasma density to reach its quasi-stationary value corresponds to the ionization relaxation time. For example, for argon, discharge when pre-ionization plasma density is about 10^9 - 10^{11} cm^{-3} this time is about 50 μs. Each point of the discharge characteristic represents a pair of voltage and current oscillograms. We detected inhomogeneity of the discharge plasma or cathode spots visually, using filters, or by photographing the discharge.

The current-voltage characteristic of the low-pressure quasi-stationary discharge in a magnetic field had four different parts corresponding to stable forms of the discharge. Figure 4 shows a typical CVC of the discharge in argon at 10^{-1} torr pressure and 0.4 kG magnetic field. One can differentiate two parts: part *1* corresponds to the magnetron discharge with current up to 0.2 A and voltage range from 260 to 280 V; part *4* corresponds to the high-current low-voltage arc discharge of current greater than 1 kA and 10 - 30 V voltage with a cathode spot. In addition, we found out experimentally that two other stable forms of quasi-stationary discharge could exist. Both the plasma and cathode layer had a diffuse character at cathode current density much higher than that of typical magnetron discharge. If the discharge current ranged from 0.2 to 15 A, a high-current magnetron discharge having initial discharge characteristics was observed (part 2 of the oscillogram).

In this case the discharge voltage was rather high, approximately 350 - 500 V. If the current was increased and ranged from 15 to 1000 A, a diffuse regime of high-current discharge was observed (part *3*); its CVC was a straight line parallel to the current axis. The discharge voltage was about 90 V over the current range. The cathode current density was about 50 A/cm^2.

It should be noted that the boundaries of regimes could vary depending on the discharge conditions, e.g., on pressure, magnetic field strength, etc. Then, we studied regimes *2* and *3* separately to determine the boundary parameters of their occurrence, such as current, voltage, pressure, and magnetic field.

We studied the regimes both in the planar magnetron and shaped-electrode system geometries and found out that both regimes could occur regardless of the type or particular parameters of the discharge configuration.

Figure 5a exhibits representative CVC of the high-current magnetron discharge. They were measured in the discharge in Ar and N$_2$, as well as in or Ar–N$_2$ (10 - 90% of argon) or He : H$_2$ = 1 : 1 mixtures at 10^{-3} - 10 torr pressure range and 0.4 - 1.0 kG magnetic field. The cathodes we used were made of Cu, Ti, Al, Mo, or stainless steel. To reduce the effect of cathode surface quality on the discharge parameters, the electrodes were preconditioned by multiple discharges or cleaned by glow discharge in argon. The dependence $U_d(I_d)$ remained qualitatively the same for all values of were the pressure p, transverse magnetic field $B_\perp$, sort of the gas, cathode material, electrode configuration and discharge size. The discharge voltage increased monotonically with current up to a maximum $U_d^{\max} \simeq 500 - 1100$ V depending on the magnetic field strength, sort of the gas, and cathode material. Then the discharge transferred to regime *3* or to the arc regime. If the voltage pulse duration τ was less than 20 ms, the current of transition amounted to 250 A, which corresponded to 25 A/cm^2 cathode current density j. A decrease in magnetic field strength resulted in an increase in the discharge voltage $U_d^{\max}(B_\perp)$ up to some value U_d^{II} depending only on the cathode material and sort of the gas. A further decrease in B_r caused the discharge to transit to a high-voltage regime which was characterized by a steep CVC and low discharge current (about 1 A).

As the decreasing magnetic field approached the value of the discharge transit to the high-voltage regime, the discharge voltage increased smoothly, and the discharge current decreased.

We measured the CVC of the high-current magnetron discharge for two different discharge diameters. The CVC turned out to be independent of the diameter in the max B_r region. It should be noted that, being transferred to the high-current regime, the discharge expands over a considerably larger area of the cathode surface than it occupied in the stationary pre-ionization regime. In the case of the planar magnetron, the discharge occupied either the ring area beyond the circular region of max B_r or the disk area bounded by the circle of max B_r; the area depended on the magnetic field configuration. Because the discharge current was the same in both cases, the current densities differed considerably, but the CVCs were similar. The current density values characteristic of these regimes for the argon discharges were $j \simeq 4$ A/cm^2 ($U_d = 540$ V, $I_d = 225$ A) and $j \simeq 25$ A/cm^2 ($U_d = 500$ V, $I_d = 218$ A).

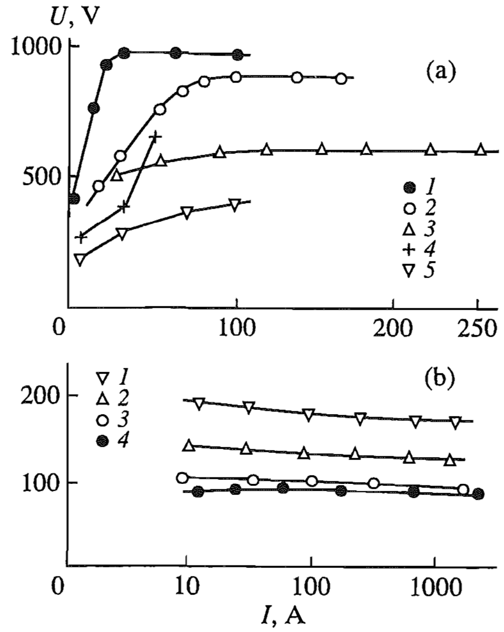

Fig. 5. (a) High-current magnetron discharge: (*1*) planar magnetron, Cu, $p = 5 \times 10^{-3}$ torr, Ar; (*2*) planar magnetron, Ti, $p = 5 \times 10^{-3}$ torr, Ar : N$_2$ = 4 : 1; (*3*) planar magnetron, Ti, $p = 10^{-2}$ torr, N$_2$; (*4* and *5*) shaped-electrode system, Cu, $p = 5 \times 10^{-2}$ torr, He : H$_2$ = 1 : 1, and Cu, $p = 10^{-1}$ torr, Ar. (b) High-current diffuse regime: (*1* and *2*) shaped-electrode system, Cu, $p = 1$ torr, He : H$_2$ = 1 : 1 and Cu, $p = 10^{-1}$ torr, He : H$_2$ = 1 : 1; (*3*) planar magnetron, Cu, $p = 10^{-1}$ torr, Ar; (*4*) planar magnetron, Cu, $p = 10^{-1}$ torr, Ar : SF$_6$ = 4 : 1.

The roughness of the cathode surface was not important for the occurrence of regime 2, though the probability of discharge transit to the arc discharge was greater for the cathodes with rougher surfaces.

A feature of the shaped-electrode discharges in the He–H$_2$ mixture was a second form of high-current magnetron regime at a 400 - 650 V discharge voltage that was independent of discharge current until transferring to regime *3*.

Regime *2* was characterized by an intense cathode sputtering due to both high energy and density of ion flow. To study the sputtering, we used a probecollector placed 120 mm from the cathode. The pulsed deposition rate of cathode material (copper was used) turned out to be about 80 μm/min in the argon discharge, $I_d = 65$ A, $U_d = 900$ V. The current pulse duration was 25 ms, and the repetition frequency was 10 Hz, which corresponded to ≃20 μm/min averaged deposition rate. We used a scanning electron microscope REM-101 (Russian trade mark) to measure the thickness of deposited layers.

We measured the plasma density n_i in the region near the collector by applying to the collector a pulse of biased voltage with respect to the anode. The density turned out to be about 3×10^{12} cm^{-3} in the regime of $I_d = 60$ A and $U_d = 900$ V.

Figure 5b presents typical CVCs of high-current diffuse discharge measured at various pressures, gases, cathode materials, magnetic fields, and pre-ionization parameters. Analyzing the CVCs, we found out that the discharge voltage weakly depended on the magnetic field geometry and its strength, and on the cathode material; the constant voltage turned out to range from 70 to 140 V as the current ranged from 5 to 1800 A. The voltage was slightly (within 50 V) changed from gas to gas. Transferring to regime *3*, the discharge occupied a significantly larger cathode surface than in the stationary regime.

The parameters of the shaped-electrode discharge transit to regime *3*, as well as the condition of its transit to arc regime *4*, could be well determined for every given set of the discharge parameters. The point of the planar-magnetron discharge transit to the arc regime was determined by discharge voltage and structure changes; the structure changes were recorded by optical diagnostics. To study the structure of the discharge in regime *3*, we photographed it using neutral light filters of various attenuation factors. The filters and exposure times were chosen so that the pre-ionization discharge glow was not recorded. One can see from the photographs presented in Fig. 6 that the discharge was spatially uniform even at about 1 kA discharge currents. If the current was raised above 1.8 kA or the pulse duration was increased to 2 - 10 ms, an instability development and discharge contraction was observed. The planar-magnetron discharge transfer to regime *3* resulted in a smearing of the annular structure of the pre-ionization discharge: the discharge plasma and current area were seen to expand and cover the whole cathode surface (Fig. 6). If the discharge current or pulse duration were increased, the instability development accompanied by the plasma column contraction and the occurrence of one of several cathode spots were also observed in the planar magnetron.

Chemical analysis of the collector surface layer was done; the cathode material was not detected there. Hence, there was no cathode sputtering in these regimes.

We elaborated on a pulsed probe technique specially designed to measure the plasma parameters in regime *3*. The technique provided probe characteristics to be measured in ≃10 μs time intervals and allowed the probe current to amount to 50 A [10].

We measured the parameters of pulsed high-current quasi-stationary discharge in a cusp magnetic-field configuration with B ranging from zero to 1 kG in various gases. The pressure ranged from 10^{-1} to 1 torr; the discharge current ranged up to 1500 A. The pulse voltage applied to the probe was 100 - 500 μs delayed with respect to the discharge current pulse, i.e., T_e and n_i were measured after the establishment of the quasi-stationary regime of the high-current discharge.

The plasma parameters were determined from the probe measurements. Ion density measured at the system center in regime *3* in argon increased almost linearly with the discharge current at various pressures and magnetic field strengths. The density ranged from (2 - 2.5) × 10^{14} cm^{-3} at 360 - 540 A current up to (1 - 1.5) × 10^{15} cm^{-3} at 1100 - 1400 A current. The maximal plasma density of high-current diffuse discharge in argon was measured to be $n_i \simeq 1.5 \times 10^{15}$ cm^{-3}, while the electron temperature T_e was 4 - 6 eV, the discharge current was 1100 A, magnetic field strength B was 0.8 kG, and the pressure p was about 0.2 torr. The ion saturation current of the probe j_{sat} was about 11 A/cm^2. Ion density increased with pressure; the density increase was accompanied by a decrease in the electron temperature.

The plasma density in He–H_2 discharge also increased with the discharge current. However, the maximum of ion density was $n_i \simeq 2.4 \times 10^{14}$ cm^{-3} at the conditions similar to those mentioned above: p = 1.5 torr, $B = 0.8$ kG, $I_d \simeq 1100$ A.

4. DISCUSSION

We obtained a generalized CVC of the quasi-stationary low-pressure discharge in a magnetic field (Fig. 7) based on a variety of measured AV discharge characteristics under various conditions. Parts *1* and *4* correspond to stationary magnetron and arc discharges, respectively. They were inherent in the discharge throughout the pressure and magnetic field ranges. These two regimes were comprehensively described in [1, 11].

Part *2* pertains to the high-current magnetron discharge regime occurring in the 0.2 - 250 A current range. The voltage increased with current up to some critical value of current and then became constant. The discharge voltage was rather high – up to 1.2 kV. The discharge had a greater probability of being realized if the pressure ranged from 2×10^{-3} to 10^{-1} torr.

We suggested that this discharge was structurally very close to the high-current discharge described in [4]. The reasons are the following: both the pressure and magnetic field ranges were almost the same, the discharge did not exhibit contraction, and their CVCs were very similar. However, the discharge we dealt with had a higher discharge voltage (500 - 1200 V) than the 300 - 500 V discharge described in [4]. Hence, one could expect the cathode sputtering to have more importance.

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