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超功率体放电的形成及其应用

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摘要:研究了氮气中的高压体(扩散)放电特性,实验中施加的极间隙脉冲电压达数百千伏,持续时间为数纳秒,上升时间为几个纳秒,给出了实验结果。研究了氮气压强为 $(0.4\sim 2)\times 10^5$ Pa时,从扩散形式到火花放电的放电转换过程。确定了在氮气压强下电流幅度与逃逸电子束电流脉宽的关系。结果表明,导致隙间扩散放电的超短雪崩电子束(SAEB)对放电过程有重要的影响。在该压强下得出了SAEB瞬间产生相对放电电流的时延与压强的关系,根据该关系,时延随着压强增加而变化,并且在压强为 2×10^5 Pa时最小,同时扩散放电电流脉冲的峰值随压强增加而减小。在 0.5×10^5 Pa的压强下,使用刀片电极和6 cm长的 $N_2:SF_6=10:1$ 的激活媒质,得到了输出能量为2 mJ、脉冲功率为0.55 MW的激光。最后,在大气压强下,对AlBe箔片进行了重复频率放电处理(REP),其表层清除了碳而且氧原子以450 nm/300 pulse渗入箔片。

关键词:体放电;扩散放电;非均匀电场;逃逸电子;紫外激光器;修饰及清洁

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Formation of superpower volume discharges and their applications

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Abstract: The experimental results on study of characteristics of the high-pressure volume (diffuse) discharges in nitrogen at applying to the interelectrode gap voltage pulse with the amplitude of hundreds kV, duration of several ns and the rise-time of fraction ns are presented. At the pressure range of nitrogen in $(0.2-4)\times 10^5$ Pa, the discharge transformation from the diffuse form to the spark is investigated. Dependencies of the current amplitude and FWHM of the runaway electron beam current on nitrogen pressure are determined. It is shown that the generation of the Supershort Avalanche Electron Beam (SAEB) leading to the formation of diffuse discharge in the gap has a significant influence on the development of the discharge. At the pressures indicated above, the dependence of the time delay of SAEB's moment generating relatively discharge current beginning on pressure are obtained. According to this dependence, the time delay changes as pressure increases and it is minimal at pressure of 2×10^5 Pa. Also, it is shown that the maximum peak value of diffuse discharge current

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pulse decreases with increasing pressure. At a pressure of 0.5×10^5 Pa with the use of blade electrodes and the $N_2 : SF_6 = 10 : 1$ active medium of length 6 cm, the output laser energy of 2 mJ is achieved for the pulse power of 0.55 MW. It is reported that during the treatment of the AlBe foil by the Runaway Electron Preionized (REP) discharge in atmospheric pressure air, its surface layer is cleaned from carbon, and atoms of oxygen penetrate into the foil (by 450 nm per 300 pulses).

Key words: volume discharge; diffuse discharge; non-uniform electric field; runaway electrons; UV laser; modification and cleaning

1 Introduction

In recent years, study of high-pressure ns volume discharges formed in a nonuniform electric field at high voltages across the gap has received much attention. When forming this type of discharges, runaway electron beams and X-ray are registered, and the discharge plasma can be used to a create powerful source of spontaneous^[1] and a laser^[2] radiation, as well as for the metal's surface modification^[3]. Reduction of voltage pulse duration and (or) decreasing in gas pressure, as well as increasing in the interelectrode gap lead to the process of formation of high-pressure diffuse discharges in a nonuniform electric field in various gases markedly facilitated. Diffuse form of discharge persists when voltage pulses of positive polarity are applied to the electrode with small radius of curvature^[4] when the cathode and anode spots appear on the electrodes^[5]. In Ref. [6], this type of discharge REP DD (Runaway Electron Preionized Diffuse Discharge) was proposed. This mode of discharge consists of three main stages^[7]. Another unique feature of the diffuse discharge is high excitation power density (\sim hundreds MW/cm³).

For the first time, REP DD at atmospheric pressure was carried out apparently in the late 60's in helium^[8] and air^[9]. However, the electrical characteristics of ns volume discharges in a nonuniform electric field and the impact of runaway electrons for their formation is not well understood. This is due to the difficulties in the

registration of the discharge current pulses with subnanosecond resolution. Even greater difficulties arise in the registration of the SAEB^[5-6].

The main objective of this paper is to study the characteristics of a diffuse discharge in nitrogen, which is formed at high overvoltages in the conditions of generation of the runaway electrons, as well as to present some applications of REP DD.

2 Experimental apparatus and measurement technique

In this paper the diffuse discharge was formed in a chamber with a diameter of 54 mm which was filled with gases of high pressure. In the experiments, the chamber filled with nitrogen at pressures of 20 – 400 kPa and air at atmospheric pressure. The generator RADAN-220^[10] was used as a source of voltage pulses applied to the gap. Its impedance was 20 Ω . The amplitude of the voltage pulse formed by this source on high-resistance load was 250 kV. The pulse duration at the matched load and the rise time of voltage in the transmission line were 2 ns and 0.5 ns, respectively. High-voltage forming line of generator RADAN-220 filled with transformer oil was connected to the load through compact spark-gap, the inductance of which increases the rise time of the voltage pulse in the transmission line. Insulator of the gas diode was made of polycaprolactam.

Discharge gap was a flat anode and cathode with small radius of curvature which reinforce

the electric field near it. The cathode had the appearance of tube made of steel foil with thickness of $100\ \mu\text{m}$. Its diameter was 6 mm. In the experiments, the distance d between the electrodes was 6 and 12 mm.

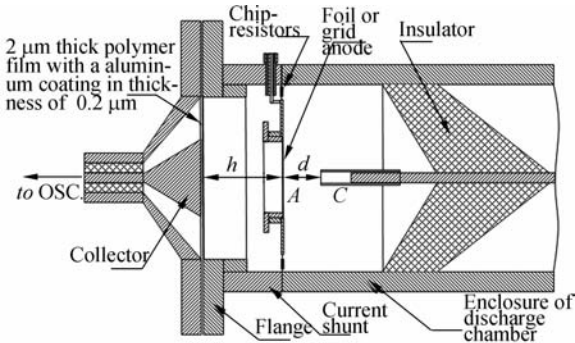


Fig. 1 Scheme of simultaneously registration of the discharge current and runaway electron beam current

Fig. 1 shows the scheme of simultaneous registration of the discharge current and runaway electron beam current. For simultaneous recording of these signals a special current shunt was made. It consists of 88 thin-film chip-resistors with a nominal value of $3.75\ \Omega$. The design had the appearance of a parallel connection of resistive elements which was achieved by placing them around the current-collecting part in the form of disc made of brass. On the opposite side, the shunt had contact with an enclosure of the discharge chamber. In the center of current-collecting part there was a hole with a diameter of 20 mm, which could be mounted foil or grid of the same sizes and shape and which eventually played role not just anode but the filter. This design provides both the registration of the discharge current and displacement current by shunt and the registration of the SAEB current and capacitive current by collector located behind the anode. Collector was in the form of a cone with a diameter of the receiving part of 20 mm and located at a distance of 27 mm from the anode. The time resolution of the detector was 0.1 ns. To exclude the possible influence of electromagnetic pickup on the signal electron beam cur-

rent in front of collector with a transition flange (Fig. 1) a set of two copper discs with a thickness of $50\ \mu\text{m}$ was installed. In the center of each disc was to make a hole with a diameter of 20 mm and between them was placed the polymer film thickness of $2\ \mu\text{m}$ with a aluminum coating in thickness $0.2\ \mu\text{m}$, through which the electron beam could pass. Since the experiments were carried out at high pressure gases, then, to avoid the damage to the film, it was fixed with steel grids on both sides. Grids have transparency on the light of 64 %.

Synchronization of signals of the REP DD current and SAEB current was performed relative to time moment corresponding to their appearance in the plane of the anode by virtue of registration of displacement current with the collector and the shunt.

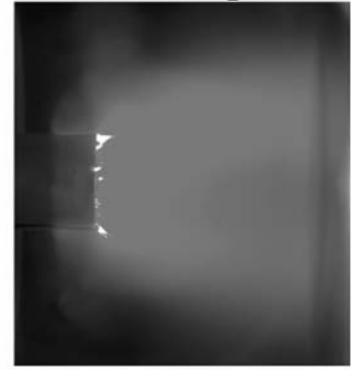
Electrical signals recorded with a digital real-time oscilloscope Tektronix DPO-70604, bandwidth and sampling frequency is 6 GHz and $25\ \text{GS} \cdot \text{s}^{-1}$, respectively. Signals from the current shunt and collector at the input of the oscilloscope were transferred to broadband coaxial cables. To attenuate the signals, attenuators Barth Electronics 142-NMFP were used. Shooting of an integrated picture of the glow discharge was carried out using a digital camera SONY A100 through the side windows of the discharge chamber made of CaF_2 . Radiation pulses of the discharge plasma were recorded using a photomultiplier (Photek PD025) with a temporal resolution of 0.1 ns, which was located at a distance of 20 cm from the side window.

3 Experimental results

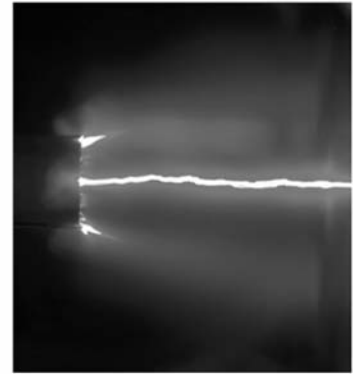
We have already noted that when voltage pulse with duration of ns applying the gap, depending on conditions, both diffuse and constricted discharges are realized. Moreover, in the early stage of the constricted discharge, initially diffuse discharge is formed, and then spark channel

bridges gap^[7]. Our investigations confirm earlier results on the formation of diffuse discharge and its contraction. At relatively large gaps (12–16 mm) at ns voltage pulse and atmospheric pressure of nitrogen, the air discharge is usually diffuse, as shown in Fig. 2(a). The bright plasma formations which are evenly distributed on the edge of the tubular electrode are visible only on the electrode with a small radius of curvature. In nitrogen at the electrode gap 12 mm and the cathode with a small radius of curvature of the diffuse discharge formed in the pressure range of nitrogen from 20 to 400 kPa. In all range of these pressures behind the anode foil SAEB was recorded. At high pressures with a reduction in the interelectrode gap up to 6 mm on the integral photographs of radiation from the gap the radiation of the spark channel was recorded, as presented in Fig. 2(b). However, the generation SAEB continued with a decrease in the electrode gap, with the contraction of the discharge in the entire range of pressures. Changing the gap would only affect on the SAEB amplitude and time delay of the SAEB relative to the front of the voltage pulse. Fig. 3 shows the dependence of time delay of the appearance of the intensive light in the UV and visible spectrum on nitrogen pressure. The radiation in the UV region belongs to the second positive system of nitrogen and has the highest intensity in diffuse discharge^[11]. Broadband radiation in the visible spectrum belongs to the spark channel dense plasma. It is seen, from the Fig. 3, that the emission of the spark channel is delayed relative to UV radiation of the diffuse discharge, which confirms that the formation of the diffuse discharge occurred before the spark formation.

Typical oscillograms of the discharge current and electron beam current are presented in Fig. 4. Pulse of the SAEB current is synchronized with discharge current. This is done by the displacement current, which was recorded by means of the collector simultaneously with an e-



(a)



(b)

Fig. 2 Photographs of the diffuse discharge (a) and constricted discharge (b) in nitrogen

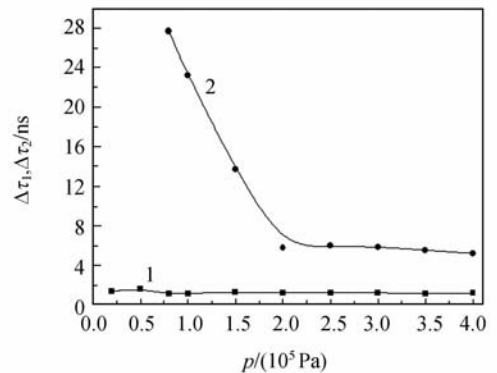


Fig. 3 Dependencies on nitrogen pressure of time delay of the UV radiation's appearance $\Delta\tau_1$ (1) and time delay of the spark's appearance $\Delta\tau_2$ (2) relatively discharge current beginning. RADAN-220, $d=6$ mm

lectron beam current when the anode foil was replaced by the grid. At the gas pressure of tens and hundreds Torr (1 Torr = 133 Pa), the high-

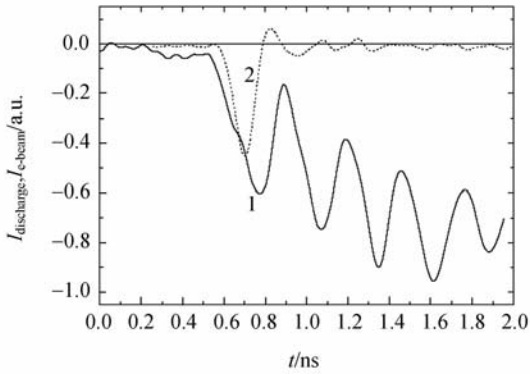


Fig. 4 Typical oscillograms of the discharge current (1) and runaway electron beam current (2)

est values of the discharge current are reached at the time corresponding to the time of SAEB generation. This value reduces as the pressure increases. The maximum value of the discharge current is reached after the runaway electron beam generation, as depicted in Fig. 4. Dependencies of the maximal amplitude value of the discharge current and its time delay relative to the beginning of the discharge current on nitrogen pressure obtained with the generator RADAN-220 and with a gap of 12 mm are presented in Fig. 5. Pressure enlargement leads to an increase in the time delay between the start of the discharge current and the time moment corresponding to the maximum amplitude value of the discharge current. The change in SAEB amplitude as a function of nitrogen pressure is illustrated in Fig. 6. It is evident that in these conditions (tubular cathode and the electrode gap 12 mm) the amplitude of the beam current decreases with increasing pressure. Note that these amplitudes of SAEB, presented on Fig. 6, were recorded through the aperture diameter of 20 mm behind the three grids with transparency on the light of 64 %. Amplitude of the runaway electron beam current from the whole surface of the anode is several times greater^[5]. When reducing the interelectrode gap up to 6 mm the SAEB amplitude was decreased by two orders of magnitude. Dependence of the SAEB pulse duration at FWHM on the pressure is illustrated in Fig. 7(a). With

elevating of nitrogen pressure up to 2 atm FWHM of the electron beam current reduces and then increases. Minimum of the SAEB duration corresponds to the minimum time delay Δt until the SAEB generation. As we noted above, at the nitrogen pressure of 2 atm the closing time of gap by the front of the plasma is minimum. The increase in pulse duration with elevating pressure over 2 atm may be associated with reduce in movement velocity of front of the ionization wave. Such an increase in the duration of the SAEB pulse was previously observed by us in SF6 when the pressure increased^[12]. In a heavy gas pulse beam current of fast electrons, when applying voltage pulses from the generator RADAN-220, began to increase significantly at the pressure of 0.8 atm. We believe that due to slowing of the front of the ionization wave increases the time during which the conditions for SAEB generation are saved.

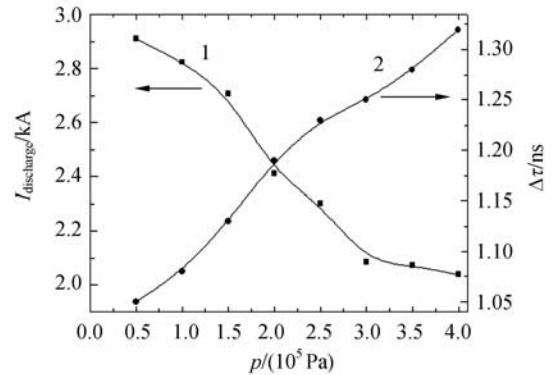


Fig. 5 Dependencies of discharge current amplitude (1) and its time delay relative to beginning of the discharge current (2) on nitrogen pressure

The dependence of the time delay Δt of SAEB generation on nitrogen pressure is shown in Fig. 7(b). As observed from this dependence, with increasing nitrogen pressure, the moment of generation of runaway electron beam occurs all before, and at a pressure of 200 kPa Δt reaches its minimal value. Re-increase in value Δt observed at nitrogen pressure above 200 kPa. On this basis, one could argue that the growing

nitrogen pressure in the gap result in the time during which the plasma front reaches the anode is reduced. The pressure $p \sim 200$ kPa is the point at which this time has a minimum value. A further increase in pressure leads to the fact that the velocity of propagation of the ionization wave front from the cathode to the anode decreases.

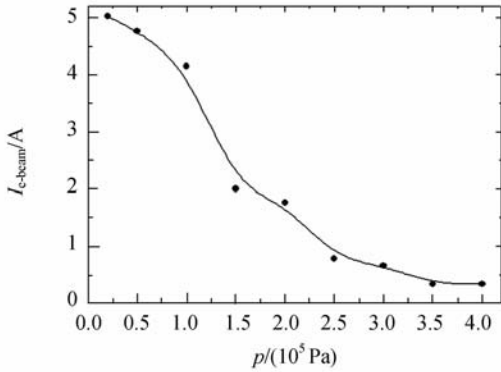
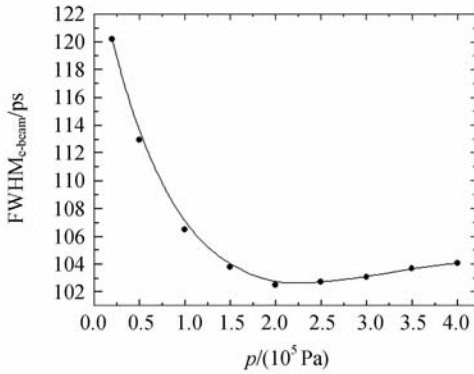
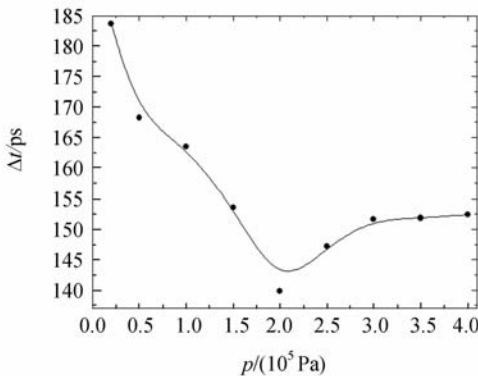


Fig. 6 Dependence of the amplitude of runaway electron beam on nitrogen pressure



(a)



(b)

Fig. 7 Dependencies of FWHM of runaway electron beam current (a) and time delay Δt of SAEB generation relative to beginning of discharge current (b) on nitrogen pressure

4 UV lasing in nitrogen pumped by a runaway-electron-preionized diffuse discharge

Fig. 8 shows the design of a laser chamber. The distance between the cathode and anode was 14 mm. The cathode of length 6 cm and anode of length 8 cm were made of a 120- μm -thick stainless steel foil. The two electrodes were blades with rounded edges, which provided a more homogeneous pump energy input over the length of the interelectrode gap. Laser radiation was detected with a FEK-22 photocell and an IMO-2N calorimeter. The output signals from the FEK-22, the capacitive divider, and the current shunt were recorded with a TDS-3054B oscilloscope (0.5 GHz, five samplings for 1 ns). Experiments were performed with nitrogen and its mixtures with argon, helium, and SF_6 as active media.

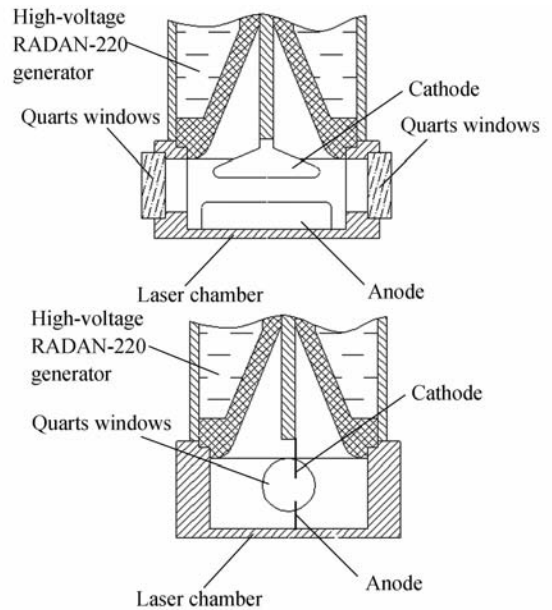


Fig. 8 Laser chamber design; cross sections of the chamber along (top) and perpendicular (bottom) to the optical axis of the cavity

During lasing experiments, a diffusive discharge was realized without the preliminary

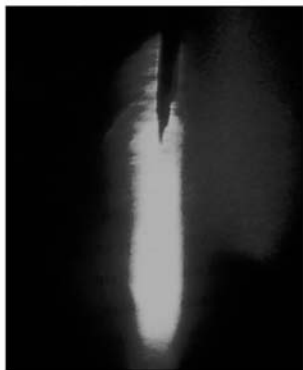
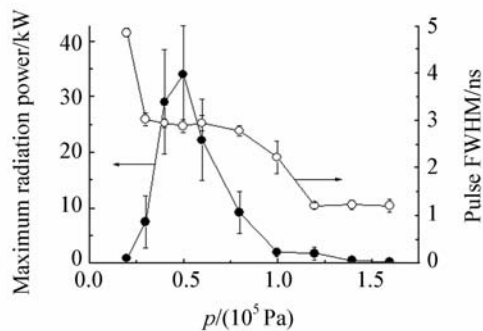


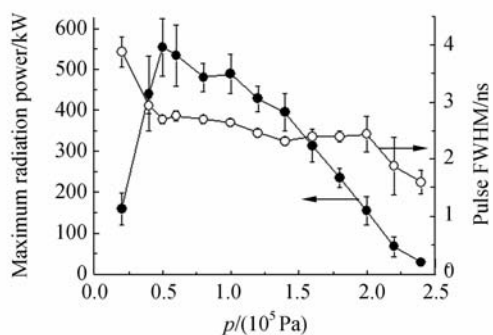
Fig. 9 Photographs of luminescence of white paper excited by UV laser radiation. The $N_2 : SF_6 = 10 : 1$ mixture, the mixture pressure is 50 kPa

preionization of the discharge gap both in nitrogen and its mixtures with argon, helium, and SF_6 at pressures up to a few hundred kPa. Lasing was obtained both in nitrogen and its mixtures with SF_6 . Fig. 9 presents the photograph of luminescence of paper excited by UV laser radiation obtained in the $N_2 : SF_6 = 10 : 1$ mixture. A similar picture was observed for lasing in pure nitrogen. The use of two electrodes with a small radius of curvature provided a more uniform radiation intensity distribution along the discharge gap length compared to the knife-plane electrode configuration.

As the nitrogen pressure decreases, the leading edge of the laser pulse becomes less steep, and the pulse duration increases. A similar result was obtained for lasing in the $N_2 : SF_6 = 10 : 1$ mixture. The dependences of the laser pulse peak power and FWHM on the nitrogen pressure are presented in Fig. 10(a). One can see that the radiation power achieves the maximum value at a pressure of 50 kPa, while the pulse duration decreases with increasing pressure. The minimum duration of the laser pulse equal to 1 ns was obtained in nitrogen at pressures 120–160 kPa. The average pulse energy at a nitrogen pressure of 50 kPa was 0.1 mJ. The radiation energy in mixtures of nitrogen with helium and argon was lower under the same



(a)



(b)

Fig. 10 Dependences of the maximum laser radiation power and the laser pulse FWHM on the nitrogen pressure [(a) lasing in pure nitrogen and (b) in $N_2 : SF_6 = 10 : 1$ mixture]

conditions. The dependences of the laser pulse parameters for the $N_2 : SF_6 = 10 : 1$ mixture on the mixture pressure were similar to those in pure nitrogen, Fig. 10(b). At the same time, the maximum peak radiation power at a mixture pressure of 50 kPa increased by 16 times compared to that in nitrogen and was 0.55 MW. The laser pulse energy at a pressure of 50 kPa was 2 mJ, corresponding to the specific energy output 0.1 mJ/cm^3 . The lasing efficiency with respect to the energy stored in a forming high-voltage line of the RADAN-220 generator was 0.1%, which is a high value for a laser with a comparatively small active length ($\sim 6 \text{ cm}$) and a high mixture pressure. These lasing parameters were obtained in a nitrogen laser of design considerably different from conventional one. Thus, for example, the addition of SF_6 to nitrogen in conventional nitrogen lasers leads, as a rule, to

the two or three-fold increase in the output radiation energy. Note also that the working mixture has high optimal pressures. This fact can be used for the development of lasers emitting short pulses. The nitrogen laser emitted at 337.1 nm both in N_2 and the $N_2 : SF_6 = 10 : 1$ mixture. Usually, N_2 - SF_6 mixture lasers pumped by a transverse discharge also emit at 358 nm. Our study has shown that the REP DD pump power and homogeneity are sufficient for obtaining lasing in nitrogen and the $N_2 : SF_6 = 10 : 1$ mixture at pressures up to 250 kPa. The specific output energy emitted at 337.1 nm in the second positive system of nitrogen was achieved at 0.1 mJ/cm³. These results suggest that high-power laser radiation can be obtained upon REP DD pumping of various gaseous media, in particular, dimers of heavy inert gases. For this purpose, we plan to build discharge chambers with of large volumes and large active lengths. Note in conclusion that the formation of the volume (diffusive) discharge, as shown in [1, 2, 5], is caused by pre-ionization of the runaway electrons, which are generated due to application of the electric field near electrodes and in the discharge gap. The use of the REP DD allows one to increase the working pressure of the mixture and simplify the design of the discharge gap. The REP DD pumping eliminates the need to use an additional system for preionization of the discharge gap.

5 Modification and cleaning of metal surfaces

As discussed above, a REP DD is characterized by high specific input powers. Furthermore, plasma, being a source of high-power UV and VUV radiation, generates a runaway electrons beam and a shock wave^[1,5]. These properties of the REP discharge were used for exposure to the AlBe-foil surface. Excitation of air was realized

in the gap which design is presented in Fig. 2 (a). The distance between a plane foil anode and a tube-shaped cathode was 12 mm. A RADAN-220 pulser was used as a pulse voltage source. The experiments were carried out at the discharge current amplitude of 3 kA at both voltage pulse polarities. The total duration of the discharge current pulse was 30 ns and the duration of the first half-period of the discharge current was 8 ns. At a negative polarity at the electrode with a small radius of curvature, a gas diode generated a runaway electrons beam. When recording the electrons with the energy exceeding 50 keV and the beam current FWHM of 0.1 ns, the beam current amplitude was equal to 10 A. Radiation was carried out in a pulse-periodic mode with the pulse repetition rate of 1 Hz. After the irradiation the samples were studied by means of Auger spectroscopy for the purpose of any changes in the surface chemical composition. Fig. 11 shows the results of investigation of a discharge-induced modification of the near-surface layers of an AlBe-foil. The exposure to the SAEB-induced volume discharge in air at atmospheric pressure leads to cleaning of the AlBe-foil surface from carbon contaminations and to increase in the oxygen concentration in the near-surface layers.

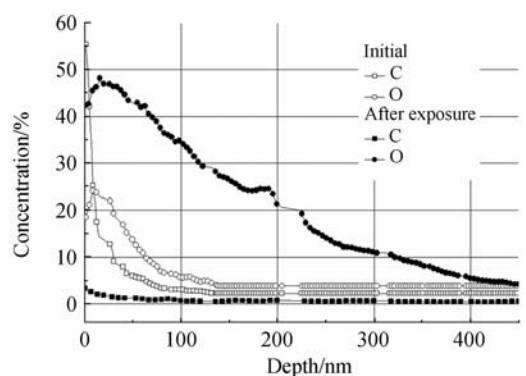


Fig. 11 Depth - concentration profiles of carbon and oxygen in the near-surface layers of an AlBe-foil before (initial sample) and after exposure to a SAEB-induced volume discharge

6 Conclusion

In a nonuniform electric field at the ns breakdown of high-pressure nitrogen and air characteristics of the volume ns discharge and the transformation of the diffuse discharge to the constricted one were studied experimentally. It is shown that the current flow through the discharge gap is substantially influenced by the generation of supershort avalanche electron beam (SAEB), which determines the formation of a diffuse discharge in interelectrode gap. At nitrogen pressures of 20–400 kPa, SAEB generation time relative to the discharge current is experimentally determined. It is also shown that the dependence of the time delay runaway electron beam generation on pressure has a minimum at nitrogen pressure of 200 kPa. The maximal amplitude of the SAEB current at generator voltages of hundreds kV is registered on the front of the discharge current pulse.

A REP DD is easily realized in various gases and at different pressures. At the REP DD, the anode is influenced by the plasma of a dense ns discharge with the specific input power up to

hundreds of megawatts per a cubic centimeter, by the electron beam, shock wave and optical radiation from discharge plasma of various spectral ranges, including UV and VUV. This allows the REP DD to apply for modification and cleaning of metal surfaces in different technological processes as well as for the dielectric surface modification and cleaning at a definite anode design. The REP DD is promising as well for creation of the VUV-range excilamps and different lasers on dense gases with a high radiation power in a pulse. We believe that there will be more applications of a REP DD in different fields.

7 Acknowledgments

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● 下期预告

硅微机械陀螺自激驱动数字化技术

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为了进一步增强硅微机械陀螺仪驱动模态的控制精度与稳定性, 提出了一种基于自激振荡原理, 以 FPGA 数字信号处理来实现控制的驱动电路。以陀螺仪驱动模态特性为出发点, 分析了自激振荡原理对驱动电路的要求。通过分析并建立驱动相位控制与驱动幅度控制模型, 提出了采用‘频率测量—补偿算法’对驱动环路进行相位控制, 采用 PID 控制算法解决了对环路幅度的控制。实验结果表明: 常温下驱动幅度控制精度达到 15×10^{-6} , 并且能跟踪驱动模态谐振频率, 由于采用了数字电路使得驱动幅度温度系数由原来模拟电路方案的 $76.9 \times 10^{-6}/^{\circ}\text{C}$ 降低到 $11.83 \times 10^{-6}/^{\circ}\text{C}$ 。相比传统模拟电路控制方案, 本方案具有驱动精度高, 温度适应性好的优点。