TWO STEP CURRENT INCREASES IN GLOW DISCHARGE DEVELOPMENT IN NEON FILLED DIODE AT 4 mbar

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Abstract. *The results are presented of investigating temporal and spatial development of electrical glow discharge in a neon filled tube under 4mbar pressure. Linear increasing voltage (at 5 V/s increasing voltage rate) is applied to the gas diode. Time dependence of 585.2 nm line light emitted from negative glow is observed from various positions in the diode during formation of electrical discharge. The results show that the development of glow discharge starts in the gap, and propagates to the cathode and in the space around and behind the cathode. An unexpected two-step current rise is found. In the stationary regime, most of the emitted light occupied the cathode carrier rod. This indicates the position where the secondary electron emission is intensive. It corresponds to the second step in the current increase app. 3 ms after the breakdown has already taken place. It is assumed that this step originates from different surface characteristics of the rode material. The analysis of time dependencies of the current and light from the negative glow, from different positions in the gas diode, suggests that the observation of deexcitation processes in gas can be used for determination of early discharge formative processes, as well as processes that lead to the stationary regime in the gas diode tube.*

Key words: *Gas Discharges, Formative Time Delay, Electrical Measurement of Gas Discharges, Optical Measurement of Gas Discharges.*

INTRODUCTION

The electrical breakdown in gases represents transition of gases from the dielectric to conducting state [1]. Voltage at which this transition takes place is known as the breakdown voltage. The investigations of the electrical breakdown and discharge in gases provide useful information about the cathode effects, concentration of ions, electrons and neutral active particles in gases during discharge and in the afterglow, which are very significant in applications [2].

The electrical breakdown of gases can be treated as a macroscopic event of a stochastic nature. Investigation of the statistical nature of the electrical breakdown starts with Zuber [3] and von Laue [4] (1925) and was developed by many authors [5]-[7]. The theory is established on the presumption of the Townsend breakdown mechanism [1]. For small pressure and small overvoltages, when the influence of the space charge is neglected, Townsend theory is applicable.

The electrical breakdown mechanism in gases can be considered as a combination of two distinct processes. The first corresponds to the occurrence of one or more physical events which lead to the creation of an initial electron. This is the Poisson random process, and the time necessary for the appearance of the initial electron is statistical time delay t_S. The second process is the process of ionization and carrier multiplication in the gas leading to the development of a low impedance conducting plasma. The second process is characterized by discharge formative time t_F. This time represents the time needed for the initial electron to create the avalanche, which leads to the breakdown and stationary discharge. Because of that, one of the most important breakdown characteristics, the electrical breakdown time delay t_D, can be expressed as the sum of the statistical time delay t_S and the formative time delay t_F ($t_D = t_S + t_F$).

The formative time delay can be expressed as the sum of three time stages [8]. The first stage begins with the appearance of the initial electron near the cathode. The end of this stage corresponds to the moment when the threshold value of voltage, or the critical value of E / N necessary to initiate breakdown, is reached. The second stage corresponds to the duration of the avalanche process, which creates a conducting channel between the anode and cathode. During the final stage the subsequent increase of the conductivity and current in the plasma channel appears (yielding a commensurate voltage drop across the ballast resistor). This results in an observable decrease in the discharge voltage. The initial electron, i.e. the first electron, which initiates avalanche, cannot be detected with experimental techniques based on the detection of electrical signals with amp-meters, volt-meters, oscilloscopes and timers. Therefore, only the second and third stages of the formative time delay can be measured with techniques mentioned above [9].

The development of the discharge is followed by the light emission from the gas. This light emission is caused by relaxation of gas atoms, previously excited in collisions with free electrons. In the rare gases for small overvoltages and lower pressures, intensive excitation of lower energy levels (metastables) is important in building up the breakdown conditions, by allowing the step-by-step ionization [10]. In stationary regime these lower energy levels are strongly populated [11], [12].

Geometry of the electrodes, pressures and the gap space determine the positions and shapes of the light zones. At low pressure, the intensity of the emitted light from the negative glow has small values, which correspond to the small values of the current density in gas. The current increase is associated with increasing the volume of the discharge area. For these reasons, discharge formation takes some extra time to reach the saturation conditions in the diode tube.

By registering the time of developing the emitted lights from different parts of the diode, it is possible to determine some stages in discharge formation in the actual experimental conditions. This is used in our investigation to determine the spatial and temporal growth of discharge in the neon-filled diode at the 4 mbar pressure.

The goal of investigations is to identify the pre-breakdown electron multiplication processes, which develop in the neon filled diode with the volume much greater then the

volume of the gap. These processes can be related to the first stage of the breakdown formation (with total current $I \leq 1\ \mu A$). According to the statistical theory of electrical breakdown, the time needed for development of these processes should be incorporated in discharge formative time. As mentioned, this stage is usually ignored in electrical measurements in gases.

EXPERIMENT

The measurements were performed with the neon filled diode at the pressure of 4 mbar and temperature of 300 K. The volume of the diode tube was about 300 cm^3. The Cu electrodes were cylindrical, 6.5 mm in diameter and 6.5 mm high. The gap between the bases of electrodes was 20 mm. The tube bulb was made of molybdenum glass, with molybdenum electrode carrier. Before the neon was admitted, the tubes had been baked out at 650 K and pumped down to the pressure of 10^{-7} mbar. After that, the tube was filled with Matheson research grade neon at pressure of 4 mbar. Before the measurement, the diode was conditioned with the 0.3 mA current during 3 hours. During all measurements diode was protected from light.

The experimental layout is presented in Fig. 1. The shape of the voltage signal, at the increasing voltage rate of 5 V/s, is determined by PC 1. Communication between computer and measurement devices is established using the Input Output module "I/O". The output module is connected with an operation amplifier, which is supplied by positive voltage from DC power supply DC 1. In this way, the voltage signal is obtained with the constant voltage of 30 V before start of linear increasing, which reaches the constant voltage of 120 V at the end of all cycles. This voltage signal is ap-

Fig. 1. Block diagrams of the experimental layouts.

plied to the anode. The cathode is at the negative voltage of 200 V supplied by DC 2 all the time. After the breakdown, the electrical current through the diode and circuit changes the voltage signal with potentiometer, which is registered by oscilloscope. This voltage signal triggers the oscilloscope. Duration of the stationary current ($I_{sat} = 0.2$ mA) is 3 s and relaxation time of the diode is 2 s.

On the other hand, the light emitted from different positions in the diode is registered simultaneously with detection of the current. The emitted light from different positions in the diode is separated by collimator. The light emission is registered with a SPM2 Karl Zeiss monochromer (M in scheme on Fig. 1), AMNICO photomultiplier, and signal amplifier (phA in scheme in the Fig. 1). The signal from the photomultiplier is recorded with the oscilloscope (100 MHz, Tektronix TDS 2012) and transferred to the computer PC 2. The intensity of the current signal can be directly read from the oscilloscope, while the detection of the light signal needs additional calculations which depend on the range of the amplifier. The time resolution of the measured light intensity signal is better than 0.1 μs.
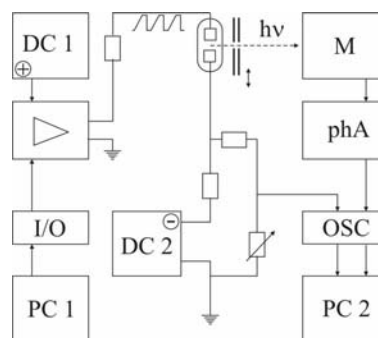
The intensive 585.2 nm line emitted from low electron excited levels in neon atoms is chosen for monitoring. For low pressures, when the self-absorption in the gas is negligible, the relative light intensity can be related to the concentration of free electrons in the gas capable to excite atoms in collisions. The intensity of light is measured perpendicular to the diode axes at more then 100 positions, in the gap, near the cathode surfaces, on cathode sides, behind the cathode and on the cathode carrier rod. The used equipment allowed changing the positions with the accuracy better than 0.1 mm.

The value of the static breakdown voltage U_S is determined according to the definition of the static breakdown voltage as the highest voltage at which breakdown has not yet taken place (see [13], [14] for more details). The estimated static breakdown voltage is $U_S = 248$ V.

RESULTS AND DISCUSSION

The temporal and spatial developments of the negative glow discharge are observed under the experimental conditions specified in Experiment. Time evolution of emitted light from negative glow is observed from the moment when the applied voltage reaches the value of the static breakdown voltage U_S up to the moment when the stationary regime in diode is established. The spatial evolution is attained by the analysis of the temporal development of light at different positions in gas diodes, with step of 0.5 mm. Measurements are performed starting from position at the anode surfaces, to the position behind the cathode. Position at anode surfaces is accepted as the zero distance. Some of temporal evolutions of the light intensity and current, for characteristic positions in diode are shown in figures Fig. 2 - Fig. 4. The light intensities are given in relative units.
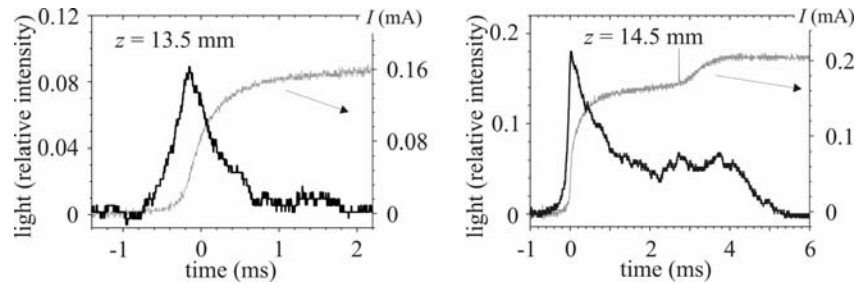

Fig. 2. The temporal distributions of light intensities and current values for indicated positions in gas diode, which correspond to first excitations in gases.

The temporal evolutions of the light intensities, for positions near the middle of the gap ($z = 13.5$ mm and $z = 14.5$ mm), are presented in Fig. 2. At these positions the light intensity is observed for the first time (with the relative intensity of order of 0.1). The positions $z = 17.5$ mm, before the cathode, to the positions $z = 33$ mm, behind the cathode, are presented in Fig. 3. In this figure, the positions which correspond to the front side, $z = 20$ mm, and back side, $z = 26.5$ mm, of the cathode, are presented. The positions behind the back side of cathode, from $z = 43$ mm to $z = 58$ mm, which correspond to the carrier rod, are presented in Fig. 4. The zero of time axis is identified with the moment

when current in the diode has maximum rise. This moment is mathematically estimated to determine the maximum of the time derivative of the current.
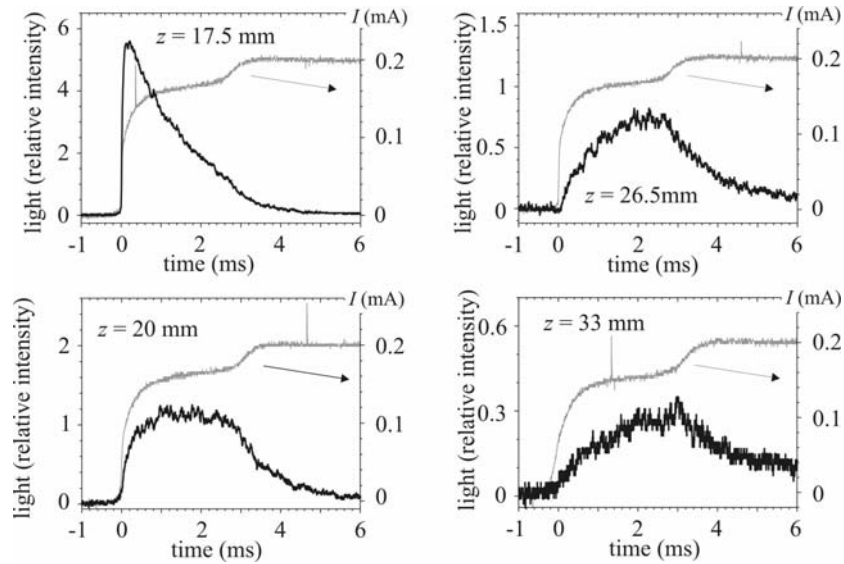

Fig. 3. The temporal distributions of light intensities and current values for indicated positions in gas diode, which correspond to positions before the diode, on the cathode and on the last side of the diode.

From Fig. 2 it is clearly seen that for the $z = 13.5$ mm light signal is observed before current signal in diode. This indicates that the first excitations in the gap, at the position $z = 13.5$ mm, occur about 0.8 ms before declared zero on the time scale. It indicates the existence of the atomic excitations and multiplications of free electrons in the gap in the pre-breakdown period. After that, light intensity grows in time for next 0.8 ms almost exponentially. This indicates the exponential growth of the number of the excited and ionized atoms in the gap. Further increase of the concentrations of excited and ionized atoms at the mentioned position in the gap is limited by the ambipolar diffusion of charged particles, which caused decreasing of the light intensity with time. With increase of distances from anode surfaces, time difference between light and current signal decreases, and decreasing of light intensity becomes slower. This is caused with further growth of concentration of excited and ionized particles in gas. The ambipolar diffusion caused the increase of the region of lighting, which led to a slower decrease of the light intensity in time.
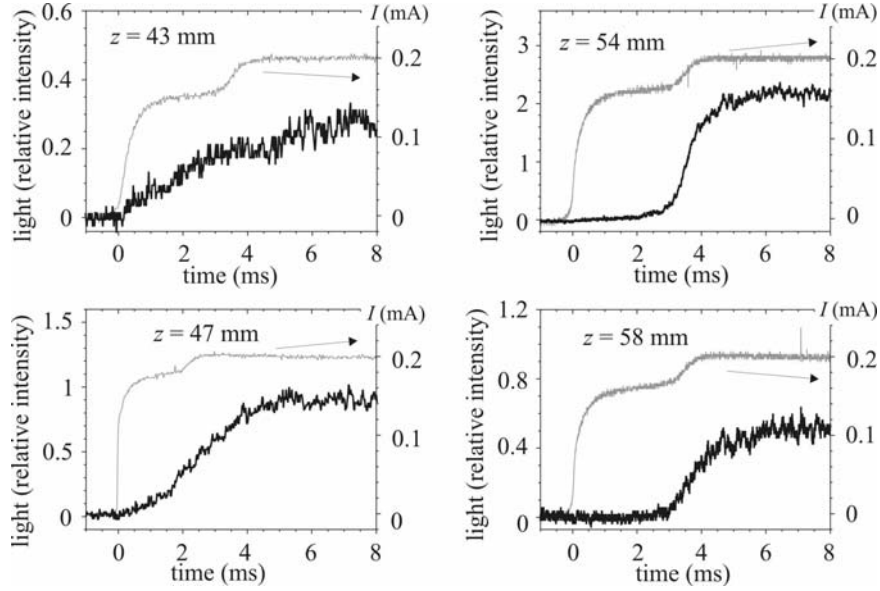
Fig. 4. The temporal distribution of light intensities and current values for indicated positions in gas diode, which corresponds to positions behind the cathode, on the cathode carrier rod.

For position in front of the cathode ($z = 17.5$ mm), light intensities and current signals are observed practically simultaneously, as can be seen in Fig. 3. The simultaneously detection of emitted light and current at positions from $z = 17.5$ mm to $z = 26.5$ mm indicates that the concentration of electrical carriers in the gas reaches the critical value for voltage drop on the diode. Note that in comparison with previous cases (at position $z = 13.5$ mm), the emitted light intensity is higher for one order of magnitude. With increasing distances the maximum of the light intensities decreases and moves to the back side of the cathode. This behavior of maximum of the light intensities is caused by diffusion of discharges around the cathode (at position $z = 26.5$ mm). The characteristic time for this process is about 3 ms.

At larger distances, at the cathode carrier rod, light intensity decreases (see positions $z = 33$ mm in Fig. 3 and $z = 43$ mm in Fig. 4). This decreasing of light intensity is determined by the ambipolar diffusion of charged particles. The diffusion is very intensive at positions behind the cathode that causes delay of the light intensity appearance with respect to the current. For larger distances, the shape of light intensities is changed, as presented in Fig. 4. The light intensity growth has maximum for position $z = 54$ mm and decreases for further positions ($z = 58$ mm). Together with increasing of the light intensities at about $3.5 - 4$ ms, current evolution can be observed an unusual step. This current step starts simultaneously increasing of the light emission. It is assumed that this step in current signal is determined with accumulated impurities on carrier rod, at position of about $z = 54$ mm. The impurities caused the increase in the secondary emission and changed the electric field on the mentioned position near the carrier rod. The secondary emission increase caused movement of negative glow maximum to this position. The time needed for movement of negative glow, from gap to cathode carrier rod, is about 3.5

– 4 ms. This time determines unusual step in current signal. Current reaches the saturation level in gas diode about 1 ms latter. Because of that, it can be concluded that the glow discharges attain saturation values for about 5 ms, after the current signal reaches maximum growth.
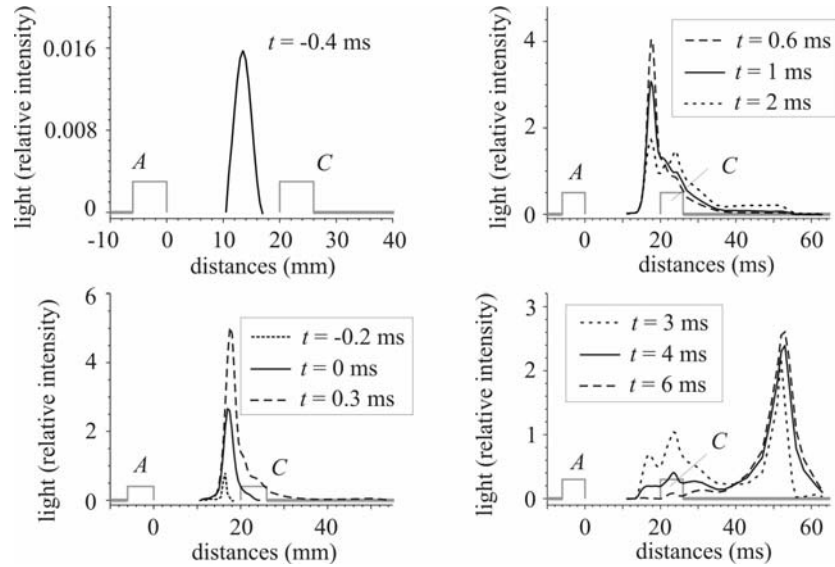

Fig. 5. The spatial distributions of emitted light, for indicated time intervals;
A - anode; C - cathode.

The spatial distribution of the intensity of the emitted light from negative glow, for some characteristic time moment, is presented in Fig. 5. These spatial distributions of emitted light intensity from negative glow at more than 100 positions in diode are constructed by analyzing measured light signals in time, for all observed positions in diode (some of these positions are presented in Fig. 2 to Fig. 4). The intensities of emitted light are read from all registered light characteristics, for selected time intervals. Thus, by measuring temporal evolution of emitted light from negative glow for different positions, the spatial distributions of emitted light in whole diode can be obtained.

From Fig. 5 it can be seen that the first detectable excitations occur near the middle of the gap. These excitations indicate the appearance of the negative glow in the diode before the current through the diode is detected. The emitted light intensity from negative glow increases with time, moves towards the cathode, and covers it. The moment when the cathode is covered by the negative glow corresponds to the moment when the current through the diode reaches detectable value.

After that, the negative glow propagates over cathode. The first maximum of the light intensity in the front of the cathode decreases, and simultaneously the second maximum at the cathode position, and small third maximum appear (see time 2 ms). After 3 ms third maximum becomes dominant, while first becomes smaller. For longer times, only the third maximum, which enclosed the cathode carrier rod (on position $z = 54$ mm), can

be detected. This maximum (as explain in discussion of Fig. 4) is a consequence of accumulated impurities on the cathode carrier rod. These impurities lead to increasing of the secondary emission at the mentioned position at carrier rod, which causes movement of negative glow to this position. This causes the unusual step in current, and consequently the long time of about 5 ms, needed for establishing the stationary regime.

Analyzing results in Fig. 2 to Fig. 5, all three stages of the gas discharge formation can be observed. From these figures it can be seen that the first stage in formation processes is determined with first detected light intensity. This stage is connected with first registered pre-breakdown multiplications of electrical carriers, and the excitation of the gas atoms in the diode gap. The movement of the negative glow toward the cathode is assumed to be caused by the secondary electrons, now realized from the cathode surfaces by the positive ions. They have a greater kinetic energy and therefore are more efficiency in excitations.

Further increasing of the excitation and ionized particles in gases is correlated with the first maximum. The developments of the first maximum correspond to the second stage in gas discharge formation. The increasing of concentration of excited and ionized particles causes the intensive increasing of current through the diode. Measured current characteristics (see figures from Fig. 2 to Fig. 4) at all the cathode positions show fast increase of the current in the second stage, as expected. Simultaneously, the light intensity fast increases at positions $z = 17.5$ mm, i.e. about 2.5 mm in front of the cathode surfaces (as presented in Fig. 3).

The third stage is related to subsequent increase of the conductivity and current in the plasma channel. From Fig. 3 and Fig 4 it can be seen that this stage is determined with the movement of maximum light intensity, i.e. negative glow discharges, from cathode to the cathode carrier rod. This movement determines recovery of the stationary regime of the gas discharge, i.e. the end of third stage. From the third light intensity maximum, which appear on the cathode carrier rod (see position $z = 54$ mm in Fig. 4), one can see that the saturation value of light intensity is reached after the saturation value of current in the diode.

The above results indicate that optical methods have to be included in order to register the beginning of the first stage, as well as, the end of third stage in gas discharge formation mechanisms. Similar results are shown in previous paper [15] for afterglow period larger than 10 ms, which corresponds to the value of the afterglow period in actual experimental conditions. However, the delay of the current pulse with respect to the lighting pulse is much smaller (less than 1 μs) in paper [15] than here. This is evidently a consequence of different shape of voltage signal and diode geometry. More precisely, in paper [15] the diode gap is 3.3 mm and the voltage pulse with increase voltage rate 14 V/μs is applied, while in present paper the corresponding values are 20 mm for diode gap and 5 V/s for increase voltage rate. The much smaller increase voltage rate and bigger gap in the present paper cause slower establishing of the electron avalanches. This effect influences delaying of the secondary electron emission, and the difference between the light appearance and current through the diode is more significant.

CONCLUSION

The unusual glow discharge development in the neon-filled diode at 4 mbar is reported. Linear increasing voltage (with the increasing voltage rate of 5 V/s) is applied on the gas diode. The glow is of the diffusion type in the diode tube with the volume much greater than the volume of the gap, with saturation current value 0.2 mA. The temporal and spatial developments of the 585.2 nm light intensity from the negative glow, emitted from the different parts of the diode, are registered.

The results of present investigations show that the first light emission in gas diode is registered in the diode gap 0.8 ms before the current increasing rate reaches the maximum value. This light emission indicates existence of pre-breakdown multiplications of electrical carriers in diode gap. It is shown that the first step in discharge formation can be determined by measuring the first emission of the light in the gap.-This overcomes lack of precise equipment for measuring primary ionization and approximations in standard electrical methods of measurements.- The first avalanche processes correspond to very low values of current which is very difficult to be measured. In addition, it is shown that the impurities of the carrier rod influence the establishment of stationary state in gas diode. These impurities lead to the increasing of the secondary electron emission from cathode carrier rod, which causes the movement of negative glow to this place. The time for establishing of the stationary regime of the negative glow determines the end of the third stage in discharge formation. It is shown that the light intensity attains saturation later then the current. This indicates that in order to register the discharge formation (i.e. formative time delay) in gas diodes optical methods have to be included. Precisely, the optical method has to be included in determination of the beginning and the finishing of discharge formation mechanisms.

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DVOSTEPENI PORAST STRUJE U RAZVOJU TINJAVOG PRAŽNJENJA U GASNOJ DIODI PUNJENOJ NEONOM NA PRITISKU OD 4 mbar

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U radu su prezentovani rezultati prostornog i vremenskog razvoja tinjavog pražnjenja u gasnoj diodi punjenoj neonom na 4 mbar. Primenjivan je linearno rastući napon sa brzinom porasta napona od 5 V/s. Detektovan je vremenski razvoj spektralne linije od 585.2 nm emitovane iz negativnog tinjanja (za različite pozicije u diodi) tokom formiranja električnog pražnjenja. Rezultati pokazuju da razvoj tinjavog pražnjenja počinje u međuelektrodnom prostoru, razvija se prema katodi i obuhvata prostor oko katode. Pored toga, detektovan je dvostepeni porast struje. U stacionarnom režimu pražnjenja najviše emitovanog svetla obuhvata nosač katode, što ukazuje na poziciju u gasnoj diodi na kojoj je emisija sekundarnih elektrona najintenzivnija. To odgovara drugoj fazi razvoja struje, za oko 3 ms nakon električnog proboja. Ovo ukazuje da dvostepeni porast struje potiče od različitih površinskih karakteristika nosača elektroda. Analiza vremenskog porasta električne struje i emitovanog svetla iz negativnog tinjanja, za različite pozicije u diodi, ukazuje da detektovanje deekscitacionih procesa u gasu može biti iskorišćeno za određivanje rane faze formativnih procesa i procesa koji dovode do stacionarnog režima u gasnoj diodi.