Discharge in the saline solutions in a vicinity of the threshold voltages

Y D Korolev[1,2, 3]**, I A Shemyakin**[1,2*]**, R V Ivashov**[1,2]**, V S Kasyanov**[1,2]**, N V Landl**[1,2]**, Y H Sun**[4]**, T Shao**[4]**, Y Gao**[4]

[1]Institute of High Current Electronics RAS, 634055 Tomsk, Russian Federation
[2]Tomsk State University, 634050 Tomsk, Russian Federation
[3]Tomsk Polytechnic University, 634050 Tomsk, Russian Federation
[4]Institute of Electrical Engineering Chinese Academy of Science, 100190 Beijing, P.R. of China

E-mail: shemyakin@lnp.hcei.tsc.ru

Abstract. This paper deals with the discharge in saline solution (0.9 % NaCl) in coaxial electrode system at voltages up to several hundred volts. The discharge was powered by bipolar pulsed generator with a pulse repetition rate of 100 kHz and by a generator of negative voltage pulses. At voltages less than a threshold value (less than 300 V), different types of gas microcavities are formed at the surface of active electrode: the microbubble, the conglomerates of microbubbles (thin gas layers) and a macrobubble with diameter of about 1 mm and less. In a vicinity of threshold voltage the breakdown in the gas cavities occur. For negative polarity at the metal electrode the discharge burns in a form of microsparks of short duration. At positive voltage pulses, the glow-type discharge is sustained in the microcavities.

1. Introduction

In recent years, plasmas generated in and with liquids have attracted considerable interest because of their great potential for applications in various fields [1−4]. One of the progressing fields is the usage of discharges in the so-called plasma scalpel for plasma surgery [5−8]. In this device, the discharge is sustained in multielectrode or two-electrode system immersed in medical saline solution (0.9 % NaCl) [5, 6]. The electrode system is powered by a bipolar voltage with a pulse repletion rate of about 100 kHz and with voltage amplitude at the exit of pulsed generator up to 300 V. This voltage is insufficient to provide a complete breakdown of the gap. As shown in [5, 7, 8], the gas discharge plasma is generated in the vapor microbubbles or in the thin gas layers adjacent to an active electrode. In the rest part of the gap, the current flows through the saline solution that serves as a kind of ballast resistor for the discharge current. When an area of the discharge plasma is in contact with the soft tissues, it becomes possible to produce ablation, healing or the other kinds of the tissue treatment.

The saline solution represents an electrolyte in which, as distinct from the distilled water [1], the gas vapor cavities are generated at a low voltage applied to the electrodes (of about 100 V and even less). As soon as the voltage reaches some threshold value, the breakdown in the gas microcavities (in microbubbles of thin vapor layers) occurs; the discharge plasma appears in the cavities, and the discharge current starts flowing in the electrode system.

When speaking about the current flowing during a pulse of several microseconds, it is often implied that the discharge operation is accompanied by a certain average current value. However,

within this time interval the current fluctuations on a scale less that 1 μs are superimposed on the above average current [7, 8]. Then the discharge in the microcavities seems to be essentially nonsteady-state phenomenon. The reasons for appearing of the current peaks and the current interruptions can be associated with the transitions from one forms of the discharge burning to the others, for example, with the glow-to-spark transitions [9–13]. Investigation of the nonsteady discharge behavior and elucidation of the nature of current and voltage fluctuations are the main goals of the present paper.

2. Experimental arrangement

Schematic of experimental arrangement is shown in figure 1. The discharge is sustained in the coaxial electrode system between active electrode *1* (from titanium or stainless steel) and the return grounded electrode *3*. The electrodes are placed in case *4* with saline solution (0.9 % NaCl). The case is equipped with the quartz windows that offer a possibility to take the discharge photographs and to obtain the time resolved waveforms of the discharge luminosity by means of photomultiplier *PMT*.
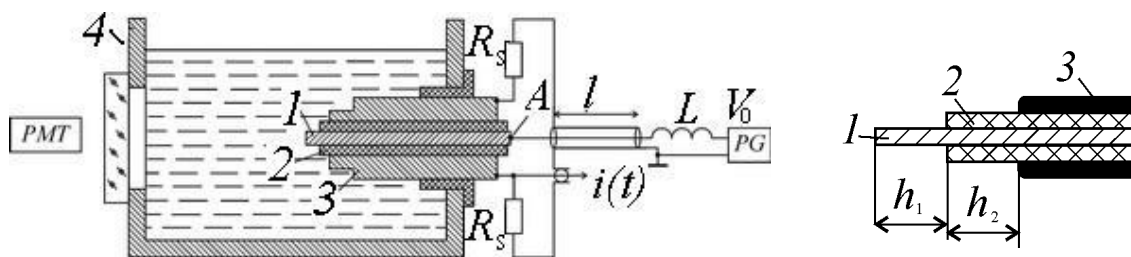

Figure 1. Schematic of arrangement for discharge investigation and sketch of electrode system. *1*−active electrode of diameter $D_1 = 0.5$ mm; *2*−ceramic insulating tube $D_2 = 2$ mm; *3*−grounded return electrode; *4*−case with the saline solution; *PG*−pulsed generator; V_0−output voltage of the pulsed generator; *L*−inductance of electric circuit; *l*−length of the coaxial connecting cable; $R_s = 1.41$ Ω − current shunt resistor; *PMT*−photomultiplier tube; $h_1 = (0.7–1.5)$ mm, $h_2 = 1.5$ mm.

The discharge was powered by two types of the pulsed generators *PG*. One of them is the generator of bipolar voltage pulses with maximum amplitude at the open circuit of 300 V and with pulse repetition rate of 100 kHz. In this case a capacitance of connecting cable was $C = 400$ pF and the inductance L at the exit of pulsed generator was $L = 13$ μH. Due to the inductance, the regime of resonant charging of the cable capacitance was realized in some conditions, which allowed us to obtain at the gap a voltage pulse higher than 300 V.

Another electric circuit was based on the generator of rectangular negative voltage pulses with maximum voltage at the open circuit up to 400 V. The pulse duration was varied from 10 to 50 μs, a pause between the pulses was 10 μs and larger, so that a pulse repartition rate could be varied from 0.15 to 50 kHz. In most experiments, for this electric circuit, we used a coaxial cable of length $l = 1.5$ m (cable capacitance $C = 150$ pF), and a ballast resistor $R_b = 490$ Ω was inserted at the exit of pulsed generator instead of the inductance L.

Current in the discharge gap was recorded with a use of the low-inductance shunt R_s and the oscilloscope Tektronix TDS 3034. Voltage at the gap was recorded between the point *A* and the grounded electrode *3* with a use of probe P6139A.

3. Formation of the gas cavities at the surface of active electrode

When a voltage is applied to the gap, a current starts flowing via electrolyte and the gas microbubbles appear at the surface of active electrode *1*. The breakdown in the gas microbubbles and in the other types of vapour cavities occurs if only the voltage at the gap exceeds some threshold value [1, 7, 14]. Below we consider the characteristic features of behaviour of the gas cavities at low voltages. It should be noted that the cavities impede the current passage via electrolyte. Then the gap resistance

turns out to be minimal when the microbubbles and the gas thin layers are absent at the electrode surface. Increasing a number of the gas cavities leads to increasing the gap resistance. Depending on the conditions in the gap, at each particular instant of time, different types of the cavities can exist at the electrode surface and in the bulk of electrolyte. Typical situations are illustrated in figure 2.
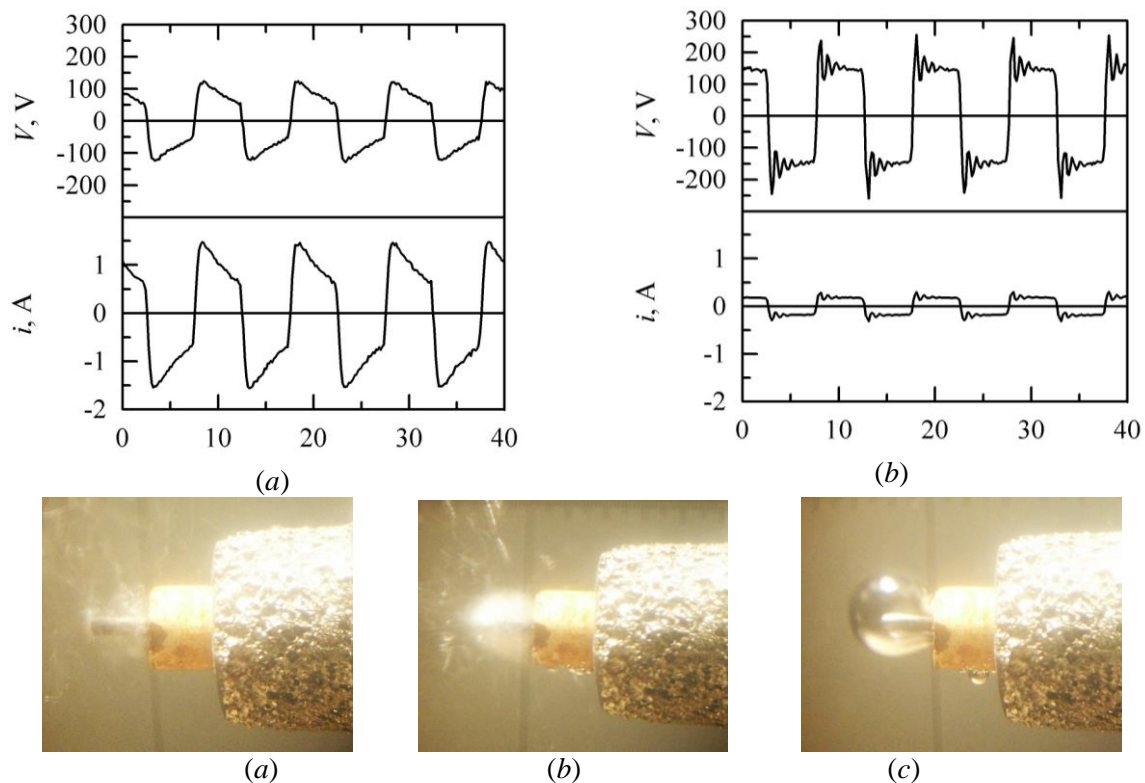

Figure 2. Voltage and current waveforms jointly with typical photographs of electrode system in the conditions when there is no discharge plasma in gas cavities. Active electrode: $D_1 = 0.5$ mm, $h_1 = 1.5$ mm. Output voltage of bipolar pulsed generator: a) $V_0 = 100$ V, b) $V_0 = 150$ V, c) $V_0 = 175$ V.

At a low voltage (of about 100 V and less), only small part of the electrode surface is covered by the cavities in a form of microbubbles (figure 2a). Some microbubbles detach from the surface and float upward. The current via the gap for this particular case is about 1 A and the gap resistance of about 80 Ω that is approximately equal to the resistance of electrolyte in absence of the microbubbles.

When voltage is increased, the microbubbles are merged with each other thus forming the conglomerate of the bubbles and thin gas layers (100 µm and less) at the electrode surface. Beside that, a lot of microbubbles can be clustered in a bulk of electrolyte near active electrode. Example of this situation is shown in figure 2b. The gap resistance is enhanced for such conditions up to typical values at a level of 1 kΩ. At a high gap resistance, we can see the oscillations at the beginning of voltage pulse that appears due to effect of resonant charging of cable capacitance.

One more pattern of the gas cavities is a single macrobubble with a size of about 1 mm which can be formed at the active electrode (figure 2c). In this case the most part of electrode is covered by the gas cavity so that the gap resistance becomes up to several kiloohms.

4. Regimes of the discharge burning

Further increase in the voltage of pulsed generator results in the conditions when a breakdown occurs and gas discharge plasma appears inside the microcavities. A threshold breakdown value is in a vicinity of 300 V and corresponds to minimum of Paschen's curve. Then the interelectrode gap can be classified as a system in which the discharge current flows between metallic and liquid electrodes. The

photographs of the gap with discharge plasma for different types of the gas cavities are shown in figure 3. It is seen that the discharge plasma can be sustained both in the thin vapour layer (figure 3*a*) and in the macrobubble (figures 3*b* and 3*c*).
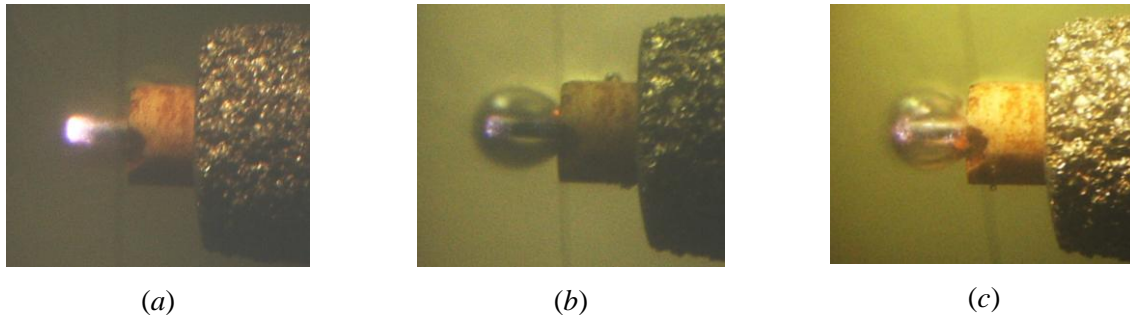
| (*a*) | (*b*) | (*c*) |

Figure 3. Typical photographs of the discharge in different regimes of its operation. Powering from generator of bipolar voltage. *a*) Discharge plasma is generated in a thin gas layer $V_0 = 200$ V; *b*) Discharge in a macrobubble $V_0 = 175$ V; *c*) Discharge in a macrobubble $V_0 = 275$ V.

Note that the photographs demonstrate an integral discharge images taken with a large exposition time. During this time the discharge burns in essentially nonsteady regime. The discharge properties are determined in a great extent whether the cathode is liquid of metallic. Let us consider the case when the pulsed generator of negative polarity is used, i.e. we deal with the metal cathode. An example of the current and voltage waveforms for this case is shown in figure 4.
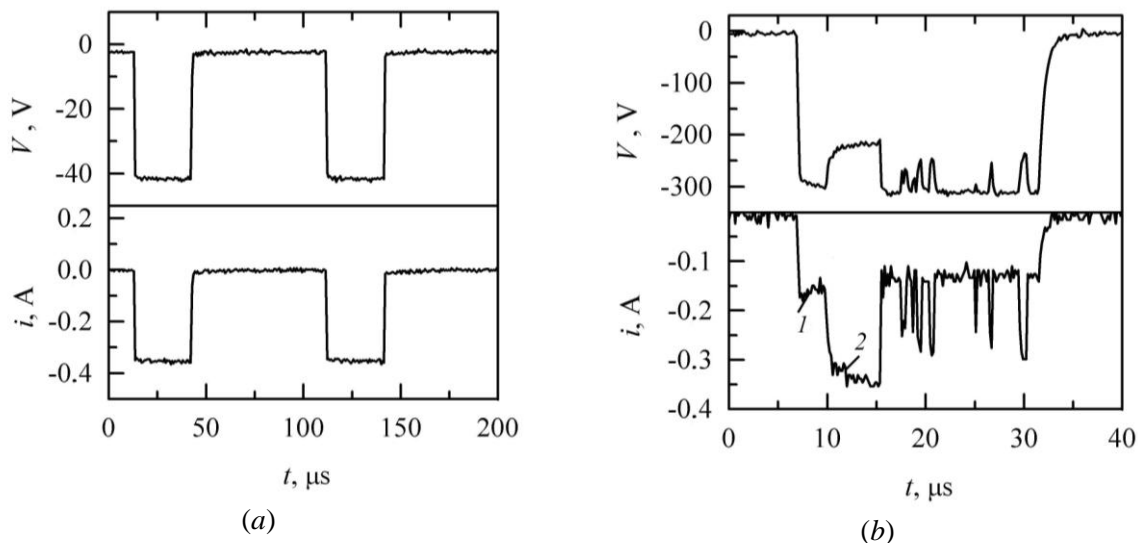
| (*a*) | (*b*) |

Figure 4. The waveforms for the conditions when a voltage of negative polarity is used. Instead of the inductance L, a ballast resistor $R_b = 490$ Ω is inserted in electric circuit. Active electrode: $D_1 = 0.5$ mm, $h_1 = 0.7$ mm. Output voltage of the pulsed generator: *a*) $V_0 = 210$ V, *b*) $V_0 = 400$ V.

At low output voltage of the pulsed generator we have the situation in the gap shown in figure 2*a*. The gap resistance is $R = 115$ Ω. The voltage waveform is the same as the output voltage of generator. When V_0 is increased to 400 V, gas discharge plasma is generated in the gas cavities, which is reflected at the voltage and current waveforms (figure 4*b*). It is seen that the discharge burns in a nonsteady regime.

At the temporal stage *1*, there is no discharge plasma in the cavities so that the gap resistance $R_1 = 2000$ Ω is determined by the area of active electrode covered with the gas microcavities. Once the breakdown occurs, the current via the gap sharply increases up to about 0.35 A, and the gap voltage decreases to 225 V (stage *2*). It seems that at the very beginning of stage *2*, a glow-type discharge

appears in the cavity and after that the glow-to-spark transition occurs [9, 15−17]. As shown in [10, 15, 18], an energy for formation of the spark channel is delivered to plasma channel from the cable capacitance C.

Since the discharge current is limited by the ballast resistor and by the resistance of saline solution, the spark discharge is not able to be transformed into a steady-state arc. At the end of stage *2*, the spark current is interrupted and the gap resistance is increased again. After that new breakdown and new current peak is observed. Then the form of discharge sustaining in the case of metal cathode can be interpreted as a sequence of the partial discharges of a short duration.

When the bipolar voltage pulse is used, the forms of discharge burning with negative polarity at the active electrode and with positive polarity differ from each other. This case is illustrated in figure 5, where the voltage and current waveforms are supplemented with the waveforms of discharge luminosity obtained from photomultiplier tube V_{PMT}.
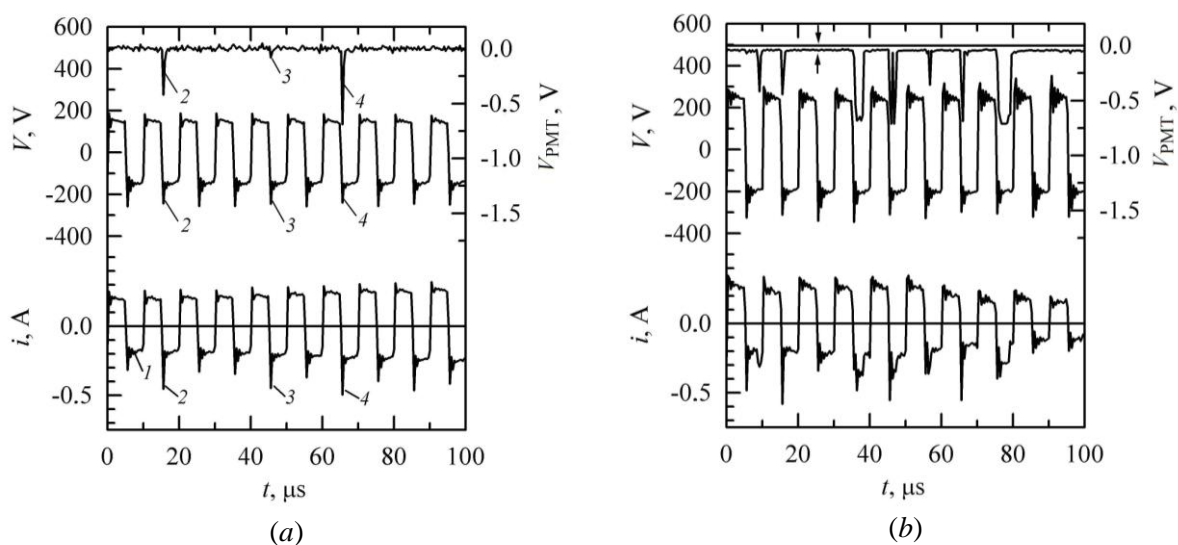

Figure 5. Voltage and current waveforms jointly with the signal from photomultiplier for the conditions when the partial discharges appear in the gas cavities. Active electrode: $D_1 = 0.5$ mm, $h_1 = 1.5$ mm. *a)* $V_0 = 150$ V, *b)* $V_0 = 225$ V.

Figure *5a* corresponds to the threshold voltage. Due to resonant charging of the capacitance C, a voltage value of 300 V is achievable at the gap at the beginning of voltage pulse. Then for negative polarity of the voltage, for some pulses the conditions are realized when the breakdowns in the microcavities occur. These breakdowns are accompanied by the current pulses of short duration. For example, in the particular case under discussion, during the pulse *1* there is no breakdown. The partial discharges are visible in the pulses *2*, *3* and *4*. These discharges are accompanied by the spikes in the voltage from PMT. For the most of negative pulses and for the positive pulses the signal from PMT is zeroes. This means that at the threshold voltage, the partial discharges occasionally appear only at negative polarity of voltage pulse. Even though a glow-type discharge arises in the microbubble, this discharge transforms into spark due to formation of the cathode spot on metal electrode [9, 17−20].

When voltage of pulsed generator is increased, the discharge is sustained not only in the negative pulses but also in the positive pulses (figure *5b*). We can see a weak steady-state signal from photomultiplier which corresponds to glow-type discharge. With metal cathode the phenomenon of glow-to-spark transition manifests itself while with liquid cathode (at the positive pulses) the discharge burns in glow mode without formation of cathode spot and successive spark channel.

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