Armenian Journal of Physics, 2021, vol. 14, issue 1, pp. 19-28

Bilateral Measurements in Electrical Circuits with Gas-discharge Devices

https://doi.org/10.52853/18291171-2021.14.1-19

A.S. Abrahamyan, R.Yu. Chilingaryan*, Q.G. Sahakyan

Institute of Applied Problems of Physics NAS of the Republic of Armenia,
25 Hrachya Nersissian Str., Yerevan, Republic of Armenia, 0014

*E-mail: rychi072@gmail.com

Received 3 March 2021

Abstract: If the electrical circuit is unbranched, then usually the current that flows through the circuit is measured only at one point of such a series circuit. Therefore, in gas-discharge devices, when powered by a current that contains a variable component, it is necessary to simultaneously measure current both from the anode side and from the cathode side. Dynamic processes will be very different from the average for the period of change in the discharge current. The experimental results of such measurements and a comparison with current measurements at one point in a series circuit with a gas-discharge device are present, for example, not only a change in the dynamic resistance of the discharge, but also a dynamic change in the electrical capacitance of the discharge.

Keywords: gas-discharge devices, acoustoplasma discharge, phase shift, dynamic current-voltage characteristic.

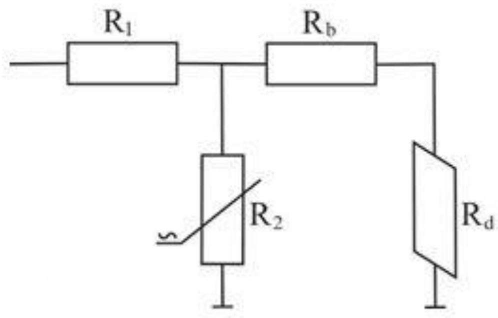
1. Introduction

If the electrical circuit is unbranched, then usually the current that flows through the circuit is measured only at one point of such a series circuit. If there are LC elements in the circuit, the currents in these elements are considered phase-shifted. When working with gas-discharge devices, and especially if they have a variable component of the discharge current, the situation changes completely. When the current in a low-temperature plasma changes, the degree of ionization and the speed of motion of charged particles changed simultaneously.

In addition, in the acoustoplasma mode, the motion of neutral particles follows to the laws of acoustics, while the movement of ions follows simultaneously both the laws of acoustics and of electrostatics. The movement of electrons is directly follows the laws of electrostatics, but due to the quasi-neutral nature of the plasma, the movement of electrons is also associated with the movement of ions, i.e. indirectly obeys the acoustic movement of ions. Since the mass of the ion is much larger than that of the electron, the effect of the electron on the movement of the ion can be very often (but not always) neglected.

We consider electrical circuits for gas discharge. In electrical engineering there are two main ways to connect the load to the power source: the circuit of the "voltage generator" and the circuit of the "current generator" [1]. We consider both the main circuits to power the discharge tube. The circuit of the "voltage generator" is shown in Fig. 1a. The constant resistance R_1 and the voltage-controlled variable resistance R_2 form a voltage divider. The voltage from the midpoint of this divider through the ballast resistance R_b is supplied to the discharge tube with an active resistance R_d. Moreover, $R_1, R_2 << R_b$. If the resistance R_2 is controlled by a constant voltage, then the resistance R_b is selected so that its value is slightly larger than the differential resistance R_{ddif} of the discharge. In this case, it is necessary to observe the condition of the circuit of the "voltage generator" $R_1, R_2 << (R_d + R_b)$.

Recall that, $R_{ddif} = \Delta U_{tub} / \Delta I_{tub}$, where U_{tub} is the voltage between the anode and cathode of the discharge tube, I_{tub} is the current flowing through the discharge tube. For a gas-discharge low-temperature plasma, when the discharge is supplied with direct current, the differential resistance of the discharge is always negative and therefore the positive ballast resistance R_b must be greater than the maximum possible discharge differential resistance, otherwise the unstable operation mode will begin in the circuit.



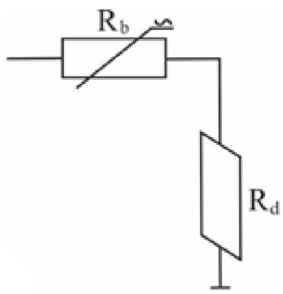


Fig. 1. Schemes for connecting the discharge tube to a power source. R_d is the active resistance of the discharge. a) voltage generator circuit; b) current generator circuit

As a controlled resistance R_2, a high-voltage generator lamp was used. If it is controlled by a sinusoidal alternating voltage, then the voltage at the midpoint of the divider will contain sinusoidal variable and constant components. This corresponds to the acoustoplasma discharge mode [2, 3].

In the acoustoplasma mode, due to the difference in the shape of the current and voltage from the sinusoidality and phase shift between the current and voltage on the discharge tube, its differential resistance varies significantly. During one period of the modulation, the differential resistance of an acoustoplasma discharge can vary from several $kOhm$ to several $MOhm$, and can be either positive or negative. R_b is usually $\sim 100 - 200 kOhm$ [4-6]. In this case, the ballast resistance is chosen larger than the differential resistance value $\langle R_{ddif} \rangle$, averaged over the modulation period, $\left\{ R_b > \left(\langle R_{diff} \rangle \right) \right\}$. It is assumed that during the modulation period the unstable regime will not have enough time to develop.

Fig. 2 shows the behavior of the differential resistance of the discharge tube with the plasma during one period of modulation of the discharge current. It can be seen from Fig. 2 that the behavior of R_{ddif} depends on the frequency of the modulation of the discharge voltage and reaches $400-500kOhm$ at certain times.

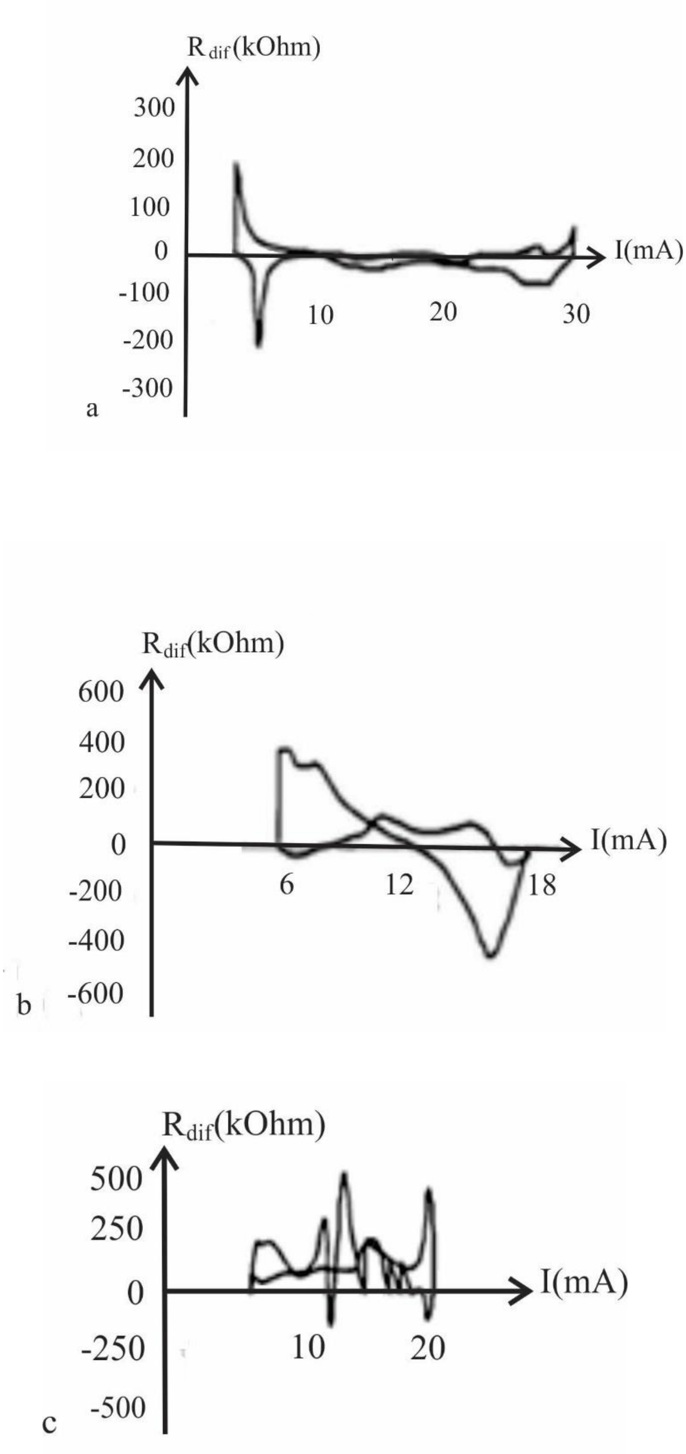


Fig. 2. The change in the differential resistance of the discharge tube during the modulation period for the voltage generator circuit. Gas CO_2: N_2: He = 1: 1: 8, P_0 = 25torr. a) f = 0.1kHz; I_0 = 20mA; $I\sim$ = 6mA; b) f = 1kHz; I_0 = 15mA; $I\sim$ = 3mA; c) f = 15kHz; I_0 = 11mA; $I\sim$ = 9mA.

During the modulation period, both the active and reactive discharge resistances can vary significantly. Our experiments showed that the active resistance of the discharge can vary from 50 to $250 kOhm$ [4-6].

When the “voltage generator” is turned on at those times when the discharge resistance becomes much less than the ballast resistance, the discharge current is entirely determined by the ballast resistance and therefore coincides in phase with the supply voltage. At those times when the discharge resistance becomes greater than the ballast resistance, the discharge current should drop sharply. It was experimentally obtained that if a discharge tends to make a jump due to a phase transition, then its resistance will increase sharply, turning into an analog of a condensed medium. But in this case, the discharge current will also drop sharply. As a result, the phase transition either will not occur or will be so blurred that it may not even be noticed. The phase of the discharge current measured at the grounded cathode will repeat the phase of the input voltage.

Fig. 1b shows the diagram of the "current generator". The controlled ballast resistance R_b changes its value depending on the control voltage. In order to match the current generator circuit, the average values for the period are $(\langle R_b \rangle) > (\langle R_d \rangle)$. The ballast resistance on the electron tube is assembled in such a way that when replacing the discharge tube with an active resistance equal to $(\langle R_d \rangle)$ when the sinusoidal control voltage is applied, the current in the circuit is also sinusoidal. The electronic circuit is assembled in such a way that, even when the discharge resistance changes during the modulation period, the discharge current is maintained in the form that is set by the voltage supplied to the control R_b. If the control voltage is sinusoidal, then the current will be sinusoidal as well. In addition to variable ballast resistance, a constant protective ballast resistance, which is small in comparison with R_d, is connected in series with the tube, this leads to the fact that the discharge tube itself can be powered by not quite sinusoidal voltage and current.

Despite the apparent simplicity, it is much more difficult to implement the circuit of Fig. 1b than the circuit of Fig. 1a. It is advisable to ground the circuit on the side of the controlled ballast resistance, in this case both electrodes of the discharge tube are under high voltage potential, and the voltage of the audio frequencies containing constant and variable components. This essentially complicates the work and measurements on such an installation.

When the discharge tube is turned on according to the “current generator” scheme, the power supply seeks to maintain the current that sets the control signal. In those moments when the discharge resistance drops, the voltage on the discharge should also fall. But if this moment coincides with the increase in the discharge current, then the voltage drop will be insignificant or the voltage may even increase. The voltage tends to repeat the phase of the modulating current. At those moments when the discharge resistance increases simultaneously with an increase in current, the voltage at the discharge will increase sharply. If, together with an increase in resistance, the current drops, then at such moments the voltage at the discharge will also drop or increase slightly, i.e. in the general case, the voltage at the discharge repeats the phase of the modulating current.

In addition, with an increase in the voltage at the discharge, the ionization conditions change, the increase in voltage increases the ionization and, therefore, reduces the resistance of the discharge. All these effects, together with the self-consistency of the plasma, lead to well-defined phase transitions. Therefore, to study jumps and phase transitions in acoustoplasma it is advisable to use the "current generator" scheme.

2. Experimental setup

In the experiments described above, the discharge current was measured at one point in the series circuit containing the discharge tube. This is a commonly used method, but for an acoustoplasma discharge this can give erroneous results. In our experiments on the study of discharge parameters, we used a more complex "current generator" circuit shown in Fig. 3.

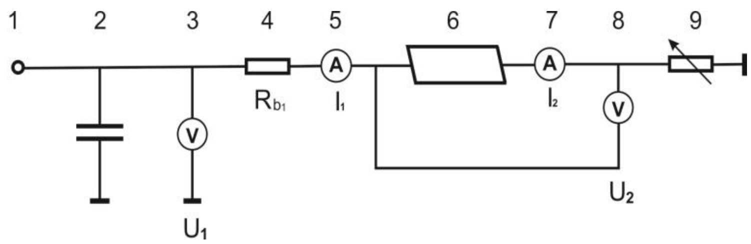


Fig. 3. The discharge tube power scheme used in the experiments.

The voltmeter 3 measures the constant high voltage U_1, which is generated by source 1 on the filter capacitor 2. The ballast 4 is protective and limits the maximum current in the circuit. It can be significantly less than the differential resistance of the discharge tube. The milliammeter 5 shows the value of current I1 (or I_a) that flows into the anode of the discharge tube 6. The milliammeter 7 shows the value of the current $I_2(I_c)$ that flows from the cathode of the discharge tube 6. The voltmeter 8 shows the voltage U_2 (or U_{tub}) at the anode-cathode gap discharge tube. The variable resistance 9 determines the current that flows from the cathode of the discharge tube. The variable resistance 9 is assembled on a high-voltage electron lamp and allows to obtain an approximately sinusoidal current at the cathode of the discharge tube 6. The filter capacitor 2, a large capacity, provides a short circuit of the alternating current component in a serial circuit, in the entire frequency range of the modulation of resistance 9.

Using special electronic devices, the instantaneous currents measured by milliammeters 5 and 7 and voltmeter 8 were fed to double-beam oscilloscopes, which allows to measure the waveforms of currents and voltages. The difference between the discharge current and voltage on the tube from the sinusoidal is due to the processes inside the discharge tube. They are the subject of the research.

3. Results and Discussion

With direct current in an unbranched electrical circuit, only one point can be measured, i.e. the current I_1 of the milliammeter 5, which flows into the anode of the discharge tube, is considered equal to the current I_2 of the milliammeter 7, which flows from the cathode of the discharge tube. One has $I_a = I_c = I_0 = \langle I_{tub} \rangle$, where I_0 is a direct current and $\langle I_{tub} \rangle$ is the direct component of the discharge current in a discharge with a modulated current.

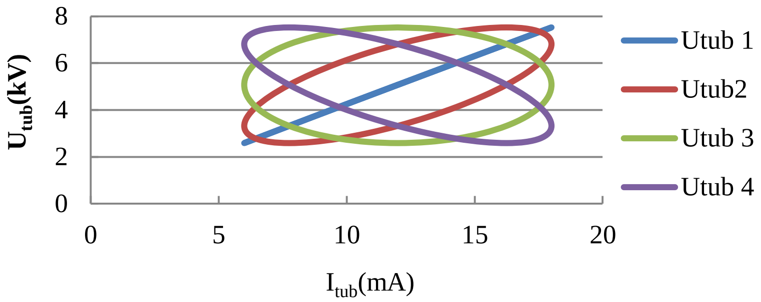
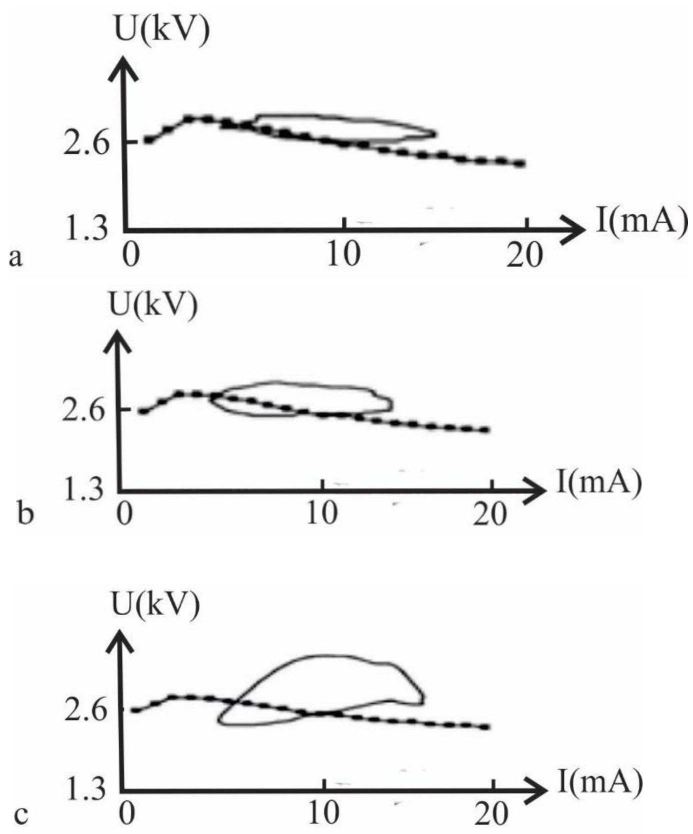


Fig. 4. Designed dynamic current-voltage characteristics when using current-voltage characteristics on a direct current. $U_{tub1} = U_{tub}$ ($\Delta\varphi = 0$); $U_{tub2} = U_{tub}$ ($\Delta\varphi = \pi / 4$); $U_{tub3} = U_{tub}$ ($\Delta\varphi = \pi / 2$); $U_{tub4} = U_{tub}$ ($\Delta\varphi = 3\pi / 4$).

If there are L or C elements in the circuit and an alternating sinusoidal current flows along the circuit, then the currents I_1 and I_2 are phase shifted. In this case, the current – voltage characteristic will have the form of Lissajous figures (Fig. 4). The dynamic current-voltage characteristics (CVC) would also look if the CVC, which were obtained for direct current, could be used.

In gas discharge devices, everything is much more complicated.



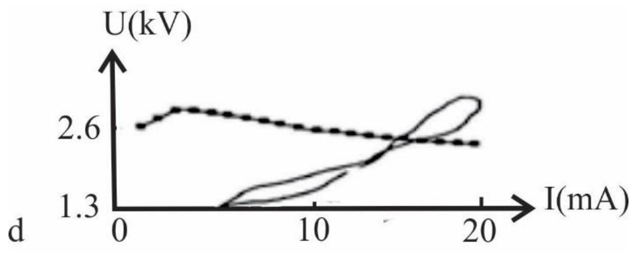


Fig. 5. Dynamic CVC of an acoustoplasma discharge. a) f = 0.1kHz, b) f = 0.3kHz, c) f = 1kHz, d) f = 15kHz. ▬▬▬ - CV characteristic of a direct current.

It can be seen from Fig. 5 that the dynamic CV characteristics of the acoustoplasma discharge depend on the frequency and essentially differ from the Lissajous figures.

When the discharge current is modulated in a low-temperature plasma, the number and the speed of charged particles also change simultaneously, in addition, the voltage at the discharge can change for other reasons. Therefore, the parameters of the dynamical processes in the plasma and especially in the acoustoplasma will be very different from the average values for the period of modulation. It should be noted that both plasma and acoustoplasma are nonlinear media. Therefore, even if the first current has a sinusoidal shape, then, due to the nonlinearity of the plasma, the second one will have harmonics. And finally, when the discharge current changes in the plasma, an additional charge can be accumulated or dissolved. In this case it is natural that during the modulation period the currents flowing into the tube and flowing out of the tube will differ. All these lead to the conclusion that in gas-discharge devices, especially when powered by a current that simultaneously contains both constant and variable components, it is necessary to simultaneously measure both the current that flows into the anode and the current that flows from the cathode.

We have not only a change in the dynamical resistance of the discharge, but also dynamical changes in the electric capacitance of the discharge, electron charges and other parameters.

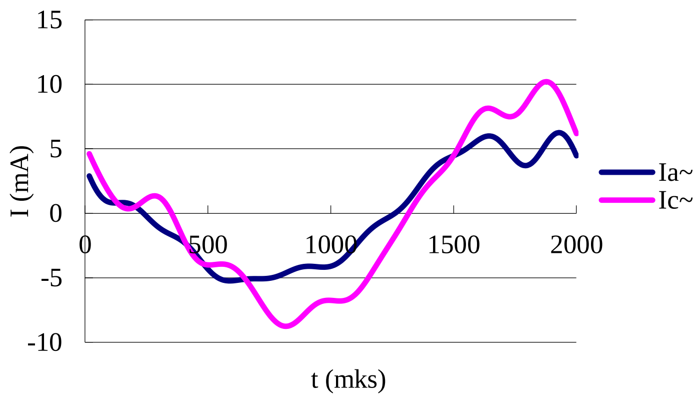


Fig. 6. Change in the current measured from the anode side (I_a) and the cathode side (I_c) during the modulation period.

Figure 6 shows the measured values of the current for the variable components of the currents I_c and I_a. Moreover, for the direct component of the discharge current one has $I_0 = \langle I_a \rangle = \langle I_c \rangle = 12mA$. For the modulation depth of the current measured from the side of the cathode we have $M_{Ic} = 0.83$ and the modulation depth of the current measured from the side of the anode is $M_{Ia} = 0.5$. The modulation depth M is the ratio of the amplitude of the variable component of the discharge current $I\sim$ to the value of the direct component of the discharge current $(M = I\sim/I_0)$.

Note that in wires and milliammeters, the current is due only to the movement of electrons, and in the anode-cathode gap the current in the plasma is due to the movement of charges of both signs, and effects similar to those that arise in Gunn diodes and avalanche-span diodes described in [7] are possible.

From Fig. 6 it is difficult to say how much the curves I_a and I_c differ from each other.

Table 1 shows the Fourier spectrum of the amplitudes of the harmonics I_a and I_c. It is seen that the second harmonic of the current measured from the cathode side is approximately 6 times greater than that measured from the anode side. In the plasma, inside the discharge tube, some processes characterized by the second harmonic occur. Usually this is a parametric pumping process [1].

Table 1. The Fourier spectrum of the amplitudes of the harmonics of the signals shown in Fig. 5.

n	1	2	3	4	5	6
I_c(mA)	7,95	1,28	0,66	0,53	0,63	0,86
I_a(mA)	5,39	0,23	0,22	0,33	0,51	0,33

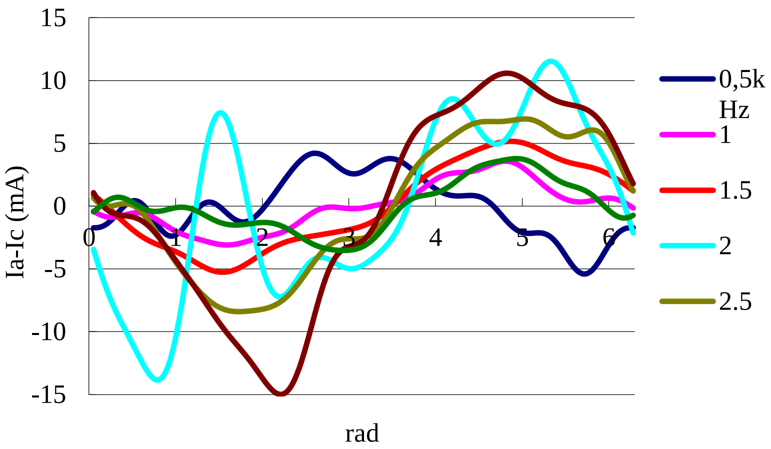


Fig. 7. Family of difference values of simultaneously measured instantaneous currents I_a and I_c for different modulation frequencies.

Figure 7 shows the difference in instantaneous values $I_a - I_c$ for different modulation frequencies. In order to be able to compare the curves for different modulation frequencies along the abscissa axis, the values are plotted in radians. It can be seen from Fig. 7 that the difference in instantaneous values $(I_a - I_c)$ has a complicated form. But this difference $(I_a - I_c)$ shows the instantaneous change in the charge inside the tube during the modulation period. Since we have already measured the current in conductors that are connected to the anode and cathode, the electron velocities can be considered the same and large in both conductors. The change in the electron velocity in the plasma can be neglected. Further, by solving the direct and inverse problems, we can determine many parameters of the acoustoplasma which, for some reason, we could not directly measure.

4. Conclusions

The main results of the paper are summarized as follows.

1. When we supply the gas-discharge devices by a current that contains constant and variable components, the dynamical processes essentially differ from the average for the period of the change in the discharge current.
2. When the discharge current inside the tube changes, the charge changes as well. Therefore, in acoustoplasma discharges and in discharges with alternating current, measuring the discharge current at only one point in the series circuit leads to errors, since this does not take into account the change in the charge inside the discharge tube itself.
3. In the measurement of the discharge current at one point in the series circuit, the dynamical change in the electric capacitance of the discharge is not taken into account.
4. For adequate and correct measurements, it is necessary to simultaneously measure the current that flows into the anode of the discharge tube and the current that flows from the cathode of the discharge tube.

Acknowledgements
The authors are grateful to the Hector Hovhannisyan for his technical support.

Funding
The paper has been supported from Basic financing of IAPP NAS RA.

Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
The authors equally contributed to all steps of the paper preparation.

References

[1] L.A. Bessonov, Theoretical Foundations of Electrical Engineering (Visshaia shkola, Moscow, 1966). (in Russian).
[2] G.A. Galechyan, A.R. Mkrtchyan, Acoustoplasma (Apaga, Yerevan, 2005) (in Russian).
[3] A.R. Mkrtchyan, A.H. Mkrtchyan, A.S. Abrahamyan, VII Int. Conf. Plasma Physics and Plasma Technology, PPPT-7, Proc., v.1, (2012) 3.
[4] A.S. Abrahamyan, T.Zh. Bezhanyan, Laser physics conf. - 2007 (2007) 225.
[5] K.P. Haroyan. Ph.D. Dissertation, IAPP NAS RA, Yerevan, Armenia (2005).
[6] Q.G. Sahakyan, Ph.D. dissertation, IAPP NAS RA, Yerevan, Armenia (2014).
[7] A.I. Lebedev, Physics of semiconductor devices (Physmatlit, Moscow, 2008) (in Russian).