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Photoemission optogalvanic effect near the instability region of a hollow cathode discharge

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Abstract

The photoemission optogalvanic (POG) effect has been investigated in a neon–neodymium hollow cathode discharge using cw laser excitation. Both positive and negative effects were observed. It was found that the amplitude of the POG signal was unstable near the instability region of the discharge.

1. Introduction

The optogalvanic (OG) effect is the change in impedance of a gas discharge caused by resonant absorption of electromagnetic radiation, and this effect is widely used for spectroscopic and analytical measurements [1,2]. The impedance change can also be produced by injecting electrons into the discharge via the photoelectric effect. This non-resonant process due to the interaction of photoelectrons emitted from the cathode with the species present in the discharge is known as the photoemission optogalvanic (POG) effect [3–6]. The release of a very short pulse of photoelectrons by a flash of ultraviolet light on the cathode of a parallel plate Townsend discharge has been reported, where the resultant transient current has been investigated for the measurement of the drift velocity and mobility of ions, electrons etc., and has been used to study the fundamental processes occurring in the discharge [7–10]. Laser excitation of photoelectrons which may produce large impedance changes has found numerous applications for discharge diagnostics [11–13], surface electrode characterization [14,15], multiphoton absorption etc. [4,16]. The time dependence of the POG signal follows the temporal characteristics of the excitation source. Most of the work reported on this effect has been done using high power pulsed lasers which are capable of producing a short and intense beam of photoelectrons [17]. In this communication we report the use of a cw laser for generating the POG effect and extend the method to investigate discharge instability.

Even though the OG effect can be positive or negative depending on the lifetime of the levels involved in the transition [2,18], the POG effect is usually positive (i.e. an increase in current) since the photoelectron emission will produce more secondary electrons by collision with atoms as the electrons move from the cathode to the anode. However, in this work we have observed a decrease as well as an increase in the POG signal, depending on the discharge conditions. The region where the POG signal begins to decrease shows evidence of discharge instabilities and the changes of the signal amplitude have some noticeable features even if all the experimental parameters are kept constant.

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2. Experimental

The experiment was performed in a commercial hollow cathode discharge (hcd) lamp (Cathodean UK) which is commonly used as a light source and for numerous applications in atomic spectroscopy. It consists of a hollow cylindrical cathode made of neodymium (Nd) with a ring anode with an inter-electrode separation of about 2 mm and contains neon gas at a pressure of about 10 Torr. Mechanically chopped radiation at 62 Hz from an argon ion laser (Spectra Physics model 171) in multiline mode was allowed to fall without focusing on to the Nd cathode. The laser beam has a TEM_{00} mode spatial distribution with a beam diameter of 1.56 mm and has a very stable output power. The discharge was produced by applying a highly regulated ripple free dc power supply (Thorn EMI model PM 28B) and was operated in the negative glow regime showing the characteristic colour of the neon glow discharge. A current limiting resistance of 66 kΩ and a milliammeter were connected in series with the cell, and the modulated POG signal was detected by blocking the dc voltage using a coupling capacitor of 0.1 μF (Fig. 1). The amplitude of the POG signal was measured using a 200 MHz digital storage oscilloscope (Iwatzu type DS-8631) after averaging twice, and the phase was measured using a lock-in amplifier (EG&G type 5208). Another lock-in amplifier (Stanford Research System type SR 850) was used to record the POG signal near the instability region of the discharge.

3. Results and discussion

The work function of the cathode material (Nd) is 3.2 eV [19] and the energy of the laser photons used was 2.6 eV. The work function of a material depends

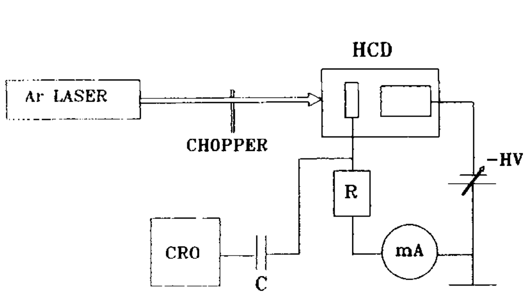

Fig. 1. Experimental setup.

on the state of the surface, viz. its contamination, roughness, temperature etc. [20]. Even at a very low voltage (100 V) the signal is observed in the absence of discharge, even though there is a mismatch between the work function of the cathode material and the photon energy. The effective work function of the cathode material will be reduced in the presence of an electric field due to the combined effect of Schottky and field emission so that a lower photon energy threshold is sufficient to generate the signal. Surface enhanced ionization can also take place. Here the interaction of radiation with positive ions of the metal surface can lower the work function sufficiently to allow efficient generation of photoelectrons by the photon flux [21].

The characteristics of the electron emission from the target is described by the generalized photoemission theory of Fowler and Dubridge [22–24]. According to this theory, the total current density is

$$J(r, t) = \sum_{n=0}^{\infty} J_n(r, t) . \tag{1}$$

The quantity J_0 is interpreted as thermionic emission and J_n as the photoemission contribution given by

$$J_n(r, t) = a_n\left(\frac{e}{h\nu}\right)^n A(1-R)^n I^n T^2 F\left(\frac{nh\nu - e\phi}{kT}\right) . \tag{2}$$

Here, R is the surface reflectivity, A is the theoretical Richardson constant, ϕ is the work function, I is the laser intensity, T is the absolute temperature of the cathode and a_n is the empirically determined constant. The function $F(x)$ is the Fowler function expressed by

$$F(x) = \sum_{n=0}^{\infty} \frac{(-1)^{m+1} e^{mx}}{m^2} . \tag{3}$$

In the presence of a discharge, as the photoelectrons move from the cathode to the anode, they are multiplied due to collisional processes, thereby producing a large number of secondary electrons. Thus, if ΔV is the change of voltage across the resistance during laser irradiation in the absence of plasma, then the multiplication factor given by

$$\alpha(V) = \frac{\Delta V_p}{\Delta V} \tag{4}$$

is greater than unity, so that the current increases and the signal amplitude in the presence of the discharge (ΔV_p) will be greater than that without plasma. On the

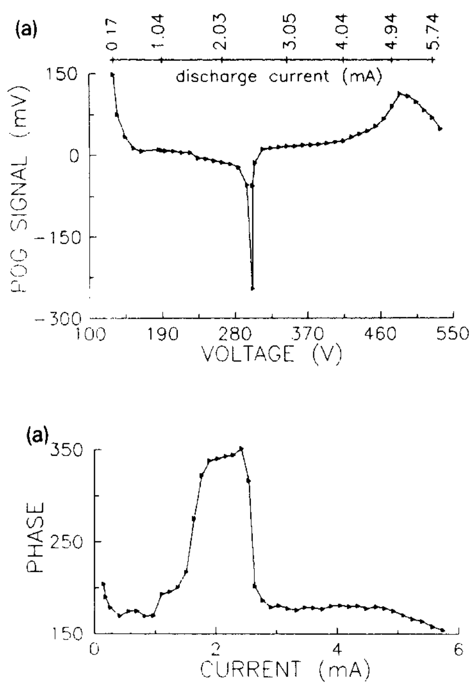

Fig. 2. (a) Variation of the amplitude of the POG signal with discharge voltage. (b) Variation of the phase of the POG signal with discharge voltage (laser power is 1 W).

other hand, the recombination of the secondary electrons with the positive ions in the discharge leads to a decrease of current. The multiplication factor and the magnitude of the POG signal depend on the irradiated laser power, the applied field dependence on the potential barrier of the cathode material [21] and the discharge characteristics.

Fig. 2a shows the variation of the POG signal as a function of voltage. The discharge noise is about 2 mV and the signal to noise ratio is very good. The signal fluctuation is mainly due to laser power variations which were less than 0.5% and the measurements were taken after two averages using the digital storage oscilloscope. In the presence of the discharge as the current is increased up to 2.3 mA, the signal decreases while a further increase in the current results in a sign reversal. The phase of the signal also changes at the maximum negative POG signal where there is a phase shift of 180° (Fig. 2b). In this region, generated photoelectrons interact with the discharge such that instead of producing more secondary electrons their number is reduced, i.e. the electron multiplication factor is less than one. An increase in current beyond this point reverses the phase, and the sign of the signal changes to positive. It has been found that in the absence of laser irradiation the discharge in the hollow cathode lamp shows instabilities leading to chaotic oscillations [25]. The experiment is carried out by varying the laser power from 0.5 W to 2.5 W in steps of 0.5 W. It was noticed that the magnitude of the POG signal amplitude increased and the negative peak (at ~2.3 mA) as well as the positive peak (at ~5 mA) were found to be shifted to the lower voltage region as the laser power was increased.

Finally, we have investigated the time dependence of the POG signal near the negative peak, where the signal becomes unstable. When the applied voltage is very close to the instability region, the signal grows and decays as shown in Fig. 3 with a time scale of about ten minutes. This occurs until a stable condition is reached. Above this region, the POG signal was always positive with a maximum amplitude at about 5 mA. The instability shows a strong dependence on the initial conditions such as current, laser power, irradiating region etc.. The factors that cause the discharge instability are related to the process that control the density of electrons (their production, spatial distribution, etc.). The extra photoelectrons emitted from the cathode will change the dynamic impedance of the discharge and consequently its charge collection efficiency. When the discharge instabilities are present the presence of laser photoemission would appear to have driven the discharge into a more stable mode with what in some cases may be a greater discharge collection efficiency and in others may be a lower collection efficiency. These observations are most likely to be a

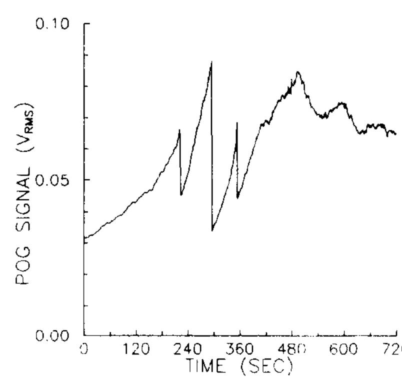

Fig. 3. Time dependence of the POG signal near the discharge instability (laser power is 1 W).

result of bulk discharge behaviour. Depending upon the closeness of the applied voltage to the peak of the unstable voltage, these oscillations have one to three peaks. The large time scale of the signal variations suggests that the instability is mainly created by thermal processes.

In brief, the following observations were made at the instability region:

(i) The POG signal is negative, i.e. the interaction of photoelectrons with the discharge reduces the current in the circuit, so that a phase shift of 180° occurs for POG signals around the instability region.

(ii) Near the peak of the negative signal, the POG signal is very unstable and depends on the intensity of the incident laser beam.

In conclusion we have noted the existence of discharge instability in an Ne/Nd hollow cathode using the photoemission optogalvanic effect. Near the instability region the POG effect corresponds to a negative signal which grows and decays a number of times till the discharge reaches an equilibrium. It is observed that the discharge instabilities depend on the laser power and can be easily identified by monitoring the POG effect indicating the possibility of using this effect for studying various non-linear phenomena in electrical discharges.

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