Self-induced optogalvanic effect in a segmented hollow-cathode discharge

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Abstract. Optogalvanic (OG) interaction is simulated and studied in a segmented hollow-cathode discharge (SHCD). HCD-lamps are used to induce an OG signal by their own emission or by that of another lamp. The efficiency of the OG of a Ne/Cu HCD lamp in the range 320-380 nm is estimated theoretically. An irregular galvanic peak arising near the inflection point in the $i$-$V$ curve ($\partial V/\partial i<0$) is detected. Its origin is related to Penning ionization of the sputtered cathode material.

1. Introduction

A glow discharge modification, known as a hollow-cathode discharge (HCD), combines two important processes, namely sputtering and excitation of atoms. The commensurability of the large contact surfaces negative glow (NG) – cathode dark space (CDS) – cathode surface yields a sufficient density of sputtered atoms mostly residing in ground state, together with a characteristic electron energy distribution function (EEDF), which contains fast beam-like electrons that excite high-lying atomic states, including those of the ion buffer [1]. This spectroscopic advantage was developed in both emission and absorption spectroscopies.

Segmentation of the cathode extends the applications of HCDs to include laser media. The electrons motion, the magnetic field effects, the number of electrode segments, the cathode-anode surface ratio, the cathode length influence [2-4] are just a few of the specific aspects to be studied of a segmented HCD. On the other hand, HCD segmentation is a prerequisite for additional optical interactions that may arise between the different segments.

Penning was the first to observe light-induced conductance in a gas discharge [5]. It is the essence of the so-called opto-galvanic effect (OGE). Resonant light absorbed by atoms disturbs their steady-state population and, ultimately, changes the voltage across the discharge, the latter thus acting as an OG detector. This galvanic analogue of absorbed light can be measured more precisely than the absorbed light itself, making the OGE spectroscopy a modern and promising alternative of absorption spectroscopy [6].

We report here manifestations of OG phenomena in a SHCD observed and analyzed, to the best of our knowledge, for the first time.

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2. Experimental set-up
The experimental set-up used for measuring OG signals is presented schematically in figure 1. The optical interaction between two neighboring HCD-segments was simulated by using either: i) the same HCD lamp (HCDL) as a light source and an OG detector simultaneously (section HCDL 2 – Ch – f – l – Mr and back to HCDL 2) or ii) two HCDLs as a light source (HCDL 1) and an OG detector (HCDL 2) (section HCDL 1 – l – f – Ch – HCDL 2). In these simulations, different chemical cathode-buffer pairs were studied by using commercial Ne/Cu (Narva) and Ne/As (Pye Unicam) HCDLs, and Ne/Cd and Ar/Cd (Pye Unicam) HCDLs.

Simultaneously, controlling i-V curves were measured by using a Fluke 8062A multimeter. The discharge current values i were chosen taking into account the discharge stability. Also, He/Ne and Ar lasers were used in comparative control measurements of the light-induced conductance.

An OG signal arises as an absorbed photon, hv, causes a corresponding small perturbation of the atomic states populations -Δni and +Δni; their relaxation brings about the OG effect. The latter manifests itself as a light-induced change in the gas discharge plasma resistance ΔR, discharge current Δi and voltage across the discharge ΔU. The quantity measured is the OG signal amplitude (AOGS), ΔU\(^{\text{AOGS}}\), i.e. the OG-effect induced by the chopped light emission beam and averaged by the r-constant of the amplifier. A 232B lock-in nanovoltmeter (Unipan) provided the ΔU(i) signal whose shape is close to that of the first derivative \(\partial U(i)/\partial i\); A type 237 selective nanovoltmeter was also used.

![Figure 1. Experimental set-up:](image)

- HCDL – hollow-cathode discharge lamp, C – hollow cathode, l – lens, Ch – chopper, f – interference filter, Mr – selective reflective mirror, PS – power supply, R\(_b\) – 100 kΩ ballast resistor, C – decoupling capacitor, R\(_m\) – 200 kΩ measuring resistor, PD – photodiode, NV – type 232B lock-in nanovoltmeter or type 237 selective nanovoltmeter.

3. Experimental results and discussions

3.1. On the optogalvanic efficiency of the own spectrum of Ne/Cu HCD in the 320-380 nm region, light-induced resistance and discharge current
The OG efficiency of a discharge-detector is characterized by the ratio light-induced discharge current \(\Delta i(A)/\text{absorbed light power } P'(W)\), where \(P' = n_q\) is the number of quanta absorbed per second. We evaluated the OG efficiency vs. own spectrum for the Ne/Cu (Narva) (HCDL 2) emission within the 320-380 nm range. The OG response was simulated by the circuit \(\text{HCDL2 - Ch - f - l - Mr - and back to HCDL2}\) (figure 1). In the selected spectral band, the resonant lines CuI 324.8 nm and CuI 327.4 nm are one order of magnitude more intense than the rest of the lines, including the NeI 352 nm line. Accordingly, the cumulative impact of the resonant CuI lines can be taken as a low limit only of both the emitted and absorbed light.

The value of \(\Delta i\) was estimated by the light-induced change \(\Delta R^*\) of the discharge resistance \(R^*\). A signal \(\Delta U = 0.12\) mV was measured by the type 237 selective nanovoltmeter at \(i = 10\) mA. This signal is integral in nature. If \(V_\theta\) is the voltage across the discharge and \(R^*\), the discharge resistance, the logical
relation \( \frac{\Delta U}{R_m} \propto \frac{V_0 \Delta R}{(R_b + R')^2} \) yields \( \Delta R \propto \frac{\Delta U(R_b + R')^2}{R_b V_o} \). At \( R_b = 100 \text{k}\Omega, V_0 = 400 \text{V}, \text{and} R = 200 \text{k}\Omega \) and \( R' \ll R_b \), the light-induced resistance \( \Delta R' = 0.15 \text{\Omega} \). Then \( \Delta i = V_0 \Delta R'(R_b + R')^2 = 6 \times 10^{-9} \text{A} \).

The radiated light power \( P \) was calculated from the relation \( P = N_i V \tau_{\text{eff}} \text{, where the effective lifetimes} \ \tau_{\text{eff}} (2.0 \times 10^{-8} \text{s}, \text{Cul} 4^2P_{3/2} \text{state, and} 2.2 \times 10^{-8} \text{s}, \text{Cul} 4^2P_{1/2} \text{state}) \) are taken from Refs. [7, 8], the population \( N_i \) of the upper resonant Cul levels (\( N_i = n_e N_0 <\nu \sigma > = 2.4 \times 10^7 \text{cm}^{-3} \) and \( 1.3 \times 10^7 \text{cm}^{-3} \)) is estimated according to Refs. [9-12], and \( V \) is the discharge volume. The calculated values \( n_e = 2.4 \times 10^{14} \text{s}^{-1} \) (Cul \( 4^2P_{1/2} \)) and \( 1.2 \times 10^{14} \text{s}^{-1} \) are underestimated, since a Maxwellian is used in the rate constant \(<\nu \sigma > \) in [9, 10], \( \sigma \) being the cross-section of electron-atom interaction. The combined power of the two lines absorbed by the discharge proves to be \( 1.6 \times 10^7 \text{W}, \) and the OG efficiency, \( 73.8 \times 10^{-2} \text{A W}^{-1} \). This value is based on the two dominating in terms of power Cul spectral lines only, so that this estimate provides an approximation of the order of magnitude of the OG interaction in a SHCD.

3.2. OGSSs induced by parts of the Cul and NeI spectra. A non-resonant galvanic signal and HCD i-V inflection point

OGSSs induced by own or an external spectrum were detected in the Ne/Cu HCDL and the Ne/As HCDL lamps. Figure 2(a) illustrates the signals in the Ne/Cu HCDL lamp induced by two bands of its own spectrum when the discharge current was varied. The dielectric coating of mirror Mr (figure 1) was such as it returned to the Ne/Cu lamp 92% of its spontaneous emission in the 320-380 nm region (curve b) and 96% from the 594.5 \pm 20 nm region (curve c). For comparison, HCDL 2 was irradiated by the NeI 339.1 nm line of a He-Ne laser (curve a); curve d shows the corresponding cathode-anode (C-A) voltage across the HCD.

The monotonic curves \( \Delta U(i) \) in figure 2(a) contain local peak-like OG (POG) extremums \( \Delta U'(i) \) of type a and b, which do not follow from the analysis in section 3.1. To understand the nature of the POG appearance, we performed further measurements. The Ne/As HCDL lamp was illuminated by the Ne/Cu lamp (figure 2(b)) directly (without filter f) and through interference filters of maximum transmittance at 590 nm and 654 nm. Simultaneously, the corresponding voltage on the HCD was measured and an inflection i-V point similar to those on curve d (figure 2(a)) was observed near the discharge current value of 4.2 mA.

**Figure 2.** (a) Laser-induced (\( \lambda = 339.1 \text{~nm} \)) OG signal (curve a); spontaneous-emission-induced (320-380 nm) (curve b) and (594.5 \pm 20 nm) (curve c) integral OG signals in the Ne/Cu HCDL; i-V dependence (curve d); \( \alpha, \beta \) – peak-like OGSSs; (b) Peak-like OG signal in the Ne/As HCDL illuminated by the Ne/Cu HCDL in the vicinity of the inflection point (4.2 mA) of the i-V curve. Curve a – filter of maximum transmittance at 654 nm; curve b – filter of maximum transmittance at 590 nm; curve c – without filter.
Let us now point to the characteristic properties of the POG extremums:

\( \text{i/ they arise near an inflection } i-V \text{ point, where } \frac{\partial U}{\partial i} < 0 \) (\( \alpha, \beta \) and the others) holds true in a narrow interval of about \( \Delta i \approx (0.15 - 0.3) \text{ mA} \);

\( \text{ii/ in the vicinity of the above } \Delta i \text{ interval, the } i-V \text{ curve forms bumps of increased HCD conductance (for example curve d (figure 2a); simultaneously, the phase has identical peak-like behavior and changes by up to } 180^\circ \text{ relative to the reference signal;}

\( \text{iii/ a rise in the noise level is detected in the vicinity of the region } \frac{\partial U}{\partial i} < 0 \) (by more than a factor of three for the Ne/As HCD in the frequency range up to 20 kHz).

A symptomatic result concerning the POG effect nature was observed in the Ne/As HCDL illuminated by the 488.0 nm line of an Ar\(^{+}\) laser. This line is in resonance with none of the Ne or As atomic transitions, so that no light-induced perturbations of the populations ± \( \Delta n_{ik} \) should occur. Nevertheless, a POG signal was observed. In this case, photoemission and space ionization only form the galvanic perturbation. Thus, POG signals in figure 2 (a, b) are non-resonant in nature.

The frequency non-selectivity of the peak-like galvanic responses and their various current values for each chemical pair of \textit{buffer gas-cathode} represent a strong indication that the above facts are of more general nature. Based on these facts, a qualitative explanation can be given considering the Ohm’s law for the discharge circuit. By analogy with the anomalous glow discharge [13], one may assume that \( U(i) = V(i) + V' \), where \( V(i) \) is an explicit function of the discharge current and \( V' \) depends on the other discharge parameters. Ohm’s law can be expressed as

\[
i(R_b + r_0) = E - V(i) - V',
\]

where \( R_b \) is the ballast resistance, \( r_0 \) is the internal resistance of the current source, and \( E \) is the supply voltage. Then the total discharge current change \( \Delta i \) is

\[
\Delta i = -V'(R_b + r_0 + \partial V/\partial i)^{-1}.
\]

It is evident that the change \( \Delta i \) will increase at \( \partial V/\partial i < 0 \) (even more if \( |\partial V/\partial i| \approx R_b + r_0 \)).

We consider the correlation \( i-V \) bump – POG signal as a cause-effect relationship. The at least two-component (buffer and sputtered atoms) HCD plasma is a prerequisite for Penning ionization. In some cases, this ionization dominates the stepwise one and an \( i-V \) bump arises. Having analyzed the energy levels of As, As\(^+\) and Ne [14], the process of energy exchange between a metastable Ne\(^m\) and an As atom in ground state:

\[
\text{Ne}^m (^3P_2) + \text{As} (^3S_3/2) \rightarrow \text{Ne} (^1S_0) + \text{As}^+ (^5S_2) + \Delta E + \vec{e}
\]

could be considered as the most probable process, the reason being the negligible deficiency \( \Delta E = 3.1 \times 10^{-3} \text{ eV} \). Therefore, complicated \( i-V \) and \( \Delta U'(i) \) curve should be expected.

The above analysis of the cathode-buffer chemical pair is relevant for some commercial lamps because of their highly nonlinear \( i-V \) curves. For example, at least six regions where \( \partial V/\partial i < 0 \) are observable in the spectrum of a commercial Ar/Cd HCDL (figure 3). Thus, the parts of the \( i-V \) curve where a stable mode for operation is possible are too limited. Moreover, self-sustained oscillations of different frequency were observed near each part where \( \partial V/\partial i < 0 \). At the same time, the \( i-V \) curve characterizing another chemical pair, namely of a Ne/Cd HCDL, is much smoother and no instabilities take place. However, the noise background grows when the Ne/Cd HCD lamp is irradiated by an Ar/Cd one. Here, the emission of Cd atoms may be the only

**Figure 3.** Part of the \( i-V \) curve of an Ar/Cd HCD spectral lamp.
optical channel of resonant interaction. This circumstances should also be taken into account with regard to the SHCD, namely the optical interaction between the HCD segments multiplies the instability near the inflection point in the $i$-$V$ curve in a separate segment.

4. Conclusions

The mutual optical irradiation of two HCD segments induces an integral OG effect. This effect is an invariable property of a segmented cathode and depends on its effective length. The original emission of a Ne/Cu HCD lamp within the 320-380 nm range was calculated by us as inducing an OG signal of efficiency $\Delta i/W > 3.8 \times 10^{-2}$ AW$^{-1}$.

The correlation $i$-$V$-bump $\rightarrow$ POG signal is in a cause-effect relationship. The pair of buffer atom–sputtered atom in a HCD is a prerequisite for Penning ionization to occur. The latter changes the steepness of the $i$-$V$ curve and forms a local $i$-$V$ bump. A local peak-like OG (POG) signal arises near this inflection $i$-$V$ point; the phase is of the same peak-like behavior and changes by up to $180^0$ relative to the reference signal. The POG signal is a non-resonant galvanic response in nature and manifests itself as an instrumental effect due to the inflection $i$-$V$ point, where \( \partial U/\partial i < 0 \).

One consequence of the negative resistance is the increased noise background of the OG signal in the inflection point vicinity. This frequency instability is multiplied optically in the SHCD.

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