Magneto-galvanic signals and ionization processes in a neon hollow cathode discharge

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Abstract. The resonant change of the discharge current with the application of an external magnetic field, known as magneto-galvanic effect (MGE), is studied as a galvanic manifestation of the atomic states coherence in a hollow cathode discharge. The signal measured represents the difference in the conductivity of the self-aligned and the non-aligned ensembles. The contribution of the metastable 1s 5 and the resonant 1s 4 Ne levels to the MG signals observed is checked by laser irradiation of the optical transitions 1s 5-2p 9 and 1s 4-2p 8 in the discharge.

1. Introduction

W. Hanle was the first to observe a magneto-optical (MO) effect manifested as a light-induced coherence between atomic states with a degenerated magnetic sublevel \( m \) spaced at \( \Delta m = \pm 2 \) [1]. This coherence, known as alignment, is revealed through the polarization \( P \) of the spontaneous emission. When a magnetic field \( B \) eliminates the degeneracy, a MO depolarization resonance \( \Delta P(B) \) is observed (a Hanle signal). In the 1960s, the alignment was found to arise as a self-sustained coherence (self-alignment) in the positive column of a glow discharge (PCD) [2]. Here the spatial optical anisotropy (length \( l / \text{radius} \ r \gg 100 \)) self-aligns the excited states. In contrast to PCD, in a low pressure hollow cathode (HC) discharge (HCD) the dominating factor for self-alignment are the fast electrons [3].

Earlier, a resonant change of the discharge current with the application of an external magnetic field in the absence of an external irradiation \( \Delta U(B) \) was observed by monitoring the voltage \( U \) across a HCD simultaneously with \( \Delta P(B) \) [4]. The resonance \( \Delta U(B) \) was detected in PCD too [5]. The fact that both \( \Delta P(B) \) and \( \Delta U(B) \) react in the same way to any change of the direction of \( B \) suggests that \( \Delta U(B) \) is a galvanic manifestation of the self-aligned states. Therefore, the effect was named magneto galvanic (MGE) [5]. In contrast to the selective signal \( \Delta P(B) \), the MG signal \( \Delta U(B) \) is the contribution of the self-aligned ensemble of atoms to the conductivity.

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The resonances obtained in both types of discharges outline the general picture of the MG effect: the anisotropic excitation of the glow discharge creates a Hertzian coherence of the atomic ensemble. The magnetic field, which is not parallel to the anisotropy axis, destroys the coherence, which leads to a resonant change of the total number of ionizations in the discharge. The resonance width is close to the coherence decay constant. Nevertheless, the exact mechanisms of creation of self-induced coherence and the transformation of the destruction of alignment into a galvanic resonance in the different discharges are still not completely clarified. In a HCD, the sputtered atoms (~ $10^{11} \text{ cm}^{-3}$) complicate the above processes, mostly by Penning ionization.

This work is an attempt to specify some formation mechanisms of the MG signals in Ne filled commercial HC lamps and to distinguish between the roles of the possible ionization processes in the MG effect. Special attention is devoted to the electron collisions and to the Penning ionization.

2. Experimental

Compared to [4] the detection system used (figure 1) is improved, allowing automated recording of magneto-galvanic signals (MG), laser-induced galvanic signals (LIG) and current-voltage curves and their derivatives (U/I, dU/dI).

MG signals were detected using phase sensitive detection (PSD). A PC programmable ramp voltage is mixed with a sine signal (307 Hz) with small amplitude (about 1% from the full ramp amplitude) and fed into Helmholtz coils. The frequency of this second voltage (software adjustable) is used as a reference for the PSD. The appropriate balance between the duration of the ramp and the averaging modes provides for the good signal-to-noise ratio.

LIG signals were resolved with a PSD in a similar way. The reference frequency in this case is the one of the modulation current of the laser diode. The Ne 2p$^5$3s levels are excited. The LIGS dependence on the discharge current is acquired by its ramping with a user-adjustable step. Since the 2p$^5$3s levels are the main donors of the charge carriers, the comparison of MG and LIGS can clarify the influence of the alignment on the MG signals.

The current-voltage (U/I) curves are obtained by simultaneous recording of the differential anode-cathode voltage and the discharge current. The first derivative dU/dI is obtained by a software controlled current modulation superimposed on the lamp current by a transformer. The derivative is also acquired in real time, which allows comparison with the U/I curve.

Studied are commercial HC lamps Ne/A (A: Cd, Si, Cu, Ca, Ba) are studied.

3. Results and discussions

Since modulation of the magnetic field B was used, the shape of the MG signals is close to the first derivative $\partial U(B)/\partial B$. The curves on figure 2 illustrate both the derivative (1, 2) and the corresponding numerically integrated (1', 2') signals for the Ne-CaBa lamp. The derivative signals were recorded at a constant phase shift, which allows a direct comparison of the integrated signals from different lamps.
and currents. The dependencies $1', 2'$ characterize the difference in the conductivity between both self-aligned and non-aligned ensembles of atoms. This difference may be identified as specific (magnetic field dependent) conductivity, i.e. a coherent one. The resonant rise of the integrated MG-signals (see $1', 2'$ – figure 2) was observed in all the studied HC lamps, except for the Ne-Cd, where the $\partial U(B)/\partial B$ signal appears under a narrow dc region only and its sign corresponds to a decreasing conductivity. The rise of conductivity in a weak magnetic field in the positive column discharge has been earlier experimentally discovered and theoretically explained by Chaika et al. [5].

To check the influence of the population and/or alignment of the different Ne-2p$^3$s states on the formation of the MG-signal we apply an empirical approach based on the selective light perturbation of the 1s$_5$ and 1s$_4$ levels, using 1s$_5$ – 2p$^9$ (\(\lambda = 640.2\) nm) and 1s$_4$ – 2p$^8$ (\(\lambda = 638.3\) nm) laser wavelengths. The wavelength \(\lambda\) chosen is synchronously modulated by means of the diode laser current (alternative commutation “on” and “off” the exact transition value) in the successive steps of the magnetic field ramp. Thus the MG signals \(\Delta U(B)\) are recorded in both irradiated and non-irradiated state. The corresponding maximum LIG signal is an indication of the resonant irradiation.

The correlation MG -LIG signal is of particular interest since the LIG influences strongly the charge carrier producing levels and the population of these levels depends on the interaction with different plasma components and on the electron density.

As an example, figures 3 and 4 illustrate MG signals in Ne- Si HCL under irradiation with a 638.3 nm and a 640.2 nm laser lines. The 638.3 nm wavelength does not perturb the MG signal, therefore the contribution of the 1s$_5$ level in the MG resonance could be considered negligible. On the contrary, excitation at the 1s$_5$ – 2p$^8$ transition considerably perturbs the MG signal, which indicates the participation of the 1s$_5$ level in the formation of the corresponding resonance. The 1s$_5$ level has an essential contribution to the galvanic reaction and destruction of the MG signal.

**Figure 3.** MG signal in Ne/Si HCD lamp (“Narva”) at excitation with \(\lambda = 638.3\) nm.

**Figure 4.** MG signal in Ne/Si HCD lamp (“Narva”) at excitation with \(\lambda = 640.2\) nm.

In the following short discussion of the above results we would like to emphasize the difference between the HCD and PCD. The fast electrons from the HCD generate a considerable second order moment \(f^{(2)}(v)\) in the velocity space of the electron energy distribution function, which is described with spherical functions [6]. This moment \(f^{(2)}(v)\) characterizes the electron momentum flow and creates space anisotropy in the electron-atom excitation. Magnetic field destruction of the alignment created forms the MG signals observed.

Earlier we proposed another phenomenological model relating the MG signal in neon with the destruction of the alignment of the 1s$_5$ state [4]. According to the model, the self-alignment of this level is created through a cascade transfer of coherences from the upper (2p$^3$3p) Ne states, which are aligned by the reabsorption of their own emission. Without going into the details of the theoretical description,
we would like to point out that the magnitude of the 1s£ self-alignment essentially depends on the population of the resonant and metastable states of neon. Having used model calculations, the self-alignment of the metastable 1s£ was found to change its sign with the population of levels 2p°3s. However, the MG signal has neither been evaluated, nor considered dominant.

In contrast to a PCD, in a HCD the dc is known to play also another specific role, namely as a factor for the atomic sputtering yield. The latter is a prerequisite for Penning ionization in a HCD discharge.

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\text{Ne}^m (^3P_2) + A \rightarrow \text{Ne} (^1S_0) + A^+ + e_{\pm2}, (A \rightarrow \text{Cd, Si, Cu, Ca, Ba})
\]  

(1)

This process was found [7] to influence the current-voltage curve. However, of greater importance is the circumstance that the metastable spin state (magnetic number) may affect the efficiency of the process (1). The ionization cross-section for Penning collisions of atoms with zero orbital moment (helium) has been studied theoretically [8] and experimentally [9] as a function of the off-diagonal elements of the density matrix. Assuming that the rule of complete moment preservation applies to the Ne° atom in equation (1) as well, then the impossibility a sputtered atom to be ionized by an atom of magnetic moment more than 1 is evident. A magnetic field destroying the self-alignment takes off the above prohibition and increases both the ionization and the conductivity. In addition, the same selectivity may manifest itself in the resonant ionization due to collisions between Ne° atoms of equal magnetic moment.

We observed different MG signals in commercial HCD lamps of different cathode materials: Ne-Cu, Ne-Si and Ne-Cd. The difference was pronounced both in the shape and the amplitude in dependence on the discharge current. In our opinion, this comparison suggests the essential role of the Penning process (1) in the formation of the MG resonances. The latter were found to correlate in amplitude with the laser induced galvanic signal (LIGS). On the other hand both the MG- and LIGS correlate with the corresponding voltage-current curves behaviour. These correlations confirm the importance of the Penning ionization.

The irradiation with \( \lambda = 640.2 \) nm corresponds to a 1s£-2p° optical transition and there are no transitions from any upper states. Therefore, the galvanic contribution of this transition seems to be via a super-elastic interaction between the NeI 1s£ atoms and the electrons.

4. Conclusion
Both self-aligned and non-aligned atomic ensembles are distinguished in the conductivity of a hollow cathode discharge. This difference may be designated as a coherent conductivity. The latter does not imply conductivity with a fixed sign and depends on the degree of self-alignment. The MG signal measured represents an integral characteristic of the above coherent conductivity. The selective galvanic contribution of the optical transition NeI 1s£-2p° is checked by using selective light perturbation in an opto-galvanic scheme. The different shape of the MG resonances, measured in commercial HCL with different cathode materials, indicates the essential role of the Penning processes in the formation of the galvanic response to the coherence destruction by a magnetic field. This proposition is supported by the correlations between the MG and the LIG amplitudes on the one hand and the current-voltage curve behaviour on the other.

5. References
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