Investigations of indium halides as radiator in ICPs for lighting applications

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Indium halides such as InBr and InCl are under discussion as substitutes for mercury in fluorescent lamps. The radiation characteristics of these halides in inductively coupled discharges operating in the mbar range with different rare gases as buffer gas is investigated by using emission and absorption spectroscopy as well as by modelling with an extended corona model. Besides the broad band radiation of the indium halide molecule between 340 nm and 400 nm the two indium lines at 410.2 and 451.1 nm contribute significantly to the total radiated power. Remarkable efficiencies are obtained in a broad and stable operational range being however limited by reabsorption effects.

The on-going use of compact fluorescent lamps or standard fluorescent lamps for general lighting makes research for alternatives to toxic mercury as radiator in these plasmas highly desirable. The radiation of diatomic molecules is under discussion as being a good alternative [1]. Possible candidates are metal halides as they emit a broad and intense band spectrum in the near ultraviolet spectral range [2]. One group are the diatomic indium monohalide molecules, InBr and InCl, which are investigated in this work systematically in an inductively coupled low pressure discharge in the pressure range of 1 mbar and rf powers up to 100 W at the standard frequency of 13.56 MHz.

Figure 1 shows the experimental setup. The sealed cylindrical quartz cell (length 18 cm, diameter 2.5 cm) contains a few mg InBr or InCl salt and a buffer gas for which argon is the standard gas, but neon and krypton are also investigated. As the salts have a very low vapour pressure at ambient temperature, the whole cell is heated up to several hundred degrees centigrade using hot air. The evaporated amount of InBr is defined by the coldest spot of the wall. This cold spot can be adjusted by heating or cooling an aluminium cube. A heat pipe transfers the adjusted temperature to the wall where the cold spot temperature T_{CS} is measured. Typical variations of the cold spot temperature are between 140 and 240°C with an error of 5°C. The heating temperature is always kept above 500°C.

For diagnostics, quantitative optical emission spectroscopy covering the wavelength range from 230 nm to 1000 nm is used utilizing an axial and a radial line of sight (LOS). The radial LOS is relevant for lighting purposes, whereas the axial LOS is used for profile measurements and also for white light absorption spectroscopy. The absorption technique is used to measure the InBr (InCl) density as well as the indium density. Electron temperature and density are obtained from indium lines using an extended corona model for indium [3], as the emission lines of the buffer gas vanish with increasing amount of evaporated salt.

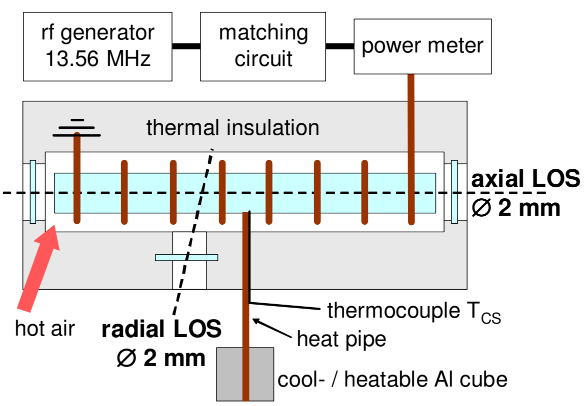

Fig. 1: Sketch of the experimental setup.

Since the cold spot temperature determines the evaporated amount of InBr (InCl) the discharge changes from an argon plasma to an InBr/In (InCl/In) plasma. This can be seen by the naked eye: the colour changes from pink to bright blue. Due to dissociation of the molecule, the amount of atomic indium changes accordingly. At an rf power of 100 W (InBr/Ar discharge) and a variation of the cold spot temperature from 140 °C to 220 °C a huge variation is been observed in the plasma parameters: the volume averaged InBr density increases by two orders of magnitude from 10^{19} m^{-3} to 10^{21} m^{-3}, the indium density by three orders of magnitude from 10^{17} m^{-3} to 10^{20} m^{-3}, the electron density by almost two orders of magnitude from 10^{18} m^{-3} to 10^{19}-10^{20} m^{-3} whereas the electron temperature decreases from 0.8 eV to 0.4 eV [4]. In the analysis of electron temperature and density from the emission lines of indium the optical depth is considered since the indium density is high enough that reabsorption becomes relevant. Reabsorption is also taken into account for the quantification of the indium density from the indium absorption lines.

The emission spectrum of the indium halide discharge is dominated by the molecular radiation of InBr (InCl) originating from the transition of the first two electronically excited states to the ground state ($A\,^3\Pi_{0+}$ – $X\,^1\Sigma_0^+$ and $B\,^3\Pi_1$ – $X\,^1\Sigma_0^+$) in the wavelength region 340-400 nm and by the two indium resonance lines at 410.2 and 451.1 nm (transition $6\,^2S_{1/2}$ to $5\,^2P_{1/2}$ and $5\,^2P_{3/2}$, respectively).

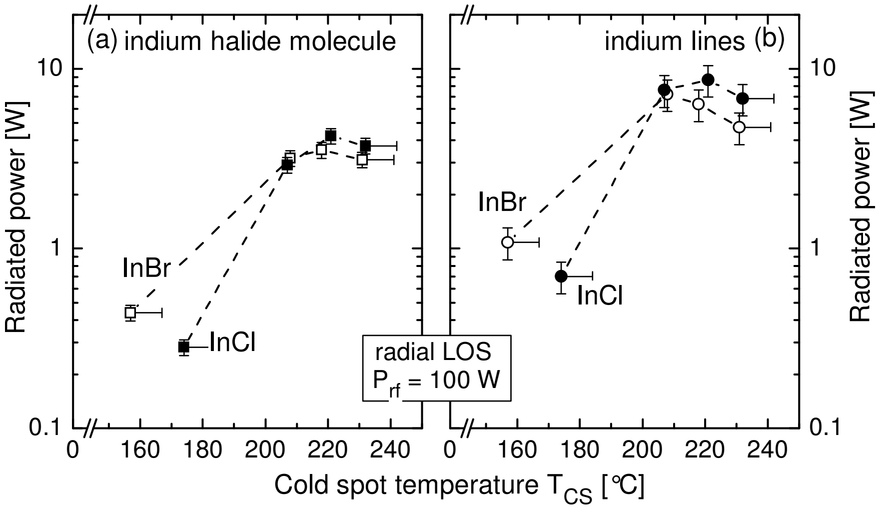

Fig. 2: Radiated power of the indium halide molecule (a) and the indium lines (b) in ICP discharges of InBr in argon and InCl in argon respectively, at a pressure of 1 mbar.

The variation of the radiated power of the indium halide molecule and the indium lines with the cold-spot temperature, and thus the amount of the evaporated salt, is shown in figure 2. At a cold spot temperature of approx. 180°C the transition from the argon to the indium halide discharge occurs. For both discharges a strong increase in the radiated power is observed reaching a broad maximum at similar radiated powers but at slightly different cold spot temperatures. Detailed investigations of the decrease of the radiated power at high temperatures revealed that the radiation is limited by the increasing opacity of the indium and indium halide emission.

An almost identical behaviour and very similar radiated powers have been obtained for neon and krypton as buffer gas, which favours the utilization of argon as stable operation and reliable ignition in a wide power and pressure range is ensured. A remarkable role for the efficiency plays the rf power as the radiated power decreases weaker than linear with rf power. At 40 W rf power efficiencies up to 24 % are observed.

The main process which limits the achievable maximum efficiency of the generated indium halide and indium emission is the reabsorption of emitted photons within the plasma volume. The impact of this effect decreases with decreasing RF-power and in addition, the opacity of the intense indium lines is smaller in the InCl/rare gas discharge, i. e. more indium radiation is emitted than from the InBr/rare gas plasma. Therefore, the utilization of InCl and the operation at the lowest possible RF-power yields the highest efficiencies. In general, the obtained results and efficiencies are very promising for an application of low pressure rare gas discharges with indium halide additives for lighting purposes.

References

[1] S. Kitsinelis, G. Zissis, E. Fokitis, *J.Phys. D: Appl. Phys.* **42** (2009) 045209.
[2] A. Körber, D. Hayashi, 28th ICPIG conference, Prague (2007).
[3] S. Briefi, U. Fantz, 30th ICPIG conference, Belfast (2011).
[4] S. Briefi, U. Fantz, LS-WLED conference, Eindhoven (2010).