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Mercury depletion as a way of changing the emission spectrum of a fluorescent lamp

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We present a promising option for changing the emission spectrum of a fluorescent lamp. In a neon/mercury discharge, neon radiation is produced when the mercury density is sufficiently low. Under certain discharge conditions, radial cathaphoresis causes depletion of mercury atoms in the center of the plasma. This effect is especially well pronounced at high electrical currents and low mercury pressures. We measured the color temperature of a fluorescent lamp containing a neon/mercury discharge at several mercury pressures and currents. The color temperature of this lamp varied from 4000 to 2100 K. We also performed ultraviolet absorption measurements. From these measurements, we obtained the mercury atom density profile in the discharge. A significant decrease of the mercury density in the center of the plasma is indeed observed under certain discharge conditions. © 2000 American Institute of Physics. [S0003-6951(00)00612-4]

In the past, several options for changing the color of fluorescent lamps have been proposed. In fluorescent lamps, the positive column of a low-pressure mercury/rare-gas discharge mainly produces ultraviolet (UV) radiation that is converted into visible radiation by fluorescent powder. The most common way to change the color of a fluorescent lamp is changing the electron energy distribution function (EEDF) in a lamp. This changing of the EEDF is usually done by using sophisticated electrical driving schemes like, for instance, pulsing or ramping.^{1,2} The emission of the lamp depends heavily on the EEDF, so changing it results in a change in the lamp color. Another option for color variation is introducing a second discharge in the lamp, for instance, a capacitively coupled radio frequency discharge.^{3,4} This is basically a way of locally changing the EEDF in the lamp.

We propose a promising way to change the color of a fluorescent lamp. This method is also based on local variation of the EEDF in a discharge lamp. However, we do not use a second discharge to achieve this change. We use the fact that the EEDF in a lamp depends heavily on the mercury density. So by locally changing this mercury density, the emission spectrum of the lamp can be changed. There are two ways of changing the mercury density in a mercury/rare-gas discharge. At first, one can change the mercury pressure by changing the temperature of the coldest part of the discharge tube (the cold spot). Second, one can change the mercury density locally by a process called radial cathaphoresis. This letter discusses the phenomenon of radial cathaphoresis. Furthermore, the measurements of the emission spectrum and the mercury density profile are discussed.

In a normal fluorescent lamp, inelastic collisions with mercury atoms are much more frequent than inelastic collisions with the rare-gas atoms because of the fact that the excited states of mercury have a much lower energy than the excited states of the rare gases. On the other hand, the electron temperature is limited by the inelastic collisions with

mercury, which favors the collisions with mercury. So we can assume that, despite the fact that we have two or three orders of magnitude more rare-gas atoms, the discharge is dominated by mercury. We will only have mercury ionization and no rare-gas ions in the discharge.

The electron-ion pairs in the positive column of a mercury rare-gas discharge are created by ionization in the bulk and lost due to ambipolar diffusion to the walls where they recombine. The resulting flux of mercury ions and electrons to the walls has to be compensated by a diffusional flux of mercury atoms in the opposite direction. The positive column of a low-pressure mercury/rare-gas discharge is a non-equilibrium plasma, which means that the ambipolar diffusion coefficient is much higher than the diffusion coefficient of neutral atoms. The result is a net flux of mercury towards the walls. This phenomenon is called radial cathaphoresis. In the stationary situation, the difference in diffusion coefficients is compensated by a gradient in the neutral density, so we will have mercury atom depletion in the center of the plasma. Radial cathaphoresis in sodium and cesium discharges has been studied extensively in the past.⁵⁻⁸ This phenomenon is also well known in mercury rare-gas discharges.⁹

We can increase the mercury depletion by either lowering the mercury pressure, or increasing the electron/ion density. The first option is based on the fact that less mercury has to be transported to the walls in order to have a significantly depleted mercury density profile. We note that, in general, a decrease in the mercury density will not lead to a decrease in the electron/ion density,¹⁰ so the ambipolar flux will not decrease. The second option is based on the fact that at a higher electron/ion density the ambipolar flux of ions and electrons will be higher. The electron density can be increased in a very simple way, by increasing the electrical current through the lamp.

If the mercury density near the axis of the discharge tube is low enough, then the electrons will not lose much energy in inelastic collisions with mercury. This means that they can gain more energy in the electric field, so the electron tem-

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FIG. 1. Correlated color temperature of the neon-mercury discharge as a function of current, for several cold-spot temperatures: 18 °C (square), 20 °C (circle), 22 °C (up-triangle), 24 °C (down-triangle), 27 °C (diamond), and 30 °C (cross).

perature will increase. When this increase is big enough, then the rare-gas atoms can be excited. This results in the addition of rare-gas spectral lines to the spectrum of the lamp. In the case of neon, red light will be added to the mercury/phosphor spectrum.

We performed lamp emission measurements for several mercury pressures and currents. We used a 26 mm diameter tube, coated with a standard triphosphor coating of 4000 K color temperature containing BAM, YOX, and CBT phosphors, filled with 10 mbar neon and 5 mg mercury. The wall temperature of the lamp is controlled by a transparent water jacket around the tube, which is connected to a thermostat bath. We used an ENI Plasmaloc 1-HF power source at 100 kHz to sustain the discharge. The spectral luminance from a small area of the phosphor coating at the position of the water jacket is measured with an optical multichannel analyzer (OMA). From the measured spectra, we calculated the chromaticity coordinates and the correlated color temperature.

The correlated color temperature T_c of the lamp is shown in Fig. 1 for several wall temperatures and currents. At low currents, the color temperature is 4000 K, this is the color temperature of the phosphor/mercury spectrum. It is clear that the color temperature decreases for higher currents and lower wall temperatures. This decrease is caused by the addition of neon radiation to the spectrum. We can conclude that at certain conditions, we will have radial cathaphoresis leading to significant mercury depletion and moreover, the production of neon radiation.

The depletion of mercury is indirectly observed in the addition of neon radiation to the spectrum of the lamp. To give direct proof of the fact that mercury depletion takes place, we have to measure the mercury density profile in the lamp. In order to measure this density profile, we built a UV absorption setup. As a UV source we used a neon-mercury discharge lamp with a quartz tube. The radiation from this source lamp is guided through a 2.3 kHz optical chopper and

FIG. 2. Measured lateral profiles of the line-integrated mercury density along with the fitted profiles, for three currents: 100 mA (square), 200 mA (circle), and 400 mA (up-triangle).

two diaphragms of 1 mm diameter. This beam is then guided through a second neon-mercury discharge lamp. This probe lamp is also made of quartz, it is filled with 10 mbar neon and 5 mg mercury. The cold-spot temperature is 18 °C. This temperature is controlled by a thermostat bath and two cooling fluid jackets adjacent to the beam. After passing the probe lamp, the beam is guided through another two diaphragms of 1 mm diameter. Then, the 253.7 nm part of the beam is detected by a photomultiplier, mounted on a monochromator. The detected signal is fed into a lock-in amplifier, which discriminates the source radiation (chopped) from the emission of the probe lamp. The lock-in signal is plotted on a (x,t) writer in order to see the time evolution of the transmission through the probe lamp. Both lamps are operated using a standard Philips BRC411/01 35 kHz ballast.

The measurements are performed in the same way as Van Tongeren measured the Cs density in a Cs-Ar discharge.⁷ The transmission of the lamp for mercury densities ranging from 6.4×10^{18} to $4.4 \times 10^{19} \text{ m}^{-3}$ is measured in the lamp-off situation. This transmission curve can be used as a calibration for the density measurements. The density measurements are performed as follows. At first, the lamp is switched on. We waited until it burned stable. Then, we measured the transmission. After this measurement, we turned the lamp off and we immediately measured the transmission in the lamp-off situation. From the change in transmission, we can calculate the line-integrated density, using the calibration curve. We measured the lateral profile of this line-integrated density $B(y)$ at a current of 100, 200, and 400 mA. By using the Abel transformation, we can obtain the radial mercury density profile from this lateral data. We assumed the following analytical expression for the density profiles $n(r)$:

$$n(r) = a + b \cdot r^n,$$

where a , b , and n are fitting parameters. We fitted the lateral profiles that belong to this expression to the measured lateral profiles. We also calculated the radial profiles directly from

FIG. 3. Radial mercury density profile resulting from the lateral profiles for the three currents: 100 mA (square), 200 mA (circle), and 400 mA (up-triangle).

the measured lateral profile. Figure 2 shows the lateral profiles of the line-integrated mercury density, along with the fits. The deviation from the fit gives an idea of the magnitude of the experimental error. Figure 3 shows the density profiles resulting from the lateral profiles. The symbols represent the directly transformed radial profiles and the lines represent the fits. For the directly transformed profiles, we used a fast Fourier transformation filter that eliminates oscillations with a spatial period lower than 2 mm in order to reduce the noise. The color temperatures of the lamp at 100, 200, and 400 mA are 4000, 3800, and 3000 K, respectively, as can be seen in Fig. 1. It is clear that a lot of mercury has to be removed for a significant change in the color temperature. We note that

the observed depletion cannot be attributed to gas heating. Based on temperature measurements by Kenty *et al.*,¹¹ it can be estimated that gas heating results in a decrease in the atom density on the axis of at maximum 10%, 20%, and 40% for the currents 100, 200, and 400 mA, respectively.

Note that the used method explicitly assumes a radially constant spectral absorption profile. This is not the case in our lamp because of a temperature gradient. We estimated the maximum influence of this gradient and also the influence of the fact that the calibration and the measurements are taken at different gas temperatures: the total error in the lateral profile was found to be less than 5%.

We have shown that it is possible to change the emission spectrum of a fluorescent lamp by introducing mercury depletion. The emission measurements show that the color temperature can be changed from 4000 to 2100 K. However, from the measured mercury density profiles can be concluded that a lot of mercury has to be removed before the discharge starts producing neon radiation.

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