Corrigendum

Corrigendum on "The temperature dependence of the work function of oxide electrodes in fluorescent lamps [Eur. Phys. J. Appl. Phys. 92, 11301 (2020)]" and "Impact of damaging and recovery on the temperature dependence of the work function of oxide electrodes in fluorescent lamps [Eur. Phys. J. Appl. Phys. 96, 11301 (2021)]"★.

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and

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In our publications above, we presented measurements of the temperature dependence of the work function of oxide electrodes in operating fluorescent lamps. For the explanation of the measurements, we assumed that the ultraviolet (UV) radiation, present in an operating fluorescent lamp, leads to a depletion of electrons from deeply lying donor levels related to colour centres in the oxide electrode. These electrons are assumed to assemble in the conduction band and thermalize there. Using this assumption a reasonable description of the work function and its temperature dependence has been obtained (see Sect. 3.4. of the second of our publications above).

However, possibly the UV radiation is not responsible for the depletion, but a depletion of the levels by the visible light generated by the phosphor layer of the fluorescent lamp or by visible lines of the mercury spectrum is a more suitable mechanism. This would not change our theoretical description given. It only concerns the mechanism of depletion assumed.

In the following we summarize the arguments which have led us to change our opinion on the depletion mechanism.

The band structure of BaO (the main component of our oxide electrodes) is given in Figure 5 of the first of our papers given above. The width of the energy gap is $E_G = 5.4\,\text{eV} - 9 \times 10^{-4}\,(\text{eV/K}) \cdot T$ (please consider the Erratum), and the electron affinity is $\chi = 0.5 \ldots 1\,\text{eV}$. Donor levels due to colour centres are lying at 1.2 eV, 2 eV, and 2.6 eV below the lower edge of the conduction band.

There are two UV lines [1] present in an operating fluorescent lamp, at $\lambda = 254\,\text{nm}$ and 185 nm, i.e. at $E = h(c/\lambda)$ of 4.9 eV and 6.7 eV, respectively. Here, h is Planck's constant, c is the velocity of light in vacuum, and e is the elementary charge (see [2] for numerical values). According to [3] about 90 % of the UV radiation is due to the 254 nm line.

Considering that the measurements of the work function are carried out at high temperatures around $T = 1000\,\text{K}$, the width of the energy gap is reduced to 4.5 eV (see equation above). Furthermore, χ increases by 0.45 eV (see Sect. 3.4.1 and Footnote 1a of the second of our papers given above). Thus, the UV lines are able to excite electrons from the valence band into the conduction band (the 254 nm line) or even towards outside the oxide electrode (the 185 nm line). Moreover, electrons in donor levels absorbing UV radiation are expected to be excited towards outside the oxide electrode by both UV lines.

However, as we discussed in Section 3.3 of our second paper above, a photo-emission current, i.e. a direct escape of excited electrons from the electrode, has not been observed by us (if present, it seems to be small). Moreover, in Section 3.4 of that paper a model for the description of the work function and its temperature dependence is presented in which it is assumed that all donors present are depleted by excitation of electrons into the conduction band where they thermalize. An excitation of electrons from the valence band is not considered and also not an escape of electrons towards outside of the electrode.

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Since our model leads to a reasonable description of the work function and its temperature dependence, it seems to us that not as originally proposed the UV radiation but the visible light produced by the phosphor layer or the visible lines of the mercury spectrum are more probably responsible for the assumed depletion of the donor levels.

Spectra for phosphors used in modern tricolor fluorescent lamps are shown in [4,5]. The main emission lines are at about $\lambda = 455\,\mathrm{nm}$ ($E = 2.7\,\mathrm{eV}$, blue) $\lambda = 545\,\mathrm{nm}$ ($E = 2.3\,\mathrm{eV}$, green), and $\lambda = 611\,\mathrm{nm}$ ($E = 2.0\,\mathrm{eV}$, red).

At these energies, an excitation of electrons from all donor levels into the conduction band is possible, but no excitation from the valence band into the conduction band. Furthermore, there is probably only the blue light which could lead to a photo-emission by exciting electrons from the $1.2\,\mathrm{eV}$ donor level. This is similar for the visible light emitted by the mercury atom at e.g. (see Fig. 4 of [6]) $\lambda = 404.8\,\mathrm{nm}$ ($E = 3.1\,\mathrm{eV}$), $\lambda = 436\,\mathrm{nm}$ ($E = 2.8\,\mathrm{eV}$), $\lambda = 546\,\mathrm{nm}$ ($E = 2.3\,\mathrm{eV}$), and $\lambda = 579\,\mathrm{nm}$ ($E = 2.1\,\mathrm{eV}$).

The reason that against our original assumption UV radiation is not responsible for the excitation of electrons may be as follows. Our measurements are performed for zero field emission (see Sect. 4.2 of our first paper listed above), i.e. at a pure thermionically emitted current from the oxide electrode (cathode). Therefore, electrons leaving the cathode need a certain path away from the electrode to be accelerated to an energy sufficient to excite a mercury atom (the relaxation of which leads to the emission of UV radiation). If then UV radiation is emitted, it is probably absorbed on its path towards the electrode by not excited mercury atoms. In a fluorescent lamp the mercury particle density is typically $1.68 \times 10^2\,(\mu\mathrm{m})^{-3}$ ([7], Sect. 2.5). A subsequent reemission of the UV radiation leads to a reduction of the possibility that the UV photon reaches the electrode because the emission probability is expected to be equal in every direction in space.

On the other hand, see Figure 4 of [6], the visible light discussed above cannot excite the mercury in the ground state (and, as the UV radiation, not atoms of the noble gas filling of the fluorescent lamp because the energy difference between the lowest excited state and the electronic ground state is $11.55\,\mathrm{eV}$ and $9.915\,\mathrm{eV}$ for Ar and Kr, respectively, see [7, Sect. 2.4]) and, thus, reach the electrode more easily.

Possibly, properties are more involved (see the discussion of the Eisenmann (visual) method to detect zero-field emission given in Section 4.2.2 of our first paper above). However, for the zero-field condition fulfilled the electrode is immersed in a medium emitting visible light (see Fig. 7b of our paper).

In the first of our papers above, plain glass tubes without phosphor layer were used for the experiments, whereas in the second paper usual commercial lamps with a phosphor layer were employed (sometimes the phosphor layer in the region close to the electrode was removed to be able to take photographs). The results of both series of experiments show the same behaviour (see Fig. 2 of our second paper from above). Since the visible light emitted by the mercury atoms is present in both cases, we conclude that this light is responsible for the depletion of the donor levels related to the colour centres. This is also valid for the donor like surface state (at $0.1\,\mathrm{eV}$ below the lower edge of the conduction band) caused by Ba adsorption, discussed in Section 3.7 of our second paper, although due to the absence of the photo-emission current the also in Section 3.7 discussed thermal activation in this case seems to be more probable.

In the case of a not pure thermionically emitted current from the oxide cathode (which is the usual operating regime of a fluorescent lamp), visible light and UV radiation reach the cathode and is even created nearby the cathode (see Fig. 7b of Richard Garner's detailed model calculation for an AC voltage driven (in our experiment a DC voltage is used) fluorescent lamp [6]). However, in this regime a cathode fall potential is present. Thermionic emission of the cathode is enhanced beyond the Richardson (i.e. zero field thermionic emission, adjusted in our experiments) level by the electric field of the cathode sheath due to the Schottky effect and mainly [6] to the patch effect (see Sect. 2.6 of our first paper above). In addition mono-energetic "beam electrons" emitted from the cathode surface by thermionic emission flow into the negative glow plasma with energy corresponding to the cathode sheath potential (the sheath potential is self-consistently calculated by the model). Electrons and ions in the positive column are created by impact ionization of mercury atoms by plasma electrons and in the negative glow additionally by inelastic scattering processes between beam electrons and mercury atoms ([6], Sects. 2.1, 2.3.2, and 2.4). The plasma electron and ion densities are equal. The density of the beam electrons is small so that the quasi-neutrality is essentially maintained ([6], Sect. 2.1). The model in [6], revealing the spatial extend of the influence of the electrode and sheath processes, describes a smooth transition in the parameters from the electrode through the negative glow plasma to the positive column.

The model is not applied to our situation of a pure thermionically emitted current from the oxide electrode in a DC driven fluorescent lamp. Thus, and because such a model calculation is not known to the authors, a detailed description of the environment of our cathode immersed in visible light cannot be presented.

Moreover, in [6] a temperature independent value of the work function has been assumed (see Eqs. (7) to (9) and Tab. I in [6]).

In order to further justify our proposed description for a temperature dependent work function in an operating fluorescent lamp the following steps would have to be performed. The model in [6] has to be considered for the case of a pure thermionically emitted DC current. Moreover, a temperature dependence of the work function caused by a depletion of the donor levels (the number of which depends on the cathode temperature, see our second paper above) in the cathode (by light reaching the cathode) and a thermalization of the electrons excited from the donor levels in the conduction band has to be considered. Relaxation processes have to be included so that the equilibrium population of the conduction band is obtained, yielding the work function. However, this is a self-consistent problem because the spectrum of the light reaching the cathode depends on the emission capability for electrons of the cathode for a given temperature, i.e. on the work function.

Finally, a comparison with measurements of the work function has to be done.

Such an elaborate modification of Garner's model [6] and its numerical realization is far beyond our capabilities.

Thus the observed agreement of our model for the temperature dependence of the work function (however, with visible light instead of UV radiation as excitation mechanism of electrons from donor levels) with experiments has to be regarded as a justification for the assumptions made.

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