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Mechanism of electron-photon conversion in YAG: Ce scintillator for SEM electron detectors

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The Everhart-Thornley imaging detector is commonly used one in SEM. In such a detector, the signal electrons are accelerated towards a conductively coated scintillator where they are converted to the visible photons within the cathodoluminescence (CL). The emitted photons are guided out of a vacuum chamber and detected by a photon detector. The scintillator is still a bottleneck of the signal electron detector, because its CL properties can highly affect the scanned image quality. For example, low CL efficiency of the scintillator can result in poor signal-to-noise ratio of the detector [1]. Also long CL decay time can decrease the image contrast during the fast scanning [2]. These problems highly motivate to clearly understand how the energy of the signal electron is converted in the scintillator. This knowledge is essential for modification of the scintillator properties in order to improve the SEM image quality.

One of the most frequently used scintillators in the SEM is the cerium-activated yttrium aluminium garnet (YAG:Ce) single-crystal. It is popular because of its relatively good CL efficiency and short decay time together with good mechanical properties and low price. Electro-optical properties of the YAG:Ce were studied by many researchers since the YAG:Ce first report in 1967 [3]. The CL behavior was explained by a couple of presented models. However, these models are either inaccurate or very complicated to use. We present a more simple CL model of the YAG:Ce which describes only essential electro-optical processes. In spite of the negligence of some luminescence processes, the model is still accurate and corresponds with the experiment.

The YAG crystal is insulating material with the band gap of 6.4 eV. The signal electron, accelerated to the energies typically between 5 and 15 keV, scatters in the YAG crystal and its inelastic diffusion generates hundreds of electronic excitations (charge carriers, free electrons and holes, coupled electron-hole pairs). The major percentage of the electronic excitations is dissipated as a non-visible ionizing radiation such as X-ray, VUV, UV. However, some of the ionizing energy is returned back since this radiation creates other electronic excitations. The duration of this process is in order of femtoseconds.

The electronic excitations can migrate across the YAG crystal lattice until they reach a Ce^{3+} activator or an oxygen vacancy. The activator captures the free electrons from the conduction band, since its $5d_2$ energy level slightly overlap the bottom of the conduction band (see Fig. 1). The capture of the free hole from the valence band is energetically unlikely, thus the hole in the ground state of the activator must be created by activator ionization. When the electron is captured, it is returned back to the conduction band, or more likely thermalized to the $5d_1$ state by a very fast process taking units of picoseconds. The electron in the $5d_1$ state recombines with the hole situated in the twofold 4f state by emitting the characteristic yellow-greenish light (500 – 680 nm). This is the desired CL radiation of the YAG:Ce scintillator. The $5d_1 \rightarrow 4f$ transition takes 70 ns on average, which gives the relatively short decay time.

The oxygen vacancy in the YAG is a crystal defect (called F-center) behaving as a hydrogen-like atom. [4] The electron at the boundary of the vacancy can be in the ground state 1s, or in one of the four excited states 3s, $3p_z$, $3p_y$, or $3p_x$. The energy of the $3p_x$ state lies very close to the bottom of the conduction band and therefore it behaves as an electron trap for the free electrons.

The captured electrons can act according to two scenarios. (1) The electron relaxes to one of the lower excited states from which it recombines with the hole in the ground state. This transition emits the near UV light with the wavelengths between 250 and 350 nm. The transition is slower than the characteristic emission of the activator; it takes approx. 1 μs on average. The part of this emission is absorbed by the activator which excites the electron from the 4f ground state to the $5d_2$ state, and then it relaxes back to the ground state followed by the characteristic emission. As a consequence, the fast activator decay is slow down, however this delayed emission contributes only approx. 1% to the the intensity of the characteristic emission. (2) The electron can be released from the oxygen vacancy by

the thermal vibration of the YAG crystal. This process takes approx. 20 μs on average at the room temperature, and the time decreases with the increasing crystal temperature. The released electrons can be consequently recaptured which prolongs the electron life-time.

The presented model can explain the influence of the scintillator on the image quality in the SEM. One of the problems is the image blurring during the fast scan. The reason lies in the long CL decay of the scintillator caused by the presence of the oxygen vacancy traps. When the "delayed" electrons from the traps reach the activator, they can significantly slow down the characteristic decay. In other words, only the non-trapped electrons are wanted. Luckily, the ratio between the trapped and non-trapped electrons can be reasonably decreased by increasing the activator concentration or decreasing the vacancy concentration. Although the increase of the activator concentration is technologically demanding, the vacancy concentration can be decreased by the annealing of the YAG:Ce in the oxygen atmosphere. This treatment decreases the CL afterglow and increases the contrast of the SEM images. In order to use the YAG:Ce for very fast scanning, the decay time of 70 ns should be shortened. However, this is not possible, because the $5d_1 \rightarrow 4f$ transition time is given by the YAG crystal field. Only the replacement of the YAG crystal by more convenient one could decrease the decay time reasonably.

1. P. Schauer, Nuclear Instruments and Methods in Physics Research Section B 269 (2011), p. 2572-2577.
2. J. Bok and P. Schauer in "Proceedings of 13th International Seminar on Recent Trends in Charged Particle Optics and Surface Physics Instrumentation" (Brno, 2012), pp. 9-10.
3. G. Blasse and A. Bril, Applied Physics Letters 11 (1967), p. 53-54.
4. N. I. Konstantinov, L. G. Karaseva and V. V. Gromov, Doklady Akademii Nauk SSSR 253 (1980), p. 909-912.

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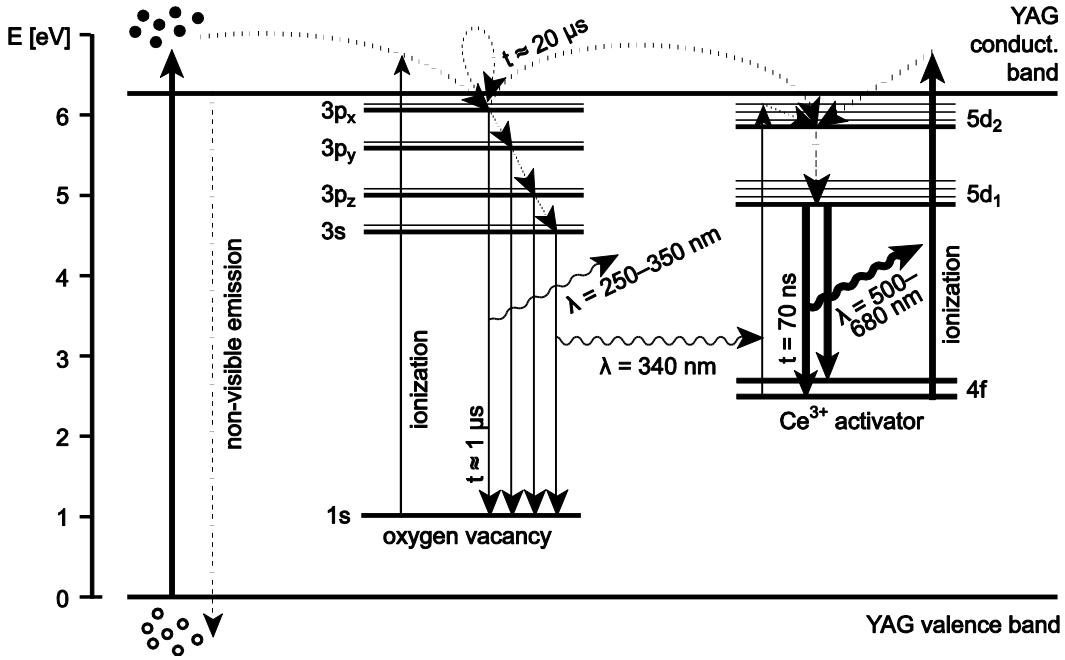

Figure 1. The diagram of the simplified YAG:Ce cathodoluminescence model. The radiative and non-radiative transitions are drawn by the solid and the dotted lines, respectively. The thickness of the lines represents the probability of the transition; the tick line is likely transition and vice versa.