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Dependence of emitting light for LEDs fabricated by YAG:Ce crystal wafer on wafer thickness

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ABSTRACT

Influence of YAG:Ce crystal wafer thickness on their optical properties were investigated. The crystal wafers were cut from the YAG:Ce single crystal grown by the Czochralski technique. XRD patterns suggest the cubic phase of the grown single crystal. The transmittance spectra of YAG:Ce crystal wafers with different thicknesses show that they have strong absorption of Ce^{3+} ions in a wide wavelength range of 420–500 nm. Under the excitation at 465 nm, YAG:Ce crystal wafer shows emission band peaking at about 535 nm, which originates from the $5d^1 \rightarrow 4f^1$ transition of Ce^{3+}. The thickness of crystal wafer has obvious influence on Ce^{3+} emission intensity, which increases with the increasing wafer thickness and reach a maximum value at a thickness of 1.5 mm. Moreover, YAG:Ce crystal wafer shows excellently thermal stability. The emission intensity of Ce^{3+} emission at 510 K is about 68.3% of its initial intensity at 300 K. The fabricated WLED by the crystal chip with the thickness of 1.5 mm reaches a maximum luminous efficacy of 112.33 lm/W and a CCT value of 4458.

1. Introduction

In the last few years, white light emitting diodes (WLEDs) were regarded as the next generation of solid state lighting on account of their remarkable properties, such as long lifetime, low energy consumption and environmental friendliness [1,2]. Currently, the most commonly used method for the fabrication of WLEDs is to combine a blue InGaN chip with $Y_3Al_5O_{12}:Ce^{3+}$ (YAG:Ce) particles [3]. In such a fabrication, YAG:Ce particles are coated onto the surface of blue chips by epoxy resin or silicone. Due to the poor heat dissipation of epoxy resin and silicone, such LEDs generally have disadvantages of luminescence attenuation, light color offset and lifetime reduction [4]. Moreover, such a configuration induces a low efficiency because that the diffuse phosphor directs 60% of total white light back toward the chip [5]. To overcome these shortcomings, one of methods is to use a remote phosphor [5–7], which means that the phosphor is separated from the LED chip by a large distance and no use of epoxy resin and silicone. In the WLEDs fabricated with a remote phosphor, single crystal wafer, transparent ceramic plates and low melt-point glass plates have potential applications due to their solid structure with a certain mechanical strength.

Ions doped YAG single crystals have been investigated in recent years due to their characteristics of high thermal conductivity, stably physical and chemical performance, as well as the mature growth process [8–15]. Ce^{3+} single doped YAG is an excellently yellow phosphor. It can meet the requirements for the production of WLEDs needing high light intensities, regardless of the color rendering index. In this work, we focus on the investigation of the optical properties of YAG:Ce^{3+} single crystal wafers and the stability of WLEDs fabricated by these crystal wafers. For these purposes, YAG:Ce^{3+} single crystals with high quality were grown through Czochralski technique. The influence of wafer thickness on the optical properties was investigated by means of transmittance, photoluminescence and thermal stability measurements. Moreover, the luminescence of the WLEDs fabricated by the crystal wafers was also investigated.

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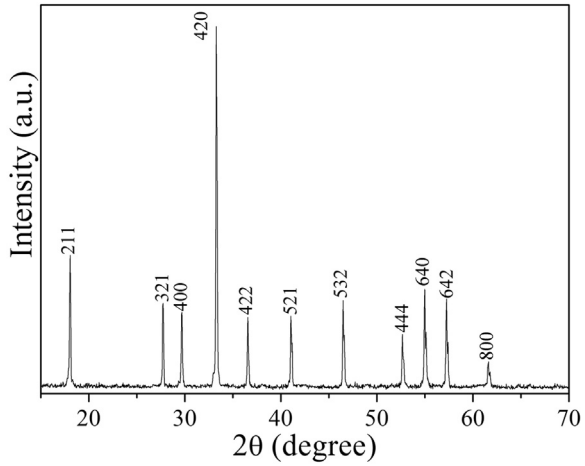

Fig. 1. XRD patterns of the grown YAG:Ce single crystals.

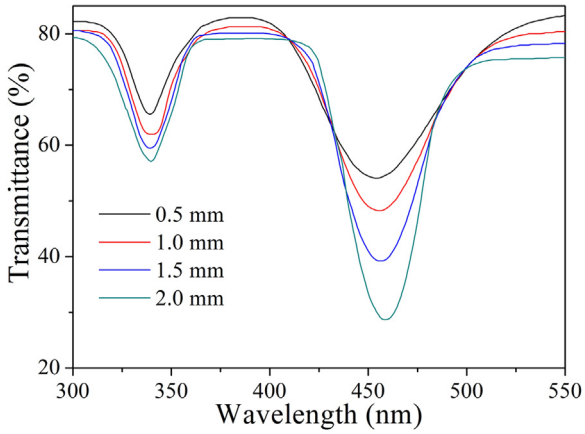

Fig. 2. Optical transmittance of YAG:Ce crystal wafer with different thicknesses.

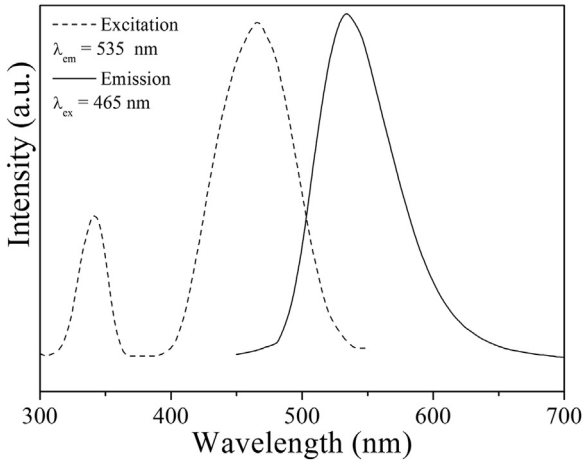

Fig. 3. Excitation and emission spectra of YAG:Ce crystal wafer with a thickness of 1.5 mm.

2. Materials and method

YAG:Ce^{3+} single crystals were grown by the Czochralski technique. Y_2O_3 (99.99%), Al_2O_3 (99.99%) and CeO_2 (99.99%) were used as raw materials. Ce^{3+} concentration was 3 mol% with respect to the Y^{3+} site. Firstly, stoichiometric materials were weighted and mixed thoroughly. Then, the mixed materials were compressed into pieces and calcined at 1200 °C for 24 h. After that, the pieces were loaded into Ir crucible. The temperature was controlled by a precision temperature controller with a precision of ± 0.5 °C. The melt temperature kept at 1950 ± 5 °C should be favorable for starting the growth. The crystals were grown along the < 111 > axis at fixed pulling and rotations rates, 1 mm/h and 10 rpm, respectively. The whole growth process is in the nitrogen atmosphere. The obtained as-grown single crystal was cut to the direction parallel to the {110} growing orientation. Then the sliced YAG:Ce crystal wafers with different thicknesses were dip in acetone solution for 20 h. Finally, the wafers were polished for 6 h.

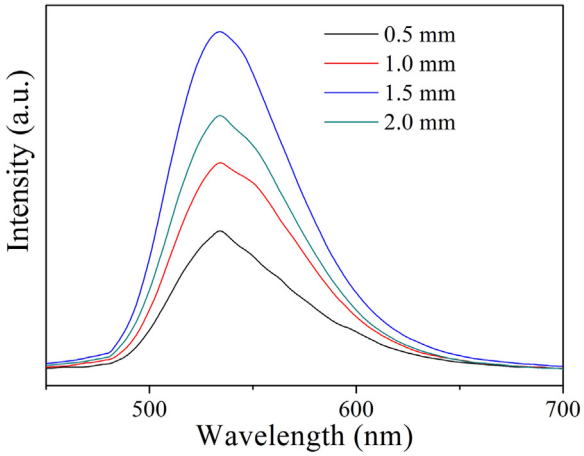

Fig. 4. Dependence of Ce^{3+} emission intensity on crystal wafer thickness.

X-ray diffraction (XRD) was performed on a Rigaku D/Max-3C X-ray diffractometer with a high-intensity Cu Kα radiation. The transmittance was recorded with a Jasco V570 spectrometer. The excitation and emission spectra were measured by an Edinburgh Instrument FLS920 spectrophotometer equipped with a 150 W xenon lamp as the excitation source. The quantum efficiency measurement was performed by using a barium-sulfate-coated integrating sphere that attached to the spectrophotometer. Temperature-dependence luminescence spectra in the range of 300–510 K were measured using a FluoroLog-3 spectrofluorometer (PL, HORIBA JOBIN YVON Fluorolog-3) combined with the heating apparatus. The photometric and chromatic parameters of the WLED devices fabricated by YAG:Ce wafers and 4 blue chips were measured in an integrating sphere of 50 cm diameter connected to a CCD detector with an optical fiber (HAAS-2000, Everfine Photo-E-Info Co. Ltd).

3. Results and discussion

Fig. 1 gives the powder XRD patterns of the grown YAG:Ce single crystals. All of diffraction peaks are well accordance with the JCPDs card no. 33–0040, indicating the single phase of the grown single crystals. YAG belongs to the space group of $Ia3d(O_h^{10})$ with whole cubic symmetry, which has the primitive structural elements of oxygen tetrahedral, octahedral and distorted cubes [16]. There are two Al^{3+} sites locating in oxygen tetrahedra (CN = 4) and octahedra (CN = 6), as well as one Y^{3+} site in distorted oxygen cubes [17,18]. And Y^{3+} ion is coordinated with eight oxygen ions. Due to the same valence and similar ion radii for Y^{3+} (1.019 Å, CN = 8) and Ce^{3+} (1.143 Å, CN = 8), Ce^{3+} ions substitute Y^{3+} sites and form solid state compound. The lattice parameters can be calculated by the formula of $sin^2\theta = \lambda^2/4a^2(h^2 + k^2 + l^2)$, where λ is the wavelength of X-ray, (hkl) is Miller index, θ is the diffraction angel and a is the lattice parameter. The calculated lattice parameter is 12.0178 Å, which is bigger than that of pure $Y_3Al_5O_{12}$ (12.009 Å). This behavior is induced by the substitution of lager Ce^{3+} to Y^{3+}.

The optical transmittance of YAG:Ce crystal wafer with different thicknesses is shown in Fig. 2. The absorptions at 340 nm and 465 nm