Gallium-doped ZnO (ZnO:Ga) films for an α-particle scintillator were grown on a sapphire (0001) substrate by radio-frequency magnetron sputtering. Spectral analysis shows that the photoluminescence and scintillation properties of ZnO:Ga films under α-particle radiation can be remarkably improved by a post rapid thermal annealing process and also by increasing the film thickness. The surface morphology, crystallinity, and scintillation properties of ZnO:Ga thin films were further improved by in situ growth interruption during the two-step growth process.

Table I presents the growth conditions of the samples, which are labeled A–D. Sample A was grown as described above, with no annealing. The ZnO:Ga films (samples B–D) were annealed by an RTA process at 900°C for 1 min under a N2 ambient because it was reported that the electrical and optical properties of n-type ZnO film was improved by an RTA process. Sample D was grown by growth interruption during the two-step growth process. As shown in Table I, the two-step growth process for sample D included an in situ annealing process at 800°C for 30 min. The structural and optical properties of the ZnO:Ga films were examined by X-ray diffraction (XRD) and photoluminescence (PL) spectroscopy using a He–Cd laser (λ = 325 nm) as an excitation source. The surface morphology was observed with a field emission scanning electron microscope (SEM). Their scintillation spectra were obtained by using He+ ions (α-particles) at 3 MeV at the Korean Institute of Geoscience and Mineral Resources. The upper surface of each film was irradiated by α-particles while emitted photons were detected through the sapphire substrate. To compare the scintillation property of ZnO:Ga films, a ZnO:Ga single-crystal wafer was also measured as a reference. The penetration depth of 3 MeV α-particles in ZnO was calculated using the “Stopping and Range of Ions in Matter” (SRIM) simulation program.

Figure 1 shows the PL intensity ratio (I_{RTA}/I_{as-grown}) of near-edge peaks of the samples as a function of the RTA temperature. The electron concentrations of the films are also shown. This plot shows that the PL intensity ratio is considerably enhanced by increasing the annealing temperature from 800–900°C. RTA also increased the electron concentration from 5.5 × 10^{16} (as-grown) to 1.3 × 10^{20}. Although sample A has good crystallinity, with a full width at half maximum (fwhm) of 340 arcsec at (0002) by α-scan, its PL was very poor, as shown in Fig. 1. This implies that the as-grown sample contains nonradiative emission centers, probably defect-related. It was reported that the free energy of Ga_{2}O_{3} for-
Thermal activation also improved the scintillation properties of ZnO:Ga films. Figure 2 compares \( \alpha \)-scan XRD rocking curves in the \((0002)\) plane for samples C and D. The fwhm of sample D is narrower, indicating that its crystal quality is higher. The large fwhm of the \( \alpha \)-scan of sample C represents the prevalence of screw and mixed-type dislocations, which also act as nonradiative recombination centers.\(^{24,25}\)

The surface morphology of the film was also improved by an in situ growth interruption process. The surface morphologies of sample C and D are shown in Fig. 4a and b, respectively. Sample C has some protrusions, but sample D shows a very clean and flat surface with a root-mean-square roughness of only 0.4 nm. These results indicate that the surface morphology, crystalline quality, and scintillation properties of ZnO:Ga films can be greatly improved by an in situ growth interruption process.

The difference in peak position of the scintillation spectra of ZnO:Ga thin films and that of a ZnO:Ga single-crystal wafer (see Fig. 2) can be attributed to the intrinsic absorption of the single-crystal wafer.\(^{11,15}\) Figure 5 illustrates this point in more detail, showing the absorption spectrum of a ZnO:Ga single-crystal wafer and its PL spectra measured from the top and bottom. As shown in Fig. 5a, the absorption spectrum is abruptly decreased from 388 nm and reaches a minimum value of absorption at 398 nm. The PL spectrum measured from the bottom side of a ZnO:Ga single-crystal wafer starts to increase from 388 nm and reaches a maximum value at 398 nm as shown in Fig. 5b. Therefore, the different peak positions of the scintillation spectra of a ZnO:Ga film grown on the sapphire surface from 1.5–3 \( \mu m \) (sample C). According to the SRIM simulation program, the penetration depth of 3 MeV \( \alpha \)-particles in ZnO:Ga film should be 9 \( \mu m \). This result shows that the scintillation light output can be enhanced by increasing the thickness of the film because more volume is available for the scintillation process. The peak position of sample C was slightly shifted to the lower energy side due to intrinsic absorption characteristics at the higher energy side. Because sample C was thicker than sample B, more volume was available for intrinsic absorption and sample C shows a different peak position compared with sample B. More detailed studies will be carried out later.\(^{H20850}H20851\)

The scintillation efficiency was further enhanced by in situ growth interruption during the two-step growth process (sample D). Figure 3 compares \( \alpha \)-scan XRD rocking curves in the \((0002)\) plane for samples C and D. The fwhm of sample D is narrower, indicating that its crystal quality is higher. The large fwhm of the \( \alpha \)-scan of sample C represents the prevalence of screw and mixed-type dislocations, which also act as nonradiative recombination centers.\(^{24,25}\)

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substrate, which is transparent to the scintillation light and a single-crystal wafer as shown in Fig. 2, are attributed to the intrinsic absorption characteristics of a ZnO:Ga single-crystal wafer at higher energy side.

In summary, we investigated the scintillation properties of ZnO:Ga thin films grown by rf-magnetron sputtering. The PL and scintillation properties of the ZnO:Ga films under α-particle radiation were remarkably improved by the RTA process. The light output was also improved by doubling the thickness of the film from 1.5 to 3 μm. The α-particle scintillation property was further improved by in situ growth interruption during the two-step growth process due to the improvement of the structural property of ZnO:Ga films. The ZnO:Ga film scintillators with a thickness of 3 μm, which were grown by a two-step sputtering process, showed the highest scintillation light comparable to that of ZnO:Ga single crystals.

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