Influence of substrate surface roughness on light scattering of TiO_2 optical thin films

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Optical thin films are used in many optical elements; however, light scattering can be problematic. We investigate the effect of substrate surface roughness on the light scattering of optical thin films. The substrates are classified according to their surface roughness, from fine to very rough, and coated with a single TiO_2 layer or a SiO_2/TiO_2 multilayer. The light scattering intensity increases as the substrate roughness increases. Scanning electron microscopy reveals that the number of nodules formed in the optical thin films increases with the substrate roughness, which affects the light scattering properties.

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Optical thin films are used in many optical elements, and as these optical elements become more advanced, higher quality optical thin films are required. The reflection, transmission, light scattering, and absorption affect the optical properties of thin films; however, light scattering is particularly important. The roughness of the substrate before the deposition of the thin film affects the light scattering. Differences in the roughness of the substrate are thought to cause variations in the level of nucleation, which results in differences in film growth, and affects the light scattering of thin films. However, few systematic studies have investigated the relationship between the roughness of the substrate and light scattering. We report the effect of substrate surface roughness on the light scattering of optical thin films.

Soda lime (float) glass, BK7 glass (Schott), and colored glass (Y50, Hoya Optics) were used as substrates for the thin films. Pieces of the BK7 glass were polished to different degrees and classified according to their surface roughness (R_a), from fine to very rough. The soda lime float glass was not polished. Electron-beam deposition (EBD) or ion beam assisted deposition (IAD) was then used to coat the substrates with either a TiO_2 single layer or a SiO_2/TiO_2 multilayer film. A change in the substrate temperature was required for EBD. The optical properties and the structure of the thin films were measured. The haze value is the conventional method for evaluating the light scattering of optical thin films. The method is imperfect, however, particularly for measuring non-visible wavelengths[1]. Therefore, we have proposed an alternative measurement value that can be used to evaluate light scattering from spectral data[2]. This method uses a spectrometer with an integrating sphere to measure all the light transmitted through the thin film and the transmitted light that was scattered. The light scattering spectrum can then be calculated by

$$((\text{scattered light})/(\text{all transmitted light}))\times 100\ (\%). \quad (1)$$

The light scattering after deposition was subtracted from the light scattering before deposition to give the light scattering of the film.

Figures 1–4 show the transmittance after deposition.

The light scattering increased with substrate roughness (Figs. 5–8). It has previously been proposed that differences in the substrate roughness alter the structure of the thin film, which then affects the light scattering. Therefore, X-ray diffraction (XRD) was used to determine the crystal structure of the films (Figs. 9–12).

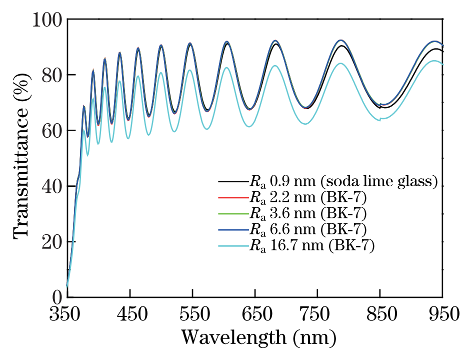

Fig. 1. (Color online) Transmittance spectra of the TiO_2 films fabricated by EBD.

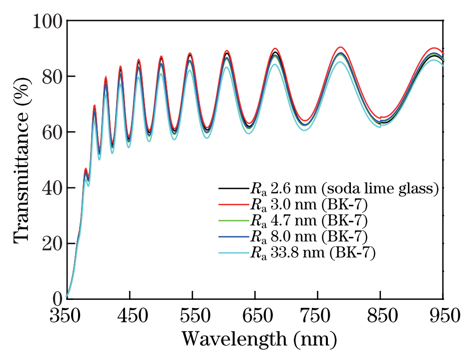

Fig. 2. (Color online) Transmittance spectra of the TiO_2 films fabricated by IAD.

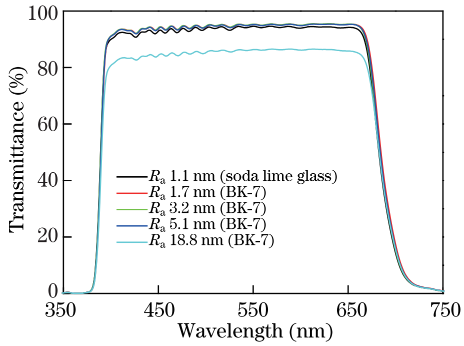

Fig. 3. (Color online) Transmittance spectra of the SiO_2/TiO_2 films fabricated by EBD.

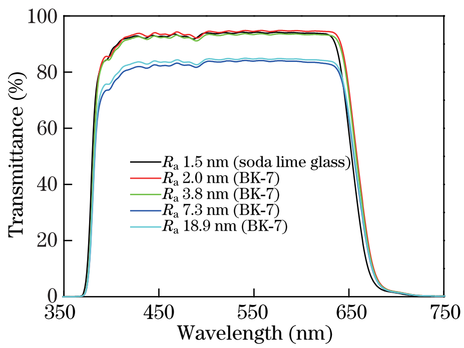

Fig. 4. (Color online) Transmittance spectra of the SiO_2/TiO_2 films fabricated by IAD.

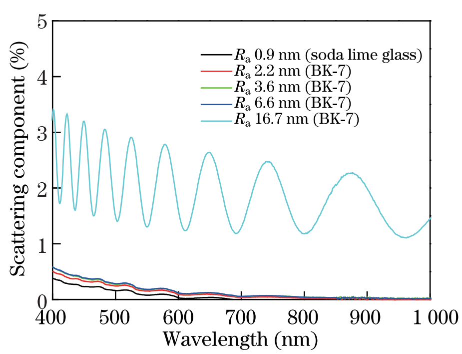

Fig. 5. (Color online) Light scattering spectra for the TiO_2 films fabricated by EBD at 300 °C.

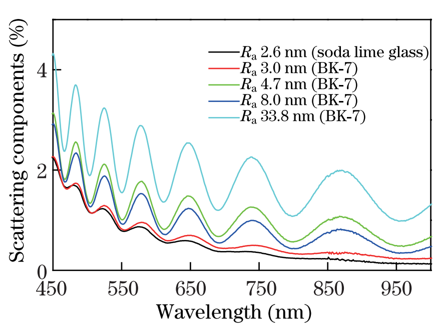

Fig. 6. (Color online) Light scattering spectra for the TiO_2 films fabricated by IAD at 150 °C.

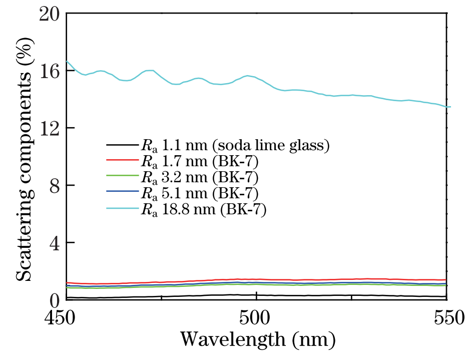

Fig. 7. (Color online) Light scattering spectra for SiO_2/TiO_2 films fabricated by EBD.

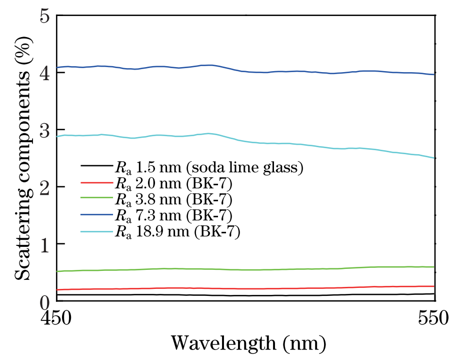

Fig. 8. (Color online) Light scattering spectra for the SiO_2/TiO_2 films fabricated by IAD.

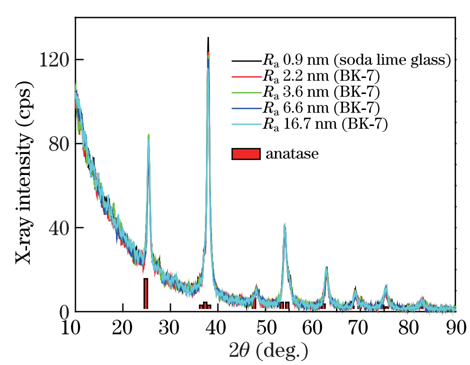

Fig. 9. (Color online) XRD spectra of the TiO_2 films fabricated by EBD at 300 °C.

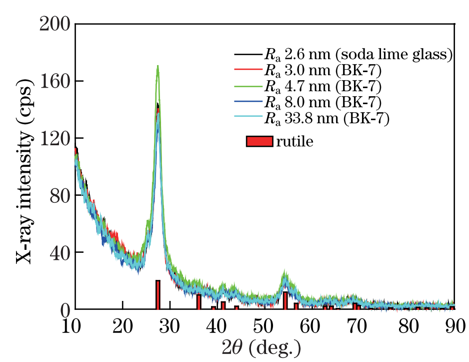

Fig. 10. (Color online) XRD spectra of the TiO_2 films fabricated by IAD at 150 °C.

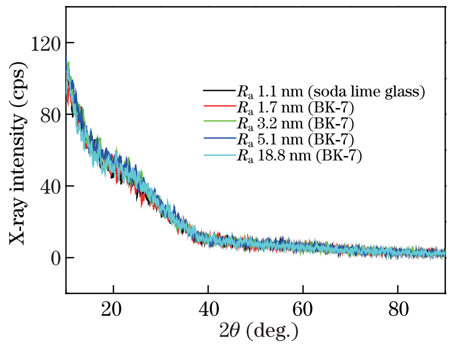

Fig. 11. (Color online) XRD spectra of the SiO_2/TiO_2 films fabricated by EBD.

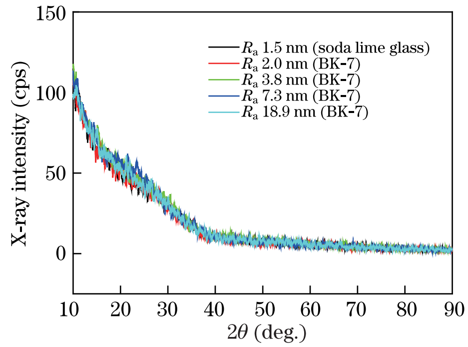

Fig. 12. (Color online) XRD spectra of the SiO_2/TiO_2 films fabricated by IAD.

Table 1. Effect of the Surface Roughness on the TiO_2 Film Fabricated by EBD at 300 °C.

Substrate Roughness R_a (nm)	Crystallization (%)	Crystal Lattice Size (nm)
0.9	89	295
2.2	90	304
3.6	89	295
6.6	89	304
16.7	89	310

XRD showed that the surface roughness did not affect the crystallinity of the films (Table 1); therefore, the crystal structure was not related to the substrate roughness. The increase in scattering can therefore be attributed to a macrostructural difference that cannot be measured by XRD. Scanning electron microscopy (SEM) was used to examine the surface structure.

Figures 13–16 show the SEM images of the thin film surfaces. The SEM images revealed that the thin films deposited on the rough substrates had nodules on their surfaces. The number of nodules increased with the substrate roughness, which in turn increased the light scattering of the optical thin films. We suggest that more nucleation occurs on rough substrates and nodules are formed around the nuclei. Figure 17 shows the growth of the nodules. The nodules on the rough substrate film fabricated by IAD were smaller than those formed by EBD; the additional energy of the ions may suppress the nodule growth.

Figures 18 and 19 show the relationship between the roughness of the substrate before and after deposition for different deposition conditions. The deposition conditions were related to the nodule growth as well as the substrate roughness. For films deposited by EBD, the size of the nodules increased with the temperature. However, the temperature did not affect how the nodules grew, even for large nodules. The nodule growth depended on the deposition method, and thus the energy of the deposition particles. Therefore, the increase in light scattering was probably caused by the growth of these nodules.

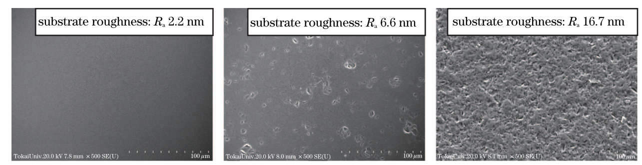

Fig. 13. SEM images of the surface of TiO_2 single-layer films fabricated by EBD at 300 °C.

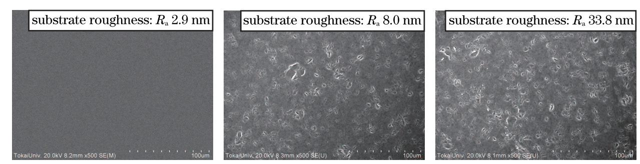

Fig. 14. SEM images of the surface of TiO_2 single-layer films fabricated by IAD at 150 °C.

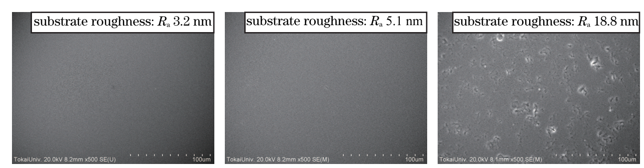

Fig. 15. SEM images of the surface of the SiO_2/TiO_2 multilayer films fabricated by EBD.

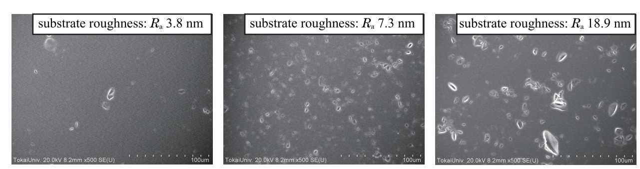

Fig. 16. SEM images of the surface of the SiO_2/TiO_2 multilayer films fabricated by IAD.

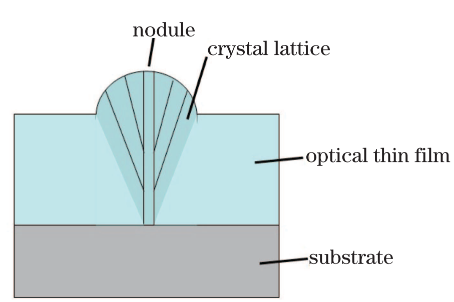

Fig. 17. Schematic diagram.

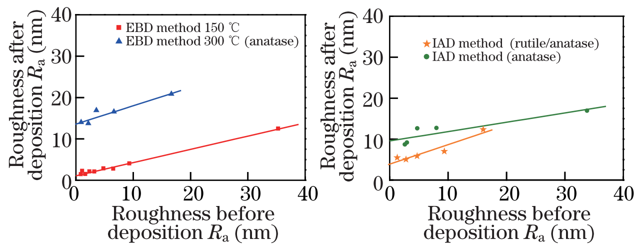

Fig. 18. Substrate roughness versus roughness after single-layer film deposition by EBD and IAD under different deposition conditions.

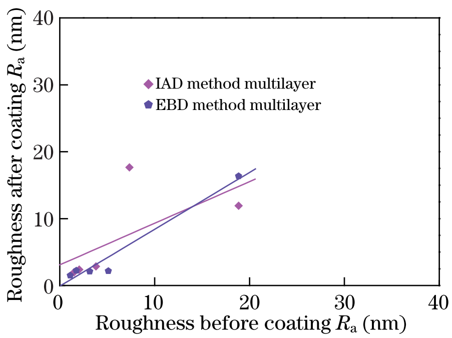

Fig. 19. Substrate roughness versus roughness after multi-layer film deposition by EBD and IAD under different deposition conditions.

In conclusion, light scattering increases as the substrate roughness increased. The surface roughness does not affect the crystallinity of the films. More nodules are observed as the substrate roughness increased. The number of nodules affects the light scattering of the films. Although the size of the nodules depends on the substrate temperature for EBD, the nodule growth depends on the deposition method, and thus the energy of the deposition particles.

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