# Annealing induced refinement on optical transmission and electrical resistivity of indium tin oxide

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The effect of annealing condition on sputtered indium tin oxide (ITO) films on quartz with the thickness of 200 nm is characterized to show enhanced optical transparency and optimized electrical contact resistivity. The as-deposited grown ITO film exhibits only 65% and 80% transmittance at 532 and 632.8 nm, respectively. After annealing at 475 °C for 15 min, the ITO film is refined to show improved transmittance at shorter wavelength region. The transmittances of 88.1% at 532 nm and 90.4% at 632.8 nm can be obtained. The 325-nm transmittance of the post-annealed ITO film is greatly increased from 12.7% to 41.9%. Optimized electrical property can be obtained when annealing below 450 °C, leading to a minimum sheet resistance of 26 Ω/square. Such an ITO film with enhanced ultraviolet (UV) transmittance has become an alternative candidate for applications in current UV photonic devices. The morphology and conductance of the as-deposited and annealed ITO films are determined by using an atomic force microscopy (AFM), showing a great change on the uniformity distribution with finite improvement on the surface conductance of the ITO film after annealing.

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Indium tin oxide (ITO) layer is an intriguing transparent anode in semiconductor organic light emitting devices[1−3] because of its high visible light transmittance and relatively good electrical conductivity. Several methods for preparing ITO films were investigated to obtain optimized performance of electrical contact, such as radio frequency (RF) magnetron sputtering[4], sol-gel processing[5], ion beam sputtering[6], and pulsed laser deposition[7]. However, both the optical and the electrical properties of the as-deposited ITO films are not good enough for most applications. Post annealing process is thus required to enhance the structural aspect and carrier transportation in ITO, leading to a great impact on both the optical transmission coefficient and the electrical contact resistivity of ITO films. In this letter, the effects of annealing conditions for indium tin oxide (ITO) on the optical transmittance and sheet resistance are demonstrated to show great enhancement from ultraviolet (UV) to near-infrared wavelength region.

The ITO films were sputtered on quartz substrate with argon and oxygen fluence ratio of 12:1, and the thicknesses of ITO films were about 200 nm. Furnace annealing process with flowing nitrogen gas in atmosphere was introduced. The post annealing time ranged between 5 and 20 min at the annealing temperature of 400 − 500 °C. The optical transmittance was measured by Ophir power meter with three different laser sources, He-Cd laser (325 nm), frequency-doubled Nd:YAG laser (532 nm), and He-Ne laser (632.8 nm). The sheet resistances of ITO films were detected with a four-point probe system.

The annealing-time dependent optical transmission coefficient of ITO films is displayed in Fig. 1, which also shows the wavelength dependence. At the annealing temperature of 450 °C, the optical transmittance of as-deposited ITO film is as small as 12.7% at 325 nm, indicating the almost opaque characteristic of the ITO at UV region. However, the transmittance greatly increases to > 66% when the wavelength red-shifts to > 532 nm. After annealing for 10 min or longer, the optical transmittance further improves to 80% and 85% at 532 and 632.8 nm, respectively. With the extending post annealing time, the optical transparency is apparently improved and reaches its highest transmittance observed as 41.9%, 88.1%, and 90.4% at 325, 532, and 632.8 nm, respectively. If we consider the influence of annealing temperature on the UV transmittance of the ITO film, Fig. 2 clearly shows an optimized condition between 440 and 480 °C, and the transmittance degradation becomes more serious at long-term annealing conditions. The annealing temperature is at 475 °C for the highest optical

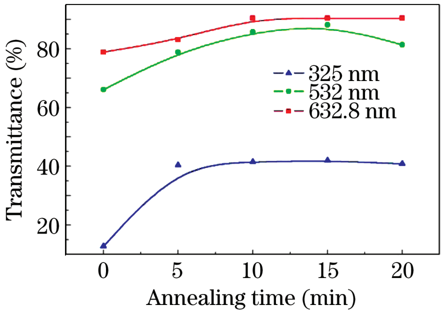

Fig. 1. Transmittance of ITO films with different annealing time under three laser sources.

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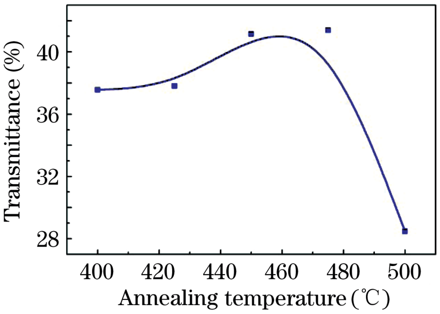

Fig. 2. Transmittance of ITO films with different annealing temperatures under the 325-nm laser source.

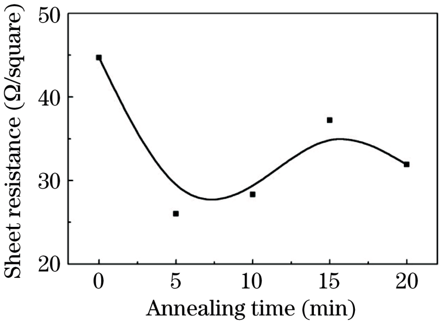

Fig. 3. Sheet resistance of ITO films with different annealing time at 450 °C.

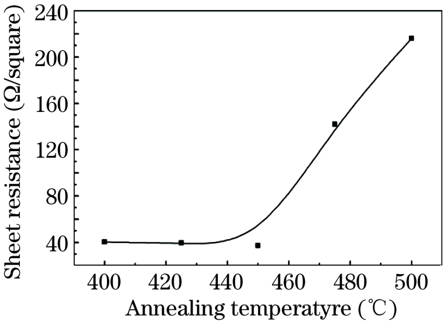

Fig. 4. Sheet resistance of ITO films with different annealing temperatures after annealed for 15 min.

transmission. The transmittance oppositely decreases to 28.5% at the annealing temperature higher than 500 °C.

Figures 3 and 4 demonstrate the annealing-time dependent electrical conductivity of ITO films and the sheet resistance of ITO films with different temperatures. At the annealing temperature of 450 °C, the sheet resistance of the as-deposited sample is observed as high as 45 Ω/square. After the annealing process, the electrical conductivity is improved. The sheet resistance reaches its minimum of 26 Ω/square, with the annealing condition of 450 °C for 5 min. When the annealing time is longer than 5 min, the electrical resistivity increases. Figure 3 displays the sheet resistance of ITO films with different annealing temperature ranging from 400 to 500 °C. The sheet resistance of ITO films reduces slightly when the annealing temperature goes from 400 to 450 °C. The minimum sheet resistance is observed about 37.2 Ω/square after 450 °C annealing. Figure 4 also indicates that the electrical conductivity declination becomes aggravated at the annealing temperature higher than 450 °C, leading to a sharp increase of sheet resistance of ITO films to several hundred ohms per square.

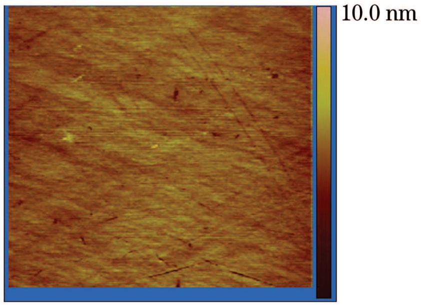

Fig. 5. AFM image of as-deposited ITO film.

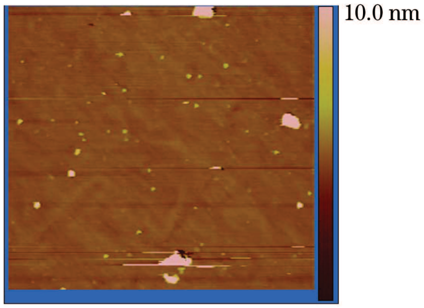

Fig. 6. AFM image of ITO film annealed under 450 °C for 15 min.

The surface morphology of the ITO films is shown in Figs. 5 and 6. Figure 5 demonstrates the atomic force microscopy (AFM) image of the as-deposited ITO film, and the AFM image of the annealed ITO film under 450 °C of 15 min is shown in Fig. 6. The as-deposited ITO film has a rougher surface. On the contrary, the surface of the annealed ITO film becomes much smoother. In Fig. 6, it is clearly shown that some particles start to agglomerate after annealing and we conjecture the clusters are Sn particles[5]. This phenomenon needs further researches.

The effect of annealing conditions on sputtered ITO films on quartz substrates with thicknesses of 200 nm is demonstrated to show enhanced optical transparency and electrical contact resistivity. High optical transparency was observed as 88.1% and 90.4% at 532 and 632.8 nm, respectively. The optical transmission coefficient is merely 41.9% at 325 nm. Optimized optical transparency can be obtained after annealing at 475 °C for 15 min. And the optimized electrical property was the obtained when annealing temperature was below 450 °C, contributing to a minimum sheet resistance of 26 Ω/square. Once the annealing temperature was higher than 450 °C, the electrical conductivity degradation becomes serious, leading to a great increase of sheet resistance of ITO films to several hundred ohms per square. The AFM images show that the annealed ITO film has a smoother surface and some clusters on the surface after annealing.

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