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Laser scribing of indium tin oxide (ITO) thin films deposited on various substrates for touch panels

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ABSTRACT

In this study, a Nd:YAG laser with wavelength of 1064 nm is used to scribe the indium tin oxide (ITO) thin films coated on three types of substrate materials, i.e. soda-lime glass, polycarbonate (PC), and cyclic-olefin-copolymer (COC) materials with thickness of 20 nm, 30 nm, and 20 nm, respectively. The effect of exposure time adjusted from 10 μs to 100 μs on the ablated mark width, depth, and electrical properties of the scribed film was investigated. The maximum laser power of 2.2 W was used to scribe these thin films. In addition, the surface morphology, surface reaction, surface roughness, optical properties, and electrical conductivity properties were measured by a scanning electron microscope, a three-dimensional confocal laser scanning microscope, an atomic force microscope, and a four-point probe. The measured results of surface morphology show that the residual ITO layer was produced on the scribed path with the laser exposure time at 10 μs and 20 μs. The better edge qualities of the scribed lines can be obtained when the exposure time extends from 30 μs to 60 μs. When the laser exposure time is longer than 60 μs, the partially burned areas of the scribed thin films on PC and COC substrates are observed. Moreover, the isolated line width and resistivity values increase when the laser exposure time increases.

1. Introduction

In recent years, transparency conductive materials were extensively used in 3C market products (i.e. computer, communication, and consumer electronics) to meet the rapid development of the electro-optical and semiconductor industry. Common transparent conductive oxide thin film materials, such as TiO_2, SnO_2, In_2O_3, and ZnO are used. The thin films of ZnO composition doped with aluminum, gallium, and tin elements are named aluminum zinc oxide (Al:ZnO), the gallium zinc oxide (Ga:ZnO), and the zinc tin oxide (ZTO) [1] films, respectively. Particularly, among them, indium tin oxide (ITO) material is popularly used in the flat panel display industry. Due to the high optical transparency and better electrical conductivity, ITO films have attracted great interests for various electrode or conductor applications in solar cells [2,3], flat panel displays [4], liquid crystal displays (LCDs) [5], and in organic light emitting diodes [6].

In order to fulfill light, thin, short, small, and flexible requirements in the electronic gadgets, plastic substrates are developed and convinced to be better candidates to replace the glass substrate in portable electronic products. The most common used substrate materials include polycarbonate (PC), polyestersulfone (PES), polyethylene terephtalate (PET), polyimide (PI), polyarylate (PAR), and polyolefin. In the electrode manufacturing process, the transparent conductive material films were coated on these substrates first using the various deposition methods, and then etching the deposited film to become the electrode of the pre-determined pixel sizes.

Traditional electrode patterning techniques used the photolithography and chemical wet etching to form the patterns on the thin deposited films. The film electrodes manufacturing process includes sequentially (a) photoresist coating, (b) soft bake, (c) exposure, (d) lithography, (e) hard bake, (f) etch, and (g) photoresist stripping [7]. Therefore, we proposed a novel method and applied the direct laser writing method on the film to obtain the designed pattern. The advantages of this method are to reduce the heavy investment of semiconductor lithography process equipment and to decrease the chemical harm to the environment. Some researches discussed the thin film ablation using different laser sources. Yavas and Takai [8,9] used the Q-switch Nd:YLF laser and flash lamp-pumped Nd:YAG laser to ablate ITO thin films, and

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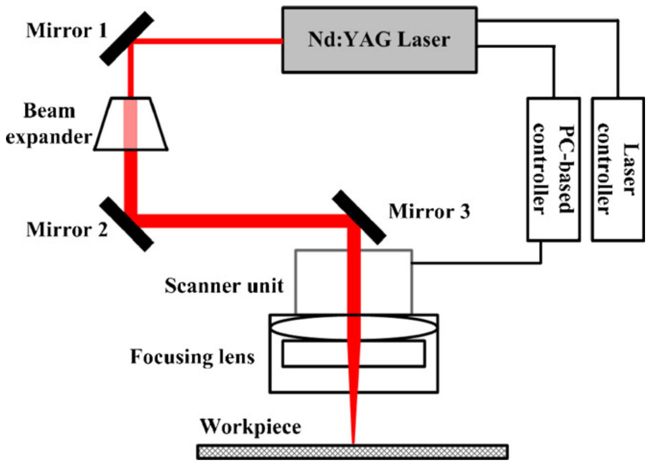

Fig. 1. Schematic diagram of Nd:YAG laser system.

Table 1
Fundamental Nd:YAG laser system parameters.

Wavelength (nm)	1064
Average power (W)	>20
Spatial mode	TEM_{00}
Beam diameter, ±10% (mm)	0.8
Pulse repetition frequency (kHz)	1–100
Pulse width (ns)	34–76

investigated the relationship between different absorption of ITO thin films and the observed morphology differences. Moreover, the temperature model was used to confirm that ITO films were removed by the evaporative mechanism. Lunney et al. [10] used the KrF excimer laser to ablate the fluorine-doped tin oxide and indium tin oxide transparent conductive thin films. The 50 μm wide conducting channel was ablated and measured by a scanning electron microscope. Molpeceres et al. [11] used three types of laser source, including KrF excimer laser, Nd:YAG laser, and diode pumped solid state (DPSS) laser, for patterning the amorphous silicon (a-Si) and ITO thin films. Park et al. [12] used an ultrafast laser with wavelength of 810 nm and pulse width of 150 fs to ablate the ITO thin film coated on the glass substrate. Both laser fluence and number of pulses affect the ablation region depth. The ablation threshold of the ITO film conducted by the ultrafast laser was found to be 0.07 J/cm^2 that is much lower than that of the glass substrate (about 1.2–1.6 J/cm^2), which leads to a selective ablation of ITO films without damage on glass substrate. Chen et al. [13] developed a third harmonic Nd:YAG laser system to direct writing patterns on ITO films and discussed the effect of the different feeding speeds and pulse repetition frequencies on the patterned line overlapping rate. By increasing the laser scanning speed and pulse repetition frequency, the patterned line width decreased. Chen et al. [14] also used the laser beam shape technique to obtain top-hat intensity distribution laser beam to perform line scribing and to perform electrode patterning on ITO thin films deposited on glass and plastic substrates. The obtained morphology of the complex patterning electrode was uniform, smooth, and free from damage in substrates after the laser patterning was performed.

This study focuses on the electrode isolation using direct writing techniques on ITO films coated on substrates used in the various mobile phones. The candidated substrates include soda-lime glass, polycarbonate (PC), and cyclic-olefin-copolymer (COC). The operation parameters for the thin films material removal in laser scribing are laser exposure time and scanning speed. After laser scribing, the morphologies are examined using a 3D confocal laser scanning microscope. The reaction between laser beam and materials can produce the partially ablated areas in the plastic substrate, and is also examined by the 3D confocal laser scanning microscope. The electrical properties are measured by a four-point probe. In addition, the isolated performance of the ITO thin films is also discussed.

Table 2
Optical and electrical properties of ITO film deposited on different substrates.

Properties	ITO/Glass	ITO/PC	ITO/COC
Thickness (film/substrate)	20 nm/0.7 mm	30 nm/1.0 mm	20 nm/0.7 mm
Transmittance (%) (400–800nm)	85.5	86.4	86.8
Sheet resistance (Ω/□)	315	433	390
Surface roughness (RMS, nm)	0.926	1.034	1.553

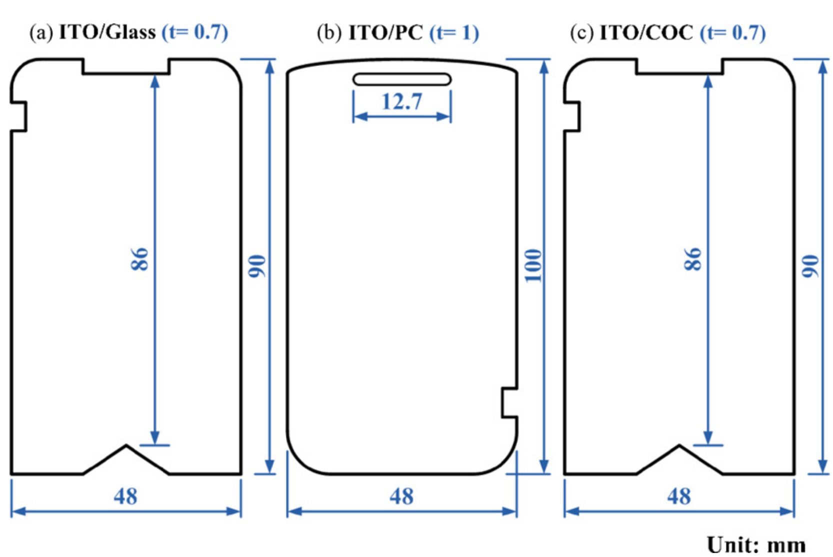

Fig. 2. Dimensions and shapes of cell phone touch panels used in this study.

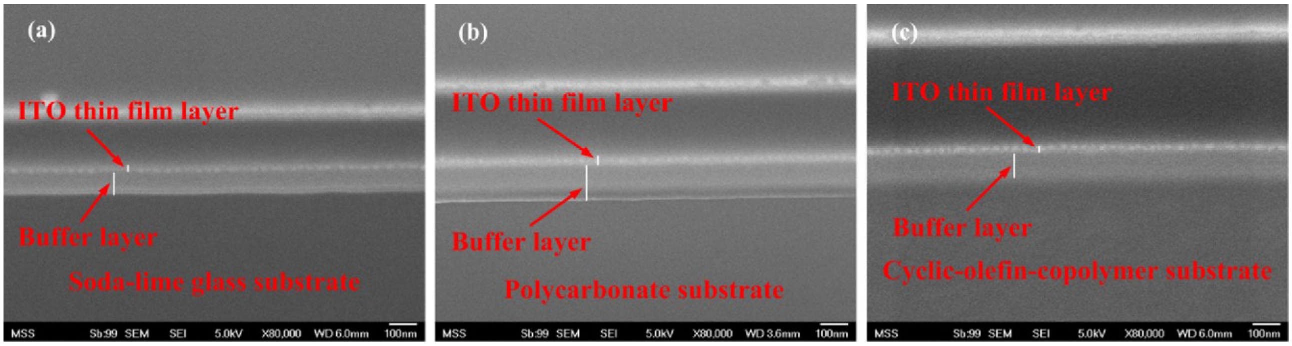

Fig. 3. SEM cross-section views of ITO films deposited on different types of substrates. (a) ITO/Glass, (b) ITO/PC, and (c) ITO/COC.

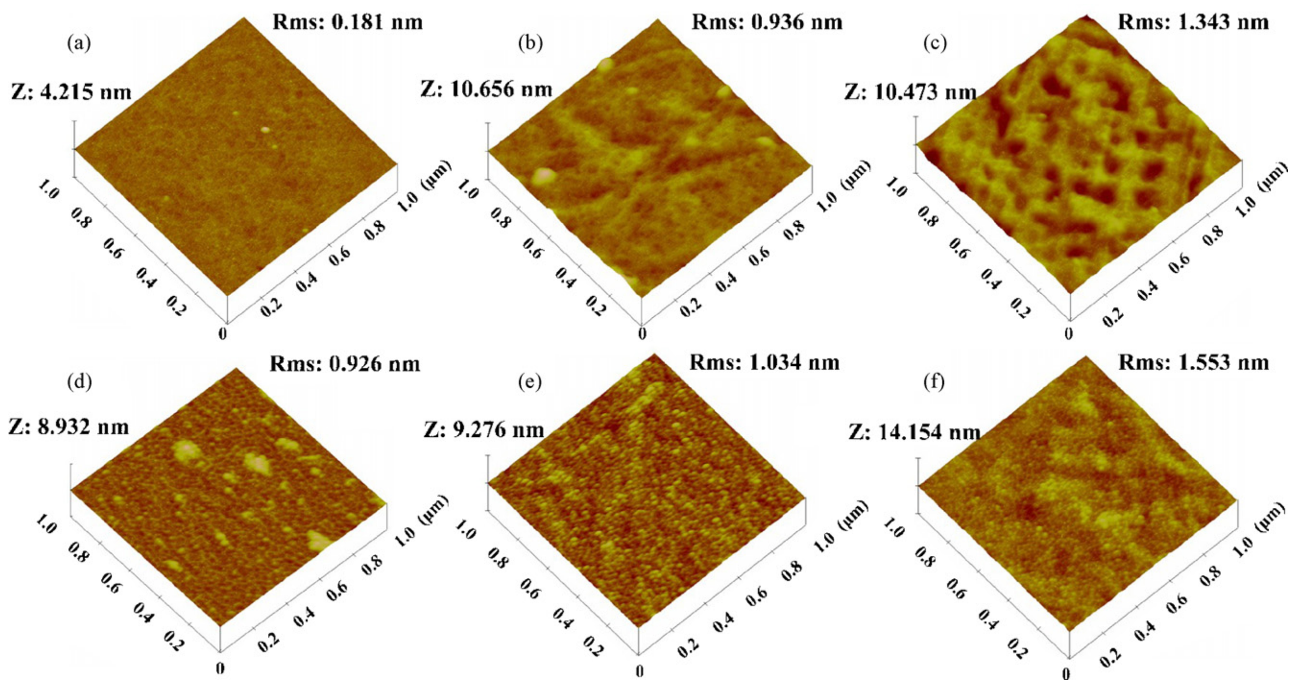

Fig. 4. Surface roughnesses of different substrates and ITO films deposited on substrates. (a) Soda-lime glass substrate, (b) PC substrate, (c) COC substrate, (d) ITO/Glass, (e) ITO/PC, and (f) ITO/COC.

2. Experimental

2.1. Laser scribing system

Fig. 1 shows the schematic diagram of the experimental system. The fundamental neodymium-doped yttrium aluminum garnet crystal (Nd:YAG) laser processing system with wavelength of 1064 nm is used for patterning isolation lines in ITO thin film of the cell phone touch panels. The laser beam was delivered through a 5× beam expander, three reflective mirrors, and a high-speed galvanometric scanning head. The f-theta focusing lens was used in this system with the focal length of 184 mm and the scanning area of 112 mm × 112 mm. The *Z*-axis movable table with ball-screw mechanism in focusing alignment is used to adjust the focal point and finally to bring the focused beam on the ablated surface of ITO thin films.

In this laser operation system, the pulse repetition frequency is adjusted from 1 kHz to 100 kHz. The values of the maximum pulse repetition rate, the maximum average output power, and the pulse width are 100 kHz, 20.8 W, and 76 ns (FWHM). The energy per pulse exceeds 10 mJ. The nominal values of the laser beam diameter at the exit port and average spot size

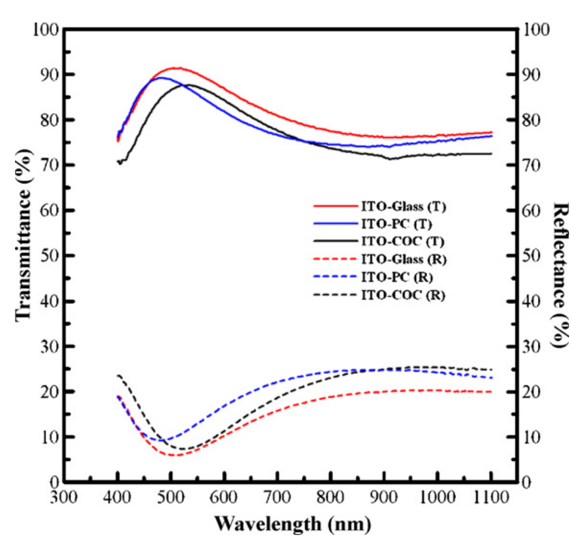

Fig. 5. Light transmittance and reflectance versus wavelength for ITO thin film at various substrates.

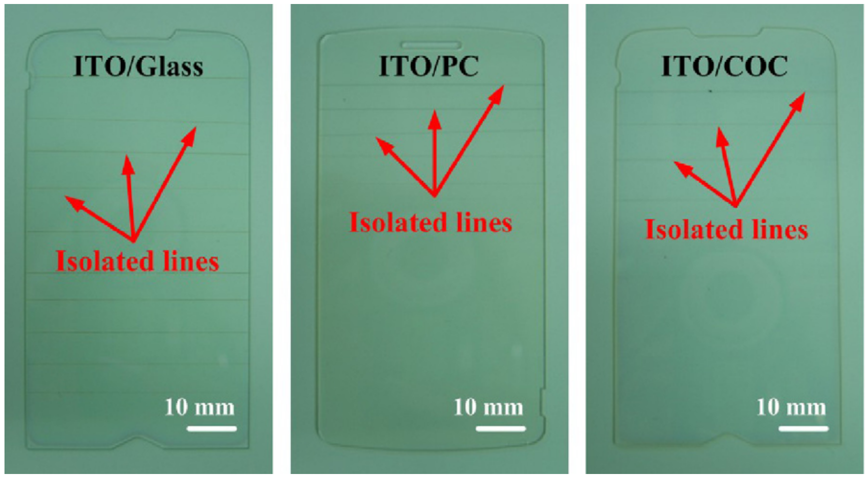

Fig. 6. Pictures of laser scribing of isolated lines on different substrates.

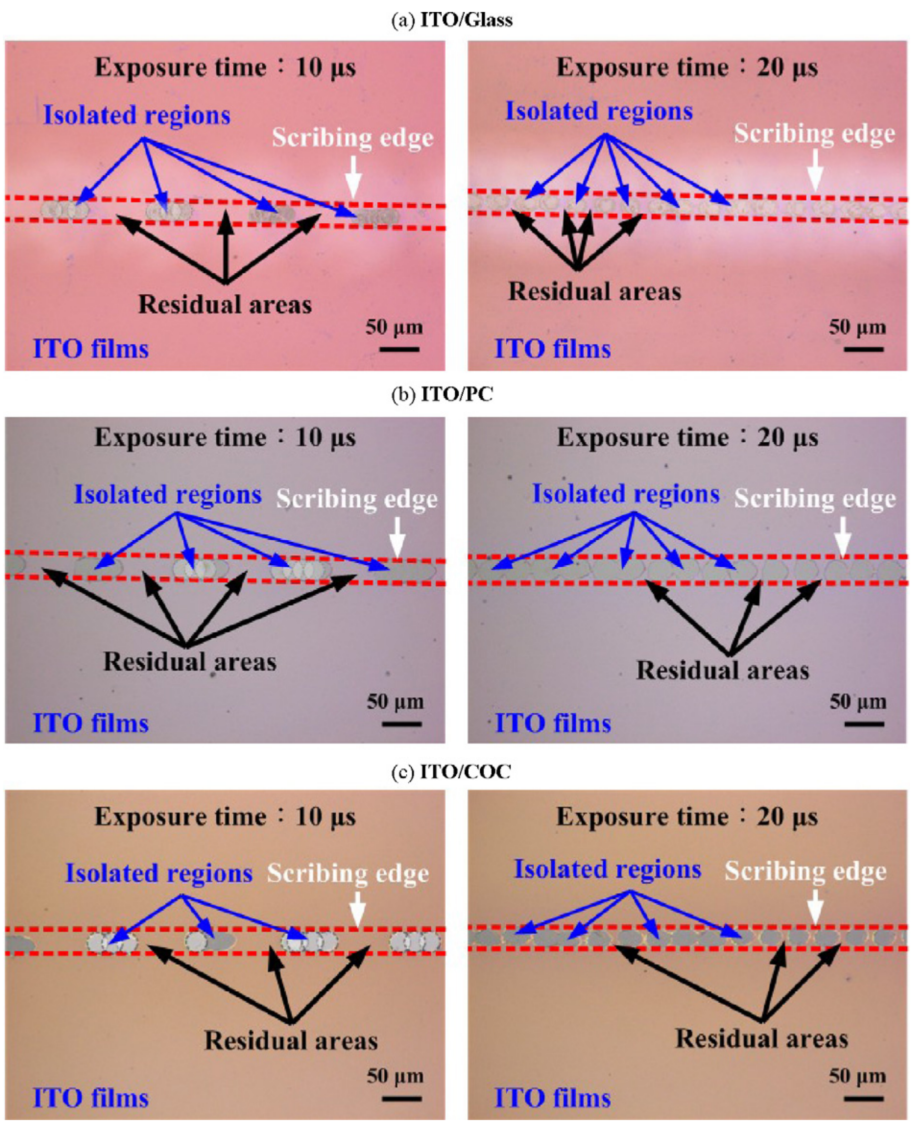

Fig. 7. Surface morphologies of laser scribing of isolated lines at laser exposure time of 10 μs and 20 μs on different types of substrates coated indium tin oxide thin films. (a) ITO/Glass, (b) ITO/PC, and (c) ITO/COC.

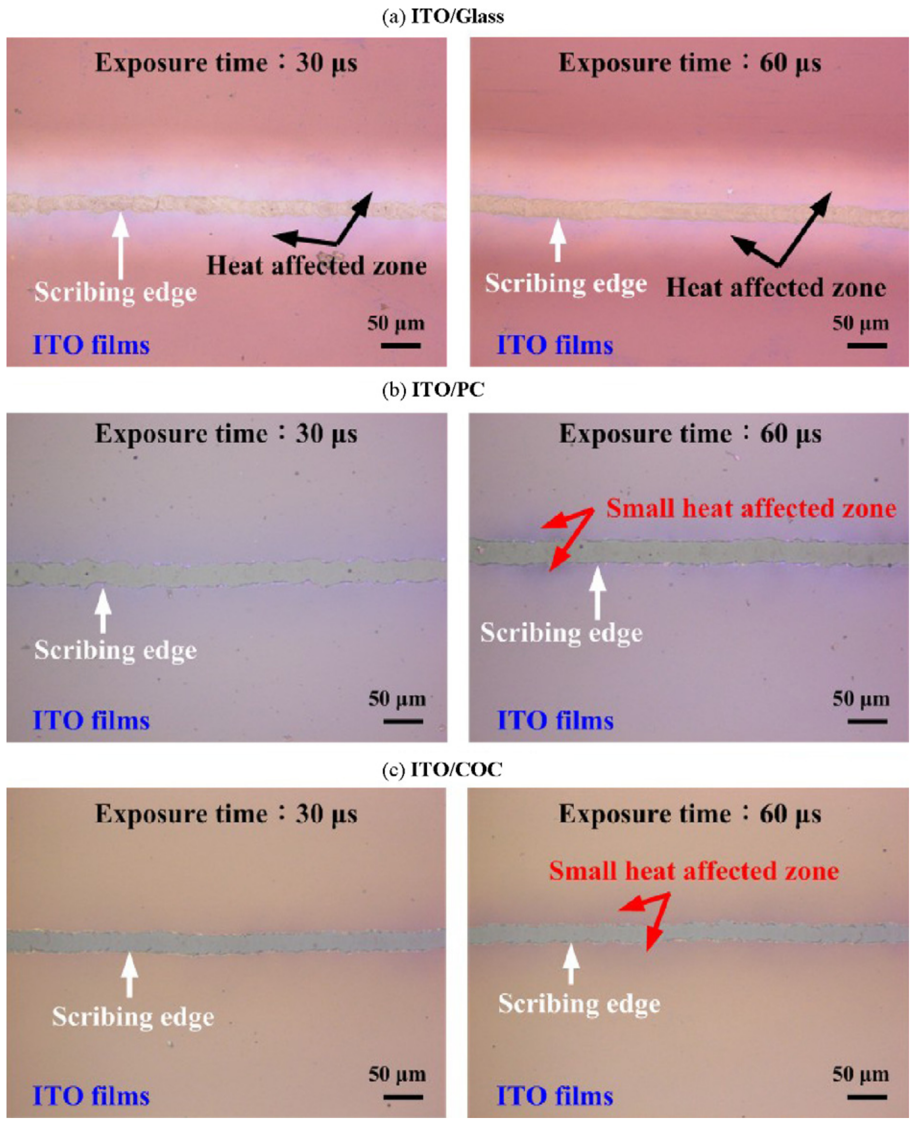

Fig. 8. Surface morphologies of laser scribing of isolated lines at laser exposure time of 30 μs and 60 μs on different types of substrates coated indium tin oxide thin films. (a) ITO/Glass, (b) ITO/PC, and (c) ITO/COC.

are approximately 0.8 mm and 30 μm, respectively. The complete specification of the laser processing system is presented in Table 1. The average output power, the pulse repetition rate, the scanning speed of the galvanometer scanners, and the pulse duration of the Nd:YAG laser can be adjusted by the Human Machine Interface (HMI), which is a self-developed program written by Borland C++ Builder software to monitor and control the processes.

2.2. Sample preparation

The Nd:YAG laser scribing system is designed to perform the electrode isolation of ITO thin films coated on different substrate materials including soda-lime glass, PC, and COC. Table 2 summarizes the properties of ITO films deposited on three substrate materials used in our experiment. These ITO films have sheet resistance of 315 Ω/□, 433 Ω/□, and 390 Ω/□, respectively. Fig. 2 depicts the dimensional layouts of the three cell phone touch panel models. The width of all three substrates is 48 mm. The lengths of the substrates are 90 mm, 100 mm, and 90 mm, shown in Fig. 2(a)–(c), respectively. Moreover, the thicknesses of the substrates are 0.7 mm, 1 mm, and 0.7 mm.

The commercial ITO thin films were deposited on soda-lime glass, PC, and COC substrates by sputtering method. An oxide buffer layer is deposited on each substrate to enhance adhesion between the ITO films and substrates. Before the thickness of these films coated on different substrates was measured by SEM, a focused ion beam (FIB) system (model SMI-3050, SEIKO, Japan) was used to mill a step for easy thickness observation. In order to protect the specimen surface during the FIB process, the silicon oxide (SiO_2), platinum (Pt), and carbon (C) were coated on ITO film surface, respectively. Fig. 3 shows the cross-section view SEM pictures of ITO films deposited on different types of substrates. Fig. 3(a) shows that the ITO film is on soda-lime glass substrate. The ITO film and buffer layer were approximately 20 nm and 100 nm thick, respectively. Fig. 3(b) shows that the ITO film is coated on PC material. The ITO film and buffer layer were approximately 30 nm and 140 nm thick, respectively. Fig. 3(c) shows that the ITO film is coated on COC material. The ITO film and buffer layer were approximately 20 nm and 100 nm thick, respectively.

Fig. 4 shows the surface roughness in 3D images of ITO films deposited on different substrates scanned by the atomic force microscope (Veeco di Dimension 3100, USA). The surface

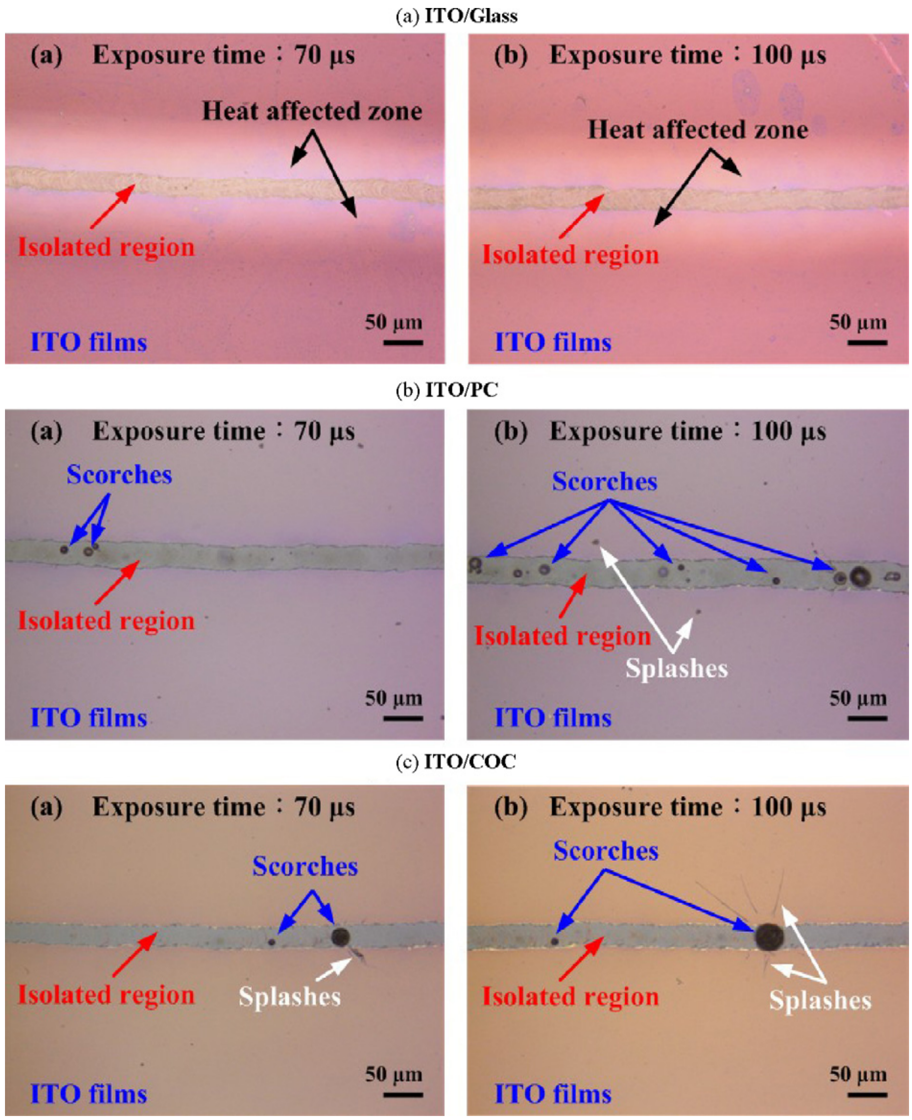

Fig. 9. Surface morphologies of laser scribing of isolated lines at laser exposure time of 70 μs and 100 μs on different types of substrates coated indium tin oxide thin films. (a) ITO/Glass, (b) ITO/PC, and (c) ITO/COC.

measuring region is 1 μm × 1 μm. The measured values of the root mean square (RMS) are of 0.181 nm, 0.936 nm, and 1.343 nm for the blank soda-lime glass, PC, and COC substrates, respectively, shown in Fig. 4(a)–(c). The RMS values of the ITO films deposited on soda-lime glass, PC, and COC optical materials are of 0.926 nm, 1.034 nm, and 1.553 nm, respectively, as shown in Fig. 4(d)–(f). Compared surface characteristic of the deposited films, the surface roughness of ITO film deposited on soda-lime glass substrate is better than that deposited on PC and COC substrates because of the flat glass surface.

Before the laser scribes isolation lines, the spectrometer (Lambda 900 UV/vis/NIR) is used to measure the transmittance and reflectance of the ITO films deposited on the various substrates. The data is shown in Fig. 5. The light transmittance values at 1064 nm wavelength are approximately 76.88%, 75.92%, and 72.37% for ITO/Glass, ITO/PC, and ITO/COC materials, respectively. The corresponding light reflectance values are 20.06%, 23.53%, and 25.17%. After the laser scribes isolation lines, the surface morphology was measured by a 3D laser confocal microscope (KEYENCE VK-9700). The electrical resistivity before and after laser scribing is measured by the four-point probe measurement system (QUATEK CH-5601Y).

2.3. Isolation line patterning parameter

Nanosecond pulsed Nd:YAG laser with wavelength of 1064 nm has been used to pattern the isolation lines of ITO thin films. The operation variables and constrains for patterning isolation lines were carried out as following:

(a) The optimal average laser power was fixed at 2.2 W, and the pulse repetition frequency was fixed at 100 kHz.
(b) The laser exposure times were adjusted from 10 μs to 100 μs, and the interval between each pulse was set by 10 μs.
(c) Machining time varies from 0.76 s to 2.25 s to pattern the isolation line length of 50 mm.
(d) The position of laser focal point and workpiece fixture was fixed for laser patterning different thicknesses of these substrates.

3. Results and discussion

3.1. Surface morphology, isolation line width, and depth

Fig. 6 shows the photo-pictures of isolated lines on three different substrates by a fundamental Nd:YAG laser source. Figs. 7–9

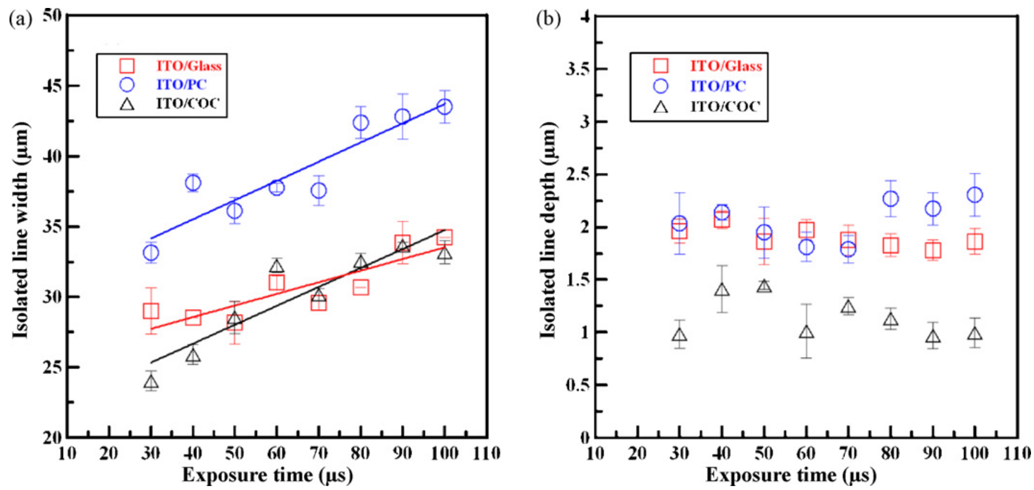

Fig. 10. Relationship of isolated line width and depth on various exposure times. (a) Isolated line width versus different laser exposure times, and (b) isolated line depth versus different laser exposure times.

show the photos of the scribed isolation lines on different substrates with 400 times magnification using the 3D laser confocal microscope. Fig. 7(a)–(c) shows the surface morphologies of patterned isolated lines subjected to 10 μs and 20 μs exposure time on ITO/Glass, ITO/PC, and ITO/COC materials, respectively. The individual ablated mark, discontinuous isolated regions, and the residual area were clearly observed in the ITO films along a laser scribing path. The ablated marks on the ITO/PC are wider than that on both ITO/Glass and ITO/COC. The ablated mark widths of ITO/Glass and ITO/COC are similar. This is due to the thickness difference between these blank substrates, which result in a different laser spot sizes focused on the ITO substrate surface. Moreover, the ITO/Glass substrate has slightly higher absorptance than the other two substrates that a few heat affected zone appeared near the ablated mark as shown in Fig. 7(a).

When the exposure time was extended to 30 μs and 60 μs, the residual areas along a scribed path were gradually decreased, shown in Fig. 8. No clear existed residual areas on the scribed path of these substrates can be seen and shown in Fig. 8(a)–(c). There are no apparent damaged spots or melt burrs observed on the ablated substrate surfaces. Furthermore, the scribed lines shown in Fig. 8(b)–(c) have slightly heat affected zone near the scribing edge when the laser exposure time is 60 μs. The scribed lines shown in Fig. 8(a) obviously have wide heat affected zone near the scribing edge of ITO/Glass substrates. Fig. 9 shows the surface morphologies of isolated lines on different substrates scribed by laser at laser exposure time of 70 μs and 100 μs. Fig. 9(a) reveals the wide heat affected zone along the scribing path on ITO/Glass substrates. When the laser exposure time is longer than 60 μs, the scorches and splashes also can be clearly observed in the isolated lines on PC and COC substrates. The photo evidences are shown in Fig. 9(b) and (c).

Fig. 10 shows a relationship of isolation line width and depth versus the various exposure times. The isolated line width increases with increasing exposure time for all of ITO substrates. When the PC is adopted as the substrate, the line width is average 10 μm wider than that of glass and COC adopted as substrate under the studied exposure time ranges, shown in Fig. 10(a). The PC thickness is 1 mm and thicker than the other two substrates, hence the thickness difference results in different laser spot sizes focused on the ITO substrate surface. The ITO thickness on PC is 30 nm compared to 20 nm thick on the other two, and the ITO thickness difference causes the larger thermal diffusion difference and results in ablated spots difference. Moreover, the isolated line depth measured on the ITO/PC increases gradually with increasing exposure time, as shown in Fig. 10(b). Because the thermal stability of glass substrate is better than plastic substrate, the ITO/Glass results show that the isolated line depth is very close with increasing exposure time. The average depth of ITO/PC and ITO/Glass substrates are approximately 2 μm. However, the isolated line depth measured on the ITO/COC is slightly low than other two substrates with increasing exposure time. The average depth of ITO/COC substrates is approximately 1.25 μm.

3.2. Electrical conductivity measurement

ITO films deposited on glass, PC and COC substrates with film thickness of 20 nm, 30 nm, and 20 nm were successfully isolated when laser exposure time is longer than 20 μs. The results of electrical conductivity near the isolated line edge were measured by the four-point probe as shown in Fig. 11. The three dash-lines represent the original resistivity levels before laser scribing, and

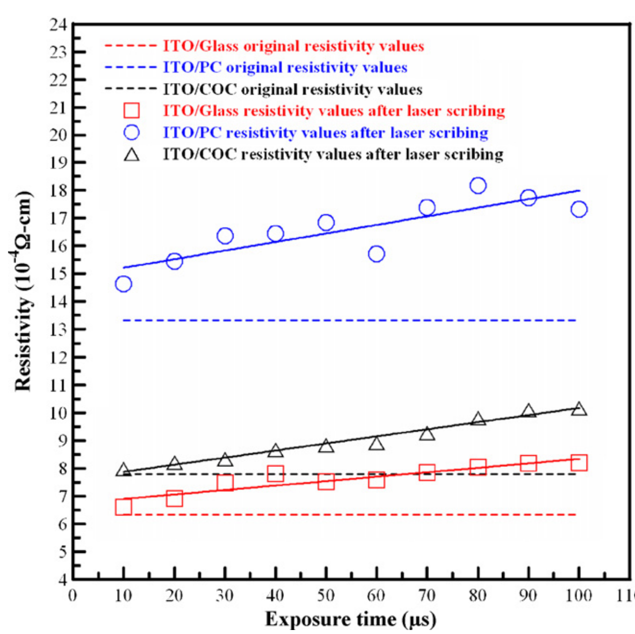

Fig. 11. Electrical properties of ITO thin films coated on glass, PC, and COC with un-scribing and after laser scribing at different laser exposure times.

the symbols represent the measured data and the solid-lines are the regression result after laser scribing. All resistivity values after laser scribing were greater than the original resistivity. The measured results show that the resistivity values gradually increase with increasing the laser exposure time. Because the thickness of ITO films coated on glass and COC substrates is the same, thus the resistivity values after laser scribing are very similar. However, the thickness of ITO films coated on PC substrate is larger than others; the resistivity values are obviously larger than others.

4. Conclusion

We successfully fabricate the isolated lines on indium tin oxide films using the direct writing technology and a nanosecond pulsed Nd:YAG laser. The line patterns were discontinuous and led to residual films produced along a laser scribing path when laser exposure time is less than 30 μs. The burned and damaged substrates can be observed by the 3D confocal laser scanning microscope when laser exposure time is larger than 60 μs. Moreover, the partial burned areas including scorches and splashes were observed in scribed thin films on PC and COC substrates. When the exposure time is tuned within 30 μs and 60 μs, the better edge quality of the scribed lines can be obtained. After laser scribing of isolated lines, all of resistivity values of substrates coated on ITO films near the isolated line edge were greater than the original ones. Moreover, the isolated line width values increase with increasing laser exposure time.

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