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Laser patterning with beam shaping on indium tin oxide thin films of glass/plastic substrate

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ABSTRACT

In this research the laser beam shaper component has been used to obtain top-hat intensity distribution laser beam to perform line scribing and to perform electrode patterning on Indium thin oxide (ITO) thin films deposited on glass and plastic substrate. ITO films were removed with third harmonic Nd:YAG laser processing system. The pulse duration, laser output power, pulse repetition rate and scanning speed parameters of straight line patterning and electrode patterning on different types of substrates were discussed, respectively. The experimental results are measured by optical microscope and scanning electron microscope to evaluate the processing parameters and surface properties of ITO thin films.

1. Introduction

In the era of information and communication, the flat panel displays have become a popular gadget around the world. The substrate materials used in the flat display are glass or plastic. In order to obtain high resolution in the display screen, an electrode patterning process is required. The traditional patterning processes needs several steps, including (1) photoresist coating, (2) soft bake, (3) exposure, (4) lithography, (5) hard bake, (6) etch and (7) photoresist stripping. In wet chemical etch process exist for the fixable plastic substrates. Several disadvantages, include higher absorption coefficient of water, lower corrosion resistance of acid and higher thermal expansion coefficient. Therefore, a new method, the laser direct writing method, is purposed to reduce the high investment of semiconductor lithography process equipment, and to decrease the chemical harm to the environment.

The relevant researches of electrode patterning on ITO thin films are usually categorized into two categories: direct writing method and mask projection method. In the direct writing process, a laser beam focuses and scans on the work-piece directly to pattern the electrode. In the mask projection process, the laser beam passes through the mask and focused on the work-piece to project on the electrode. Therefore, in the mask projection process, several important factors should be considered. They are laser beam profile or beam energy distribution. Because various types of electrode were used in the flat panel display, hence the mask development becomes costly for the industry. In addition, in the projection technique, the laser beam passes through the projection mask, therefore, the assessment of this processing demands too much laser output power, energy distribution and coated thin films on the projection mask.

Laser patterning of ITO in flat panel display manufacturing, proposed by Venkat et al. [1], introduced the direct writing method and mask projection with three laser sources, including Nd:YVO_4, Nd:YLF and Nd:YAG. In the proposed paper, Nd;YVO_4 have highest pulse repetition rate than the Nd:YLF and Nd:YAG laser sources, but the pulse energy is limited. It's also not available in large panels. Therefore, the optimum laser for ITO electrode patterning application is side-pumped Nd:YAG or Nd:YLF laser. Lunney et al. [2] provided excimer laser etching of transparent conducting oxides. Experimental samples were doped tin oxide of 430 nm thick with 10 Ω/□ and ITO of 150 nm thick with 16 Ω/□, respectively. The tin oxide etching threshold of 0.7 J/cm^2, while the value for ITO was 0.5 J/cm^2. Chen et al. [3] demonstrated the laser direct writing patterning on polycrystalline diamond film and PT polymer with maskless by helium–cadmium (He–Cd) laser. After patterning, the minimum linewidth of 1.6 µm and writing speed of 100 µm/s. Yavas et al. [4,5] investigated the effect of the various laser wavelengths on the ITO thin films absorption. They also simulated laser writing to calculate the temperature profile on the surface of ITO thin films by one dimensional thermal diffusivity equation. Their experimental results revealed that within UV wavelength band is a better process quality than that of other wavelength bands on the patterning surface of ITO thin films. Ghandour et al. [6] introduced CO_2 snow-based cleaning process that can decrease the extruding curled materials of the electrode processing. Tanaka et al. [7] investigated laser ablation on ITO thin films by first, second, third and fourth harmonic of diode-pumped Nd:YLF laser and showed that the debris was reduced by the assistance of He gas. Farson et al. [8] demonstrated Ti-sapphire laser with 2 kHz

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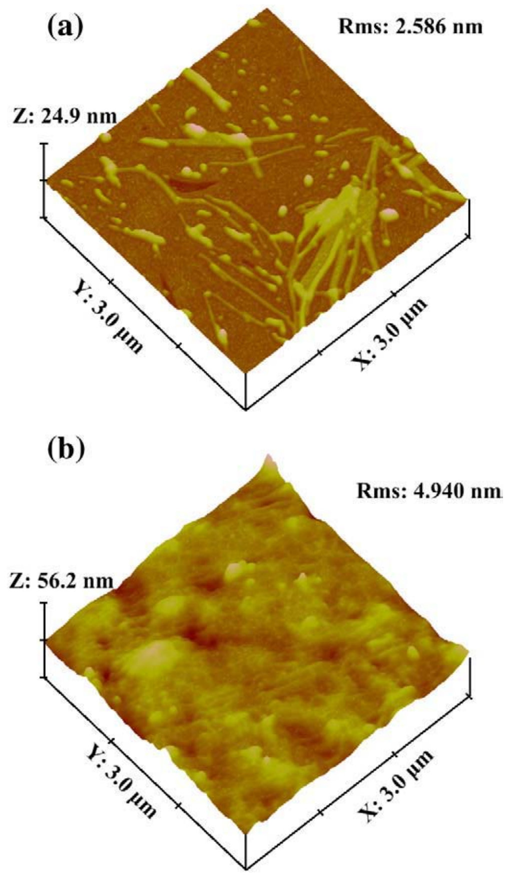

Fig. 1. The RMS surface roughness of ITO films at (a) ITO/glass with substrate thickness of 1.1 mm, (b) ITO/PC with substrate thickness of 1.0 mm.

repetition rate on laser electrode patterning in ITO thin films. Minimum ablation diameter and depth is 800 nm and 70 nm, respectively. The ablation quality was smooth enough. Li et al. [9] proposed that laser is to be used to fabricate micro-cladding electronic circuits with silver conductor on glass boards and then to measure the resistivity by a four-point probe method. Some laser beam shape methods used optical geometrical theorem, including aspheric elements, spherical-surface lens and diffraction lens [10]. In order to obtain the uniform depth of the polymer surface on the exposed region, Corbett [12] proposed that the Gaussian beam shaped to the uniform top hat distribution laser beam be applied to laser direct writing. Moreover, Pissadakis et al. [13] proposed the sub-micron InOx thin film micromachining using 248 nm excimer laser ablated grating and discussion relation physical mechanisms.

In the work presented herein, laser beam shaping technique has been used to transform a laser beam with Gaussian energy distribution to a near top-hat energy distribution. After performing electrode pattering on ITO thin films deposited on glass and polycarbonate (PC) substrates, we use optical microscope (OM) and scanning electron microscope (SEM) to exam ITO thin films and to obtain the ablated quality of the electrode.

2. Experimental setup

2.1. UV laser processing system and sample preparation

Laser electrode patterning system consists of a UV laser source, an optical system, a feeding system, a scanner unit and a PC-based controller. A wavelength of 355 nm can be obtained by laser oscillator with triple harmonic generation. The output average power of the laser source can be adjustment from 0.07 W to 3.33 W. The range of pulse repetition rates can be adjusted from 1 kHz to 10 kHz . The pulsewidth and laser pulse duration of 35 ns and 1000 µs, respectively. In addition, the accumulated energy for different repetition rate from 9.9 mJ/cm^2 to 651 mJ/cm^2 with laser output power of 0.07 W and 0.46 W. In the optical path, laser beam passes though a beam expander, aperture, beam splitter, mirrors, beam shaper component and scanning system. A laser beam for micropatterning ITO thin films are used as specimen. The films are deposited on either glass or plastic substrates. Both substrate dimensions were of 20×20mm^2. Before the patterning, samples were cleaned with distilled (DI) water and put in ultrasonic bath filled with the ethanol solution for 10 min and then dried by high pressure gas. The electronic and optical properties of ITO thin films coated on soda–lime glass and polycarbonate substrates used in the experiment are given in Table 1. The polished soda–lime glass and polycarbonate (PC) plastics substrates with thickness of 1.1 mm and 1 mm, respectively. The deposition method by DC sputtering process to coated indium tin oxide (ITO) thin films with thickness of about 400 nm. The roughness of the coated ITO thin films with different types of substrates can be shown in Fig. 1(a) and (b).

2.2. Laser beam shaping technique

Laser beam energy distribution is the major parameter for laser materials processing. A laser beam modulation system consists of focusing lens, homogenizer and mirror elements. A collimating laser beam had an energy distribution of near top-hat beam spatial profile to focus on the specimen. In the beam shaping process, laser beam intensity is a Gaussian beam distribution and the heat flux is expressed as Eq. (1) [11]:

$$q(x,y) = \frac{2(1-R)I}{\pi r^2}\exp\left[\frac{-2(x^2+y^2)}{r^2}\right] \qquad (1)$$

where q is the energy density, I is the peak energy of laser beam, R is the reflectance and r is the radius of beam spot. In this research the initial beam is a Gaussian and collimated. Before laser intensity distribution was measured by SPIRICON beam profiler that can be shown in the Fig. 2(a). In order to obtain uniform intensity distribution beam, the beam shaper (RONAR-SMITH®: BS-355) optical component has been used. After beam shaping, the top-hat intensity profile of laser beam, its cross-section of x and y axes as shown in the Fig. 2(b) is often desired in machining application such as laser ablation and micro-patterning etc. Fig. 3 shows the laser beam transmittance system. A UV laser source pass through beam expander, beam shaper and focusing lens to obtain uniform near top-hat intensity distribution laser beam. Finally, fabricate the electrode patterning that coated ITO thin films on glass and plastic substrates.

3. Results and discussion

3.1. Laser forming of isolate line patterning on ITO/glass and ITO/PC substrates

We used the diode pumped solid state (DPSS) laser installed in the linear motor stages to fabricate straight line electrode patterning on

Table 1
Electronic and optical properties of the ITO/PC and ITO/Glass in the experimental.

Items	Type	
	ITO/PC	ITO/Glass
Substrate thickness	1 mm	1.1 mm
Sheet resistivity	380 Ω/□	400 Ω/□
Surface roughness	2.586 nm	4.940 nm
Transmittance (400–800nm)	~86.5%	≧90%

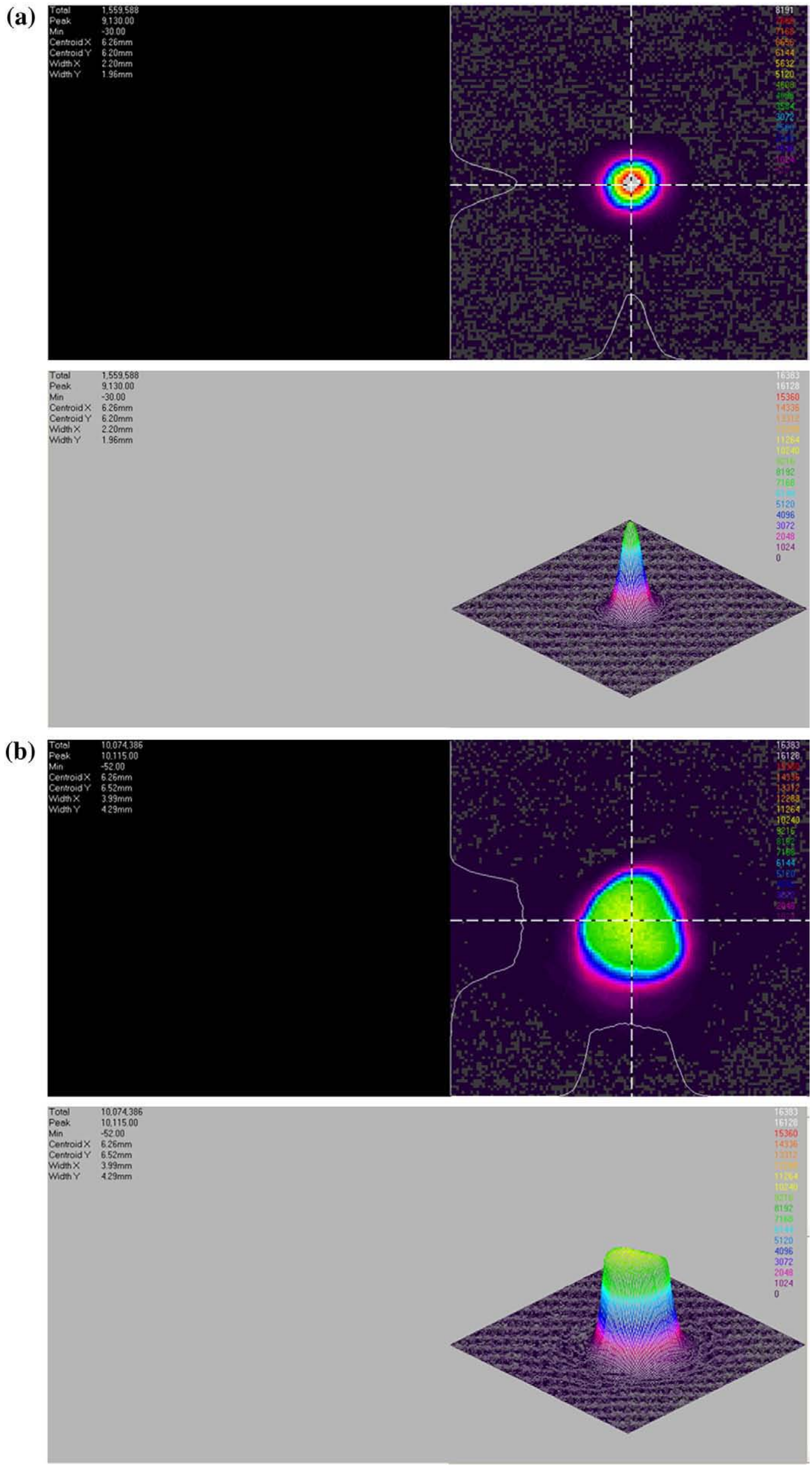

Fig. 2. Measurement 2-D and 3-D intensity distribution before and after the beam shaping. (a) Before laser beam shaping and (b) after laser beam shaping.

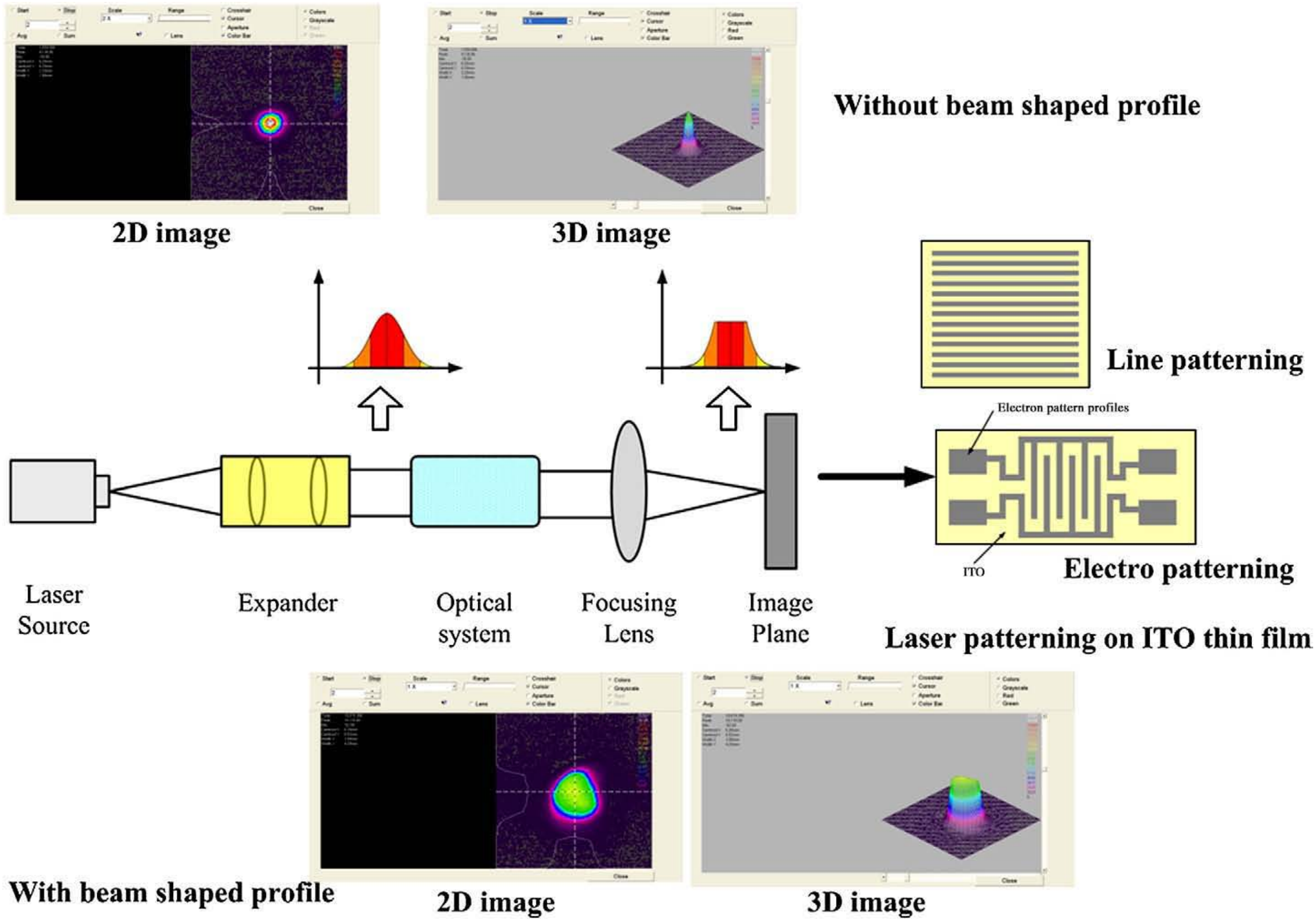

Fig. 3. Schematic diagram of laser beam transmittance.

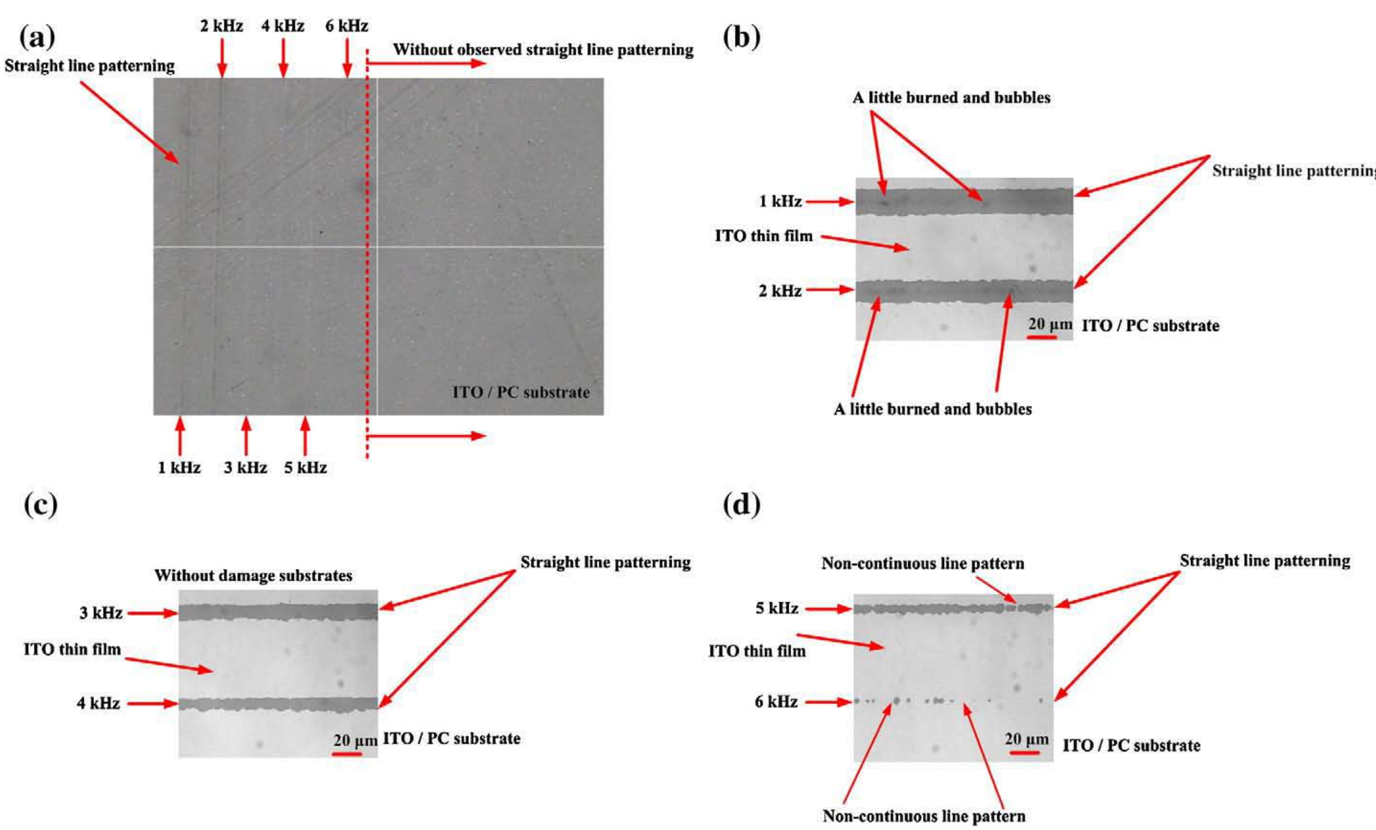

Fig. 4.

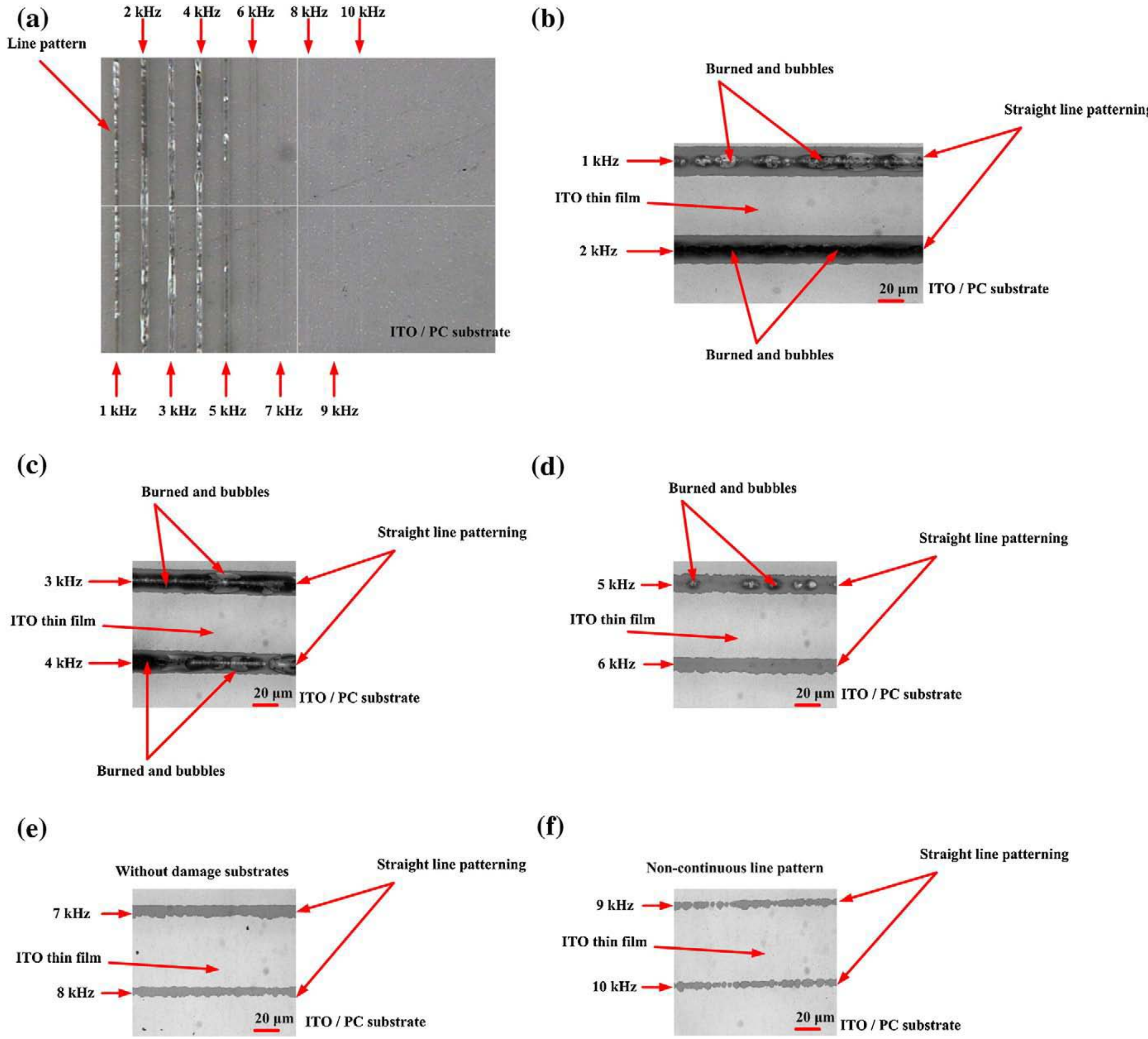

Fig. 5. OM photograph of isolate line patterned at 355 nm with different pulse repetition rate on polycarbonate substrates ($P = 0.46$ W, $v = 40$ mm s^{-1}). (a) Top view of isolate line patterning, (b) 1 kHz and 2 kHz, (c) 3 kHz and 4 kHz and (d) 5 kHz and 6 kHz, (e) 7 kHz and 8 kHz and (f) 9 kHz and 10 kHz.

ITO/glass and ITO/PC. In the line patterning process, controlling *x*–*y* axes stages to fabricate electrode line patterning with the average power of 0.07 W and 0.46 W. The repetition rate varied from 1 kHz to 10 kHz and stages feeding speed were fixed at 40 mm/s. Fig. 4(a) shows the line patterning results on the surface of the PC substrates. That displays the line patterning with different pulse repetition rate from 1 kHz to 6 kHz. In the straight line patterning of polycarbonate substrates coated ITO thin film, the pulse energy can be adjusted from 99 mJ/cm^2 to 17 mJ/cm^2. When the repetition rate is higher than 6 kHz, a lower laser power resulted in un-ablation on ITO thin films. This is because the accumulated energy density and higher pulse repetition rate could not ablate the ITO thin films. Furthermore, there was a 10× magnification optical microscope image of line patterning as shown in the Fig. 4(b), (c) and (d). The burned and bubble phenomenon of the ITO thin films and inner substrates are observed at the pulse frequency of 1 kHz and 2 kHz. Laser with lower pulse frequency accumulates more energy on the power to lead to damaged substrates or affect its performance. Non-continuous line patterning process appeared at the pulse frequencies of 5 kHz and 6 kHz, the line pattering on ITO thin films could not totally isolate electric conductivity.

Similarly, Fig. 5(a) shows the straight line patterning experimental results using an optical microscope. We use the 0.46 W laser power and the different pulse repetition rates from 1 kHz to 10 kHz to expose ITO thin films. In this case study, the pulse energy can be adjusted from 651 mJ/cm^2 to 65 mJ/cm^2. The laser output power of 0.46 W and pulse repetition rate of 6 kHz as shown in Fig. 5(a) has a good quality for line patterning. In the line patterning process, there are not only completely ablated thin films but also those without damaged or burned substrates under the different pulse repetition rates. The larger-scale inspection of the line pattering on ITO thin films was shown in Fig. 5(b), (c), (d), (e) and (f). Fig. 5(b), (c) and (d) reveals

Fig. 4. OM photography of isolate line patterned at 355 nm with different pulse repetition on polycarbonate substrates ($P = 0.07$ W, $v = 40$ mm s^{-1}). (a) Top view of isolate line patterning, (b) 1 kHz and 2 kHz, (c) 3 kHz and 4 kHz and (d) 5 kHz and 6 kHz.

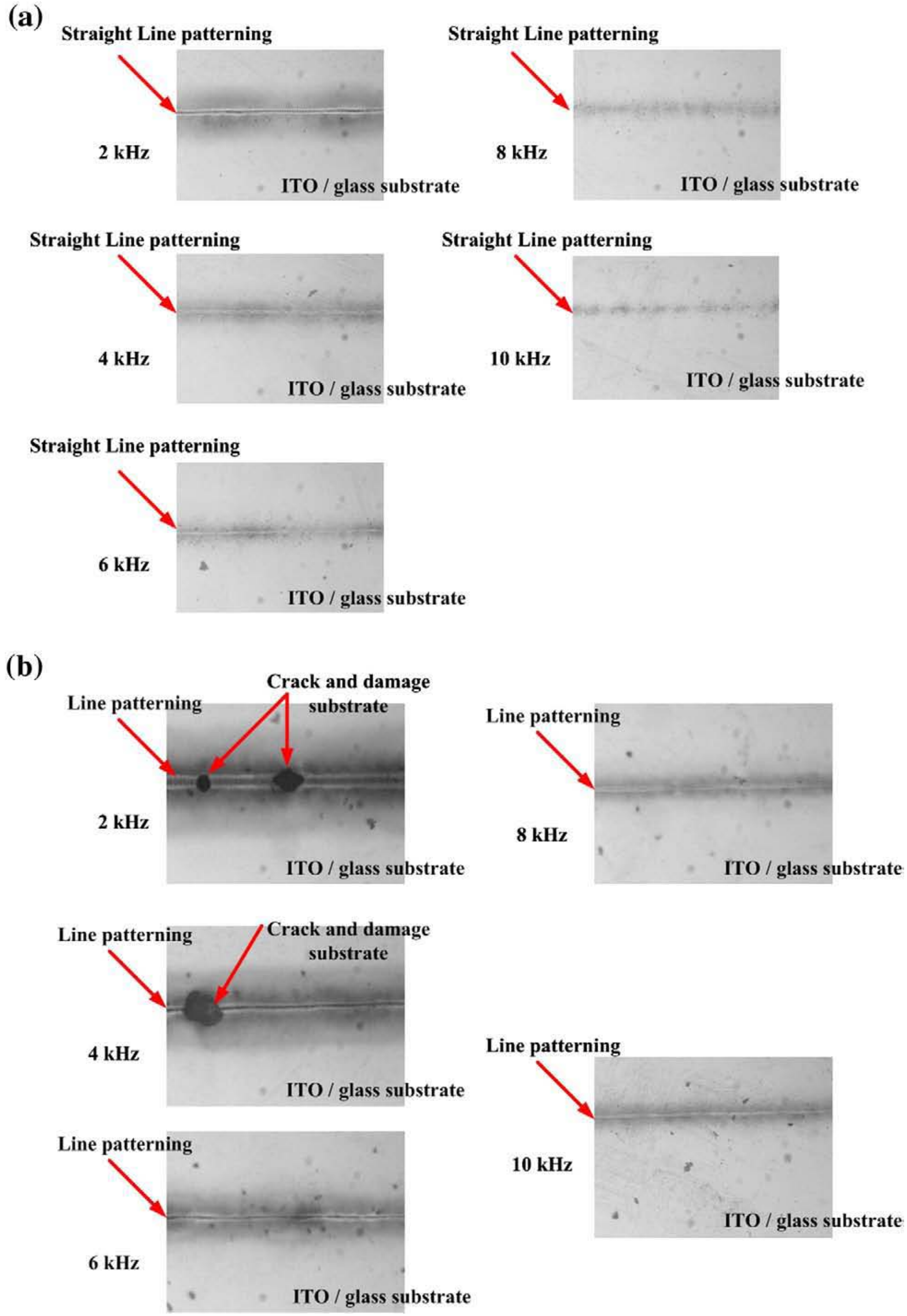

Fig. 6. OM photograph of line patterned at 355 nm with different pulse repetition rate on glass substrates. (a) $P = 0.07$ W, $v = 20$ mm s^{-1}, (b) $P = 0.46$ W, $v = 20$ mm s^{-1}.

the burned-out, bubble and damaged substrates at 1 kHz, 2 kHz, 3 kHz, 4 kHz and 5 kHz with pulse energies of 651 mJ/cm^2, 325 mJ/cm^2, 216 mJ/cm^2, 163 mJ/cm^2, and 130 mJ/cm^2, respectively. From the results of the damaged substrates by the line patterning process, it shows that pulse repetition rates of 6 kHz and 7 kHz, laser power of 0.46 W with pulse energies of 108 mJ/cm^2 and 93 mJ/cm^2, and feeding speed of 40 mm/s can obtain a much superior quality.

The straight line patterning ITO/glass substrates conditions, including the pulse repetition rate, the laser power, pulse energy and the feeding speed, are the same as that of the ITO/PC substrates. The laser powers are 0.07 W and 0.46 W, the feeding speed is 20 mm/s, and the pulse frequencies are 2 kHz, 4 kHz, 6 kHz, 8 kHz and 10 kHz. Fig. 6(a) shows the results between the different pulse repetition rates and laser power of 0.07 W with pulse energies of 50 mJ/cm^2, 25 mJ/cm^2, 17 mJ/cm^2, 12 mJ/cm^2 and 10 mJ/cm^2. Fig. 6(b) shows the results of straight line patterning on ITO/glass substrates with laser power of 0.46 W with pulse energies of 325 mJ/cm^2, 163 mJ/cm^2, 108 mJ/cm^2, 81.33 mJ/cm^2 and 65 mJ/cm^2. The morphological surface can be seen to have a large crack and damaged region on substrates when the pulse frequencies were 2 kHz and 4 kHz, respectively.

3.2. Complex electrode patterning on ITO/glass and ITO/PC substrates

Traditional complex electrode ITO film was mostly removed by wet etching method. However, this method needed many chemicals and a number of additional processing steps . Because laser beam machining had a lot of advantages, such as high-speed, non-contact processing and so on, thereby, laser beam processing can achieve the dry process without the chemical solution and reduce the steps in a process. Fig. 7(a) shows the designed complex electrode patterning. The results of complex patterning on ITO/PC substrate are shown in Fig. 7(b). The size of the electrode patterning area was about 6 mm × 9 mm. Both the lines and spaces are 600 μm. The patterning region did not damage the substrate by optical microscope measurements. Additionally, the sharp corner of the etched pattern in high magnification is shown in the Fig. 7(c). The dark part was the removed portion of the patterned area and the bright part was without the patterned area on ITO thin films. The boundary between the dark and bright parts is clearly observed and the etched process is conducted uniformly. Fig. 8 shows the result of partial complex circuit patterned on ITO/glass substrate by SEM. The laser power was 0.46 W, the laser pulse repetition rate was 8 kHz with pulse energy of 81 mJ/cm^2 and the pulse duration of 1000 μs. The complex patterned line-width was about 100 μm. In this complex patterning case, there is a heat affect zone (HAZ) as shown in Fig. 8 light part region and some particle residual around the electrode patterning, and those results lead to a worse quality in the electronic characteristics and transmission efficiency of light.

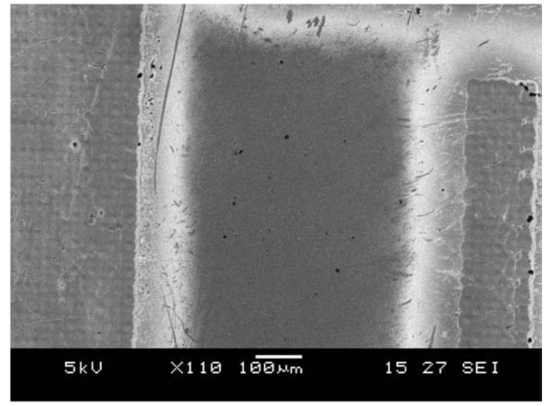

Fig. 8. SEM micrograph of complex electrode patterning on ITO/glass substrate.

4. Conclusions

This research has successfully investigated that using laser processing can selectively remove ITO films for isolated line patterning and complex electrode patterning on glass and plastic substrates. Some experimental parameters such as the laser power, the laser pulse repetition rate, the pulse energy and the feeding speed of movable stages have been discussed. By the optical microscope and scanning electron microscope, the burning, micro-crack, damaged substrates, non-continuous isolate line, heat affect zone and some particle debris of material surface and substrates were observed. Additionally, the complex electrode patterning morphology was uniform, smooth and without damage to substrates of laser electrode patterning. After laser patterning, some particle debris occurred around the electrode patterning and that phenomenon lead to a worse quality in the drift characteristics of electronic and the transmission efficiency of light.

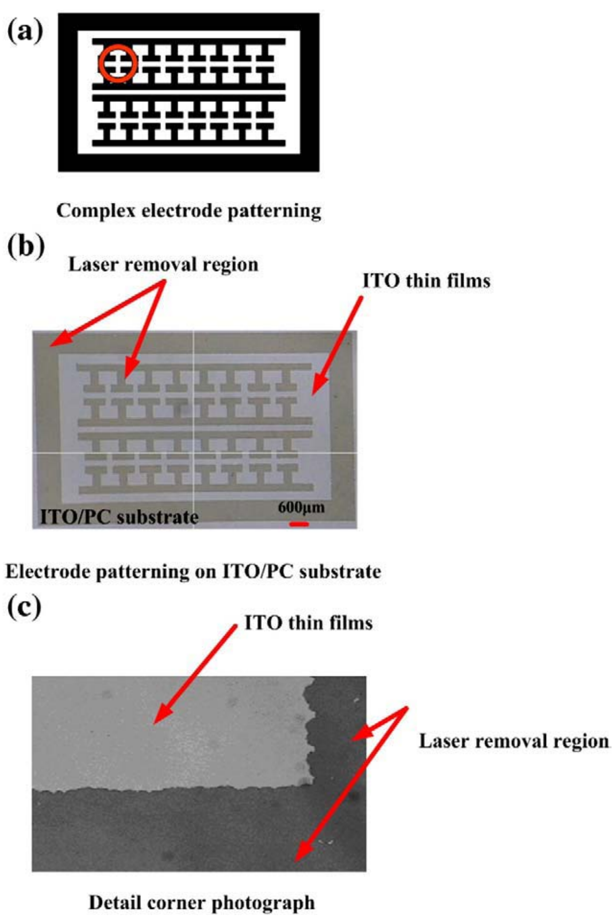

Fig. 7. Circuit patterns ablated by UV laser processing system on ITO/PC substrate.

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