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Investigation of the ablation of fluorine-doped tin oxide thin films by square top-hat ultraviolet laser beams

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ABSTRACT

This paper presents a square top-hat beam shaper in an ultraviolet (UV) laser processing system for electrode patterning and investigates the interaction between square laser beams and fluorine-doped tin oxide (FTO) thin films deposited on glass substrates. The various patterning parameters to ablate the FTO films used in this experiment are included laser fluences, pulse repetition frequencies, and feeding rates of a motorized platform. The laser pulse repetition frequency and the feeding rate of the motorized platform were used to calculate the overlapping rate of laser spot and to determine the patterning quality. The line width and depth, edge quality, three-dimensional topography, and electrical conductivity properties of the patterned FTO films were measured and analyzed using a confocal laser scanning microscope and a four-point probe instrument. Experimental results indicated that the ablated line width and depth increased with increasing laser fluence. After electrode patterning with laser fluence of 2.07 J/cm^2 and 80% overlapping rate, no damages were observed in the patterned lines on the glass substrate. Moreover, the patterned line paths were narrow, smooth, clear, and flat in response to uniform laser energy distribution interacted in FTO films. The measured values of sheet resistance ranged from 109.7 ± 3.8 Ω/□ to 139.3 ± 4.9 Ω/□ at 2.07 J/cm^2 to 9.37 J/cm^2 laser fluences, respectively. The proposed process can reduce the fabrication steps and improve the removal efficiency of transparent conductive oxide materials and no waste etching chemical solution is produced.

1. Introduction

With the rapid developments in the optoelectric and biomedical industries, the applications for transparent conductive oxide (TCO) thin films has increased tremendously. Common TCO thin-film materials include In_2O_3, SnO_2, ZnO, TiO_2, and CdO. Fluorine-doped tin oxide (SnO_2:F, FTO) thin film has recently attracted much attention due to its high transparency and low sheet resistance. Because FTO thin films contain no expensive indium (In) elements, this transparent conductive material is generally cheaper. Due to the price advantage, FTO thin films are often used as the conductive material for light-emitting diodes (LEDs), electroluminescent lamps, liquid crystal displays (LCDs), touch screens, flexible electronics, thin-film solar cells, and other optoelectronic products [1–6]. Traditional electrode patterning of thin films involves a lithographic technique combined with wet chemical etching. However, photolithography equipment is expensive and requires environmentally harmful chemicals and complex steps in the fabrication process. Consequently, laser-direct dry etching is being rapidly developed to replace the conventional photolithography electrode patterning method. The advantages of this laser-direct dry etching are that it reduces the heavy investment of semiconductor lithography process equipment and eliminates the chemical harm to the environment [7,8].

Several studies have presented dry laser patterning with the different laser sources and processing techniques on the film surfaces. Li et al. [9] adopted a Q-switched diode-pumped Nd:YVO_4 (λ=1064 nm) laser to form tin-doped indium oxide (ITO) patterns with a complex T-shape structure on glass substrates. Their experimental results revealed that higher overlapping rate of the laser beam produced better edge quality and discharging characteristics on the patterned ITO electrodes. Chen et al. [10] employed a laser beam shaping technique to obtain a top-hat intensity distribution laser beam capable of line scribing and performed electrode patterning on ITO thin films deposited on glass and plastic substrates. The resulting morphologies of the complex patterning electrode had sharp edges and smooth patterns after laser patterning. Heise et al. [11] used a picosecond

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laser processing system to ablate a zinc oxide (ZnO) layer on a copper-indium-selenide (CIS) layer. The ZnO film on the CIS layer was ablated from CIS thin-film solar cells when the experimental operating conditions had circular spots of 35 μm width, a pulse repetition rate of 321 kHz, a peak fluence below 1 J/cm^2 at a wavelength of 1064 nm, and a scribing speed of more than 6 m/s. Harrison et al. [12] presented high-speed laser patterning of ITO thin films deposited on glass substrates using a beam shaper based on microlens arrays to form a uniform square top-hat laser beam. The ablated ITO coating was fairly uniform, and the edges and corners of the ablated area were slightly darker than the center. Moreover, the re-deposition of plume generated from ablated material within the area of overlapping laser spots caused stitch lines. Molpeceres et al. [13] used nanosecond pulsed excimer (KrF, 248 nm) and diode-pumped solid-state (DPSS, 355 nm and 1064 nm) laser sources to ablate amorphous-silicon (a-Si) and ITO thin films deposited on Tempax® glass substrates. After the laser ablation on ITO and a-Si films of 500–700 nm and 160 nm thick, respectively, using the 355 nm laser source, the ablated ITO films showed excellent groove geometry due to similar values between its photo energy (3.49 eV) and material absorption (3.6–3.8 eV). The ITO film ablated by the 1064 nm laser source had a poor groove geometry because thermal affection caused the ablated film debris to accumulate on the groove edges. Račiukaitis et al. [14,15] used high repetition-rate picosecond lasers at the various wavelengths to pattern ITO films deposited on glass substrates. The removal of ITO films by a 266 nm laser radiation occurred when the laser fluence exceeded the threshold of 0.2 J/cm^2, whereas the ablation threshold for the 355 nm laser radiation was higher (above 0.46 J/cm^2). These results showed that the ablated trench had a minimum recast ridge and surface was contaminated using the ultraviolet (UV) laser radiation with a fluence close to the ablation threshold.

This study focuses on electrode patterning using a beam homogenizer in a UV laser system and investigates the interaction between square laser beams and FTO thin films deposited on glass substrates. The laser processing parameters to ablate FTO films involved in this experiment include laser fluences, pulse repetition frequencies, and feeding rates of a motorized platform. The laser pulse repetition frequency and the feeding rate of the motorized platform were used to calculate the overlapping rate of the laser spot and to control the patterning quality. The line width and depth, edge quality, and three-dimensional (3D) topography of the patterned FTO films were observed and analyzed using a confocal laser scanning microscope. All sheet resistance values of the film surfaces near the patterned line edge were measured using a four-point probe instrument.

2. Experimental details

2.1. Square top-hat UV laser processing system

The FTO electrode patterning ablated by square top-hat beam spot using a diode-pumped Q-switched Nd:YVO_4 laser processing system (Coherent Inc. model AVIA 355-14) is investigated in this study. The laser system was specially designed to emit a square beam with a uniform energy distribution. Fig. 1(a) shows a schematic diagram of the instrumental setup used to pattern the FTO electrode layer deposited on glass substrates. A UV laser beam with a wavelength of 355 nm was focused on the sample surface using four reflective mirrors, a beam expander, and a beam homogenizer. A beam homogenizer consisting of two square acylindrical lenses and a condenser lens were used to spatially homogenize the beam, and to convert a Gaussian beam profile (TEM_{00}) into a uniform square top-hat beam profile. Fig. 1(b) shows the function of a refractive free-form aspherical optical element to modulate the beam shaping in one direction. The surface of the acylindrical lens was equal to the aspherical shape in one direction.

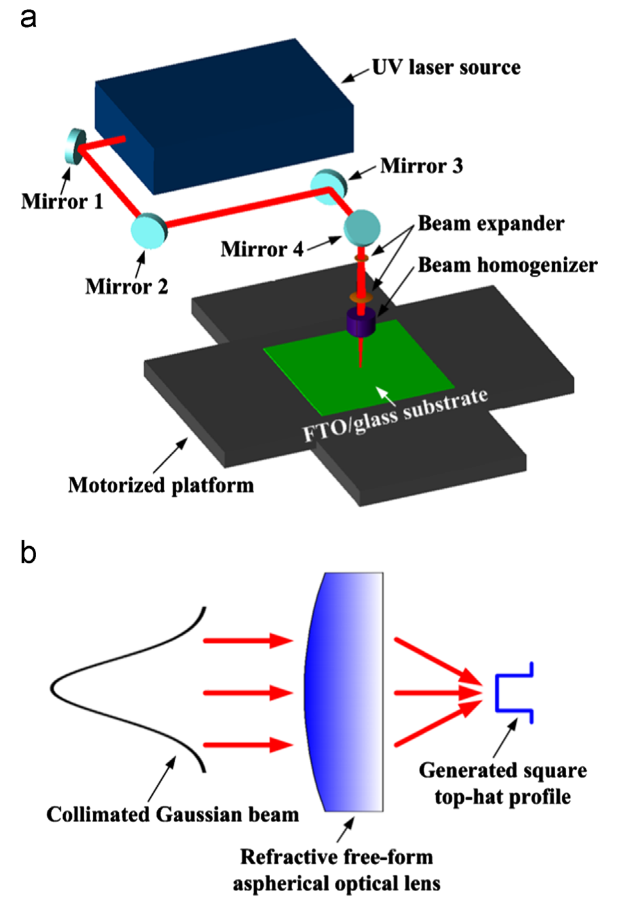

Fig. 1. Schematic setup of the UV laser processing system (a) and the operating principle of a free-form phase shifting element to transfer a Gaussian beam profile into a uniform square top-hat beam profile (b).

The nominal laser-beam diameter at the exit port of the UV laser source was approximately 3.5 mm. The average laser power was 14 W at a pulse repetition frequency of 100 kHz. The pulse repetition frequency and pulse width ranged from 1 kHz to 300 kHz and 26 ns to 38 ns, respectively. The laser average output power, the pulse repetition frequency, and the feeding rate of the motorized platform were controlled by a human machine interface (HMI), allowing automatic control during the laser patterning process.

The laser beam profile is a major factor of laser patterning parameters because the profile strongly affects the quality of ablated patterns. To obtain a uniform-intensity distribution beam and improve the removal efficiency, a beam homogenizer (LIMO GtoT_355 series 410.011) was installed in this UV laser processing system. After the beam homogenizing and shaping setup, the 2D image of the laser beam profile was measured by a beam profile instrument and the results were shown in Fig. 2. Results demonstrate that the 2D beam profile had a nearly square top-hat profile with a symmetric and uniform energy distribution. The square spot size of full width at half maximum (FWHM) was approximately 70 μm × 70 μm. The working distance of the beam homogenizer was 92 mm, and the focus depth of laser spots adjusted to pattern the FTO electrode layer was approximately ±70 μm.