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Ablation depth control with 40 nm resolution on ITO thin films using a square, flat top beam shaped femtosecond NIR laser

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ABSTRACT

We reported on the ablation depth control with a resolution of 40 nm on indium tin oxide (ITO) thin film using a square beam shaped femtosecond (190 fs) laser (λ_p = 1030 nm). A slit is used to make the square, flat top beam shaped from the Gaussian spatial profile of the femtosecond laser. An ablation depth of 40 nm was obtained using the single pulse irradiation at a peak intensity of 2.8 TW/cm^2. The morphologies of the ablated area were characterized using an optical microscope, atomic force microscope (AFM), and energy dispersive X-ray spectroscopy (EDS). Ablations with square and rectangular types with various sizes were demonstrated on ITO thin film using slits with varying *x*–*y* axes. The stereo structure of the ablation with the depth resolution of approximately 40 nm was also fabricated successfully using the irradiation of single pulses with different shaped sizes of femtosecond laser.

1. Introduction

Indium tin oxide (ITO) is widely used as a transparent conducting electrode for the fabrication of optoelectronic products such as flat panel displays, touch panels, solar cells, and organic light-emitting devices (OLEDs) due to its high electrical conductivity and high transmittance in the visible and near infrared (NIR) wavelength range [1]. In the field of display fabrication and assembly, methods of controlling the micromachining depth of the ITO thin films deposited on substrates as glass or Polyethylene terephthalate (PET) were crucial for enhancing the optical transmittance in order to reduce the power consumption and for improving the electrical conductivity of ITO thin films in order to reduce the resistance [2]. Although methods of patterning the ITO thin film structure are predominantly surface monolithic processing techniques such as photolithography [3], there have been technical issues in patterning on ITO thin films in the terms of complexity, speed, and cost; the patterning also requires sophisticated facilities and costly equipment as well as environment-unfriendly toxic chemicals [4]. If direct patterning on ITO thin films with depth controlled and well defined morphologies can be accomplished easily, it could be used at a low cost in various applications such as OLED displays, flat panel displays, touch panels, solar cells, smartphones, and various electronic devices [5].

The interactions between ultrashort, high-intensity lasers and several materials have become significant areas of interest since the advent of high-intensity femtosecond lasers. Laser ablation is the technology to remove target material from the substrate through absorbing the laser energy, which can achieve the desired area of clean patterning due to the local heating and material removal [6]. In general, ultrashort pulse lasers induce small thermal defects in the material compared with the irradiation of long pulse lasers [7]. Above all, femtosecond lasers induce a precise ablation threshold with reduced laser fluence due to their high peak intensity with low pulse energies via the ultrashort pulse duration. These attractive characteristics of femtosecond lasers have stimulated the flexibility of laser micro-machining and minimized thermal defects such as micro-cracks and debris. Thus, femtosecond lasers have been used as accurate material removal tools in optoelectronic product fabrications due to their minimized thermal effects on the materials [8]. Recently, significant attention has focused on making the control of the ablation depth on ITO thin films become more efficient, particularly for transparent electrodes in high-density optoelectronic devices [9]. Although several experiments of laser ablation on ITO thin films have been reported

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[10–12], the depth controls of the ablation area have not yet been studied in detail, primarily because laser beams with circular Gaussian spatial profiles have typically been used in previous studies [13,14]. Gaussian beams have significantly different spatial intensity profiles between the center and edge of the focused beam. Recently, some research groups have reported laser ablation on ITO thin films using several beam shaping techniques that were applied to solar cells [15,16] and electrical devices [9]. However, experimental results have not yet been reported for well-defined, square-shaped ablation structures on ITO thin films with the depth control of several tens of nanometers using the NIR femtosecond laser.

In this paper, we reported on the ablation depth control with a resolution of 40 nm on indium tin oxide (ITO) thin films through controlling the pulse numbers of the femtosecond (190 fs) laser (λ_p = 1030 nm) with a square beam. The beam that was shaped to have a flat top from a Gaussian beam passed through a slit was applied to the femtosecond laser patterning of ITO films. The morphologies of the ablated areas were characterized using an optical microscope, atomic force microscope (AFM), and energy dispersive X-ray spectroscopy (EDS). Square and rectangular ablations with different sizes were fabricated on ITO thin films using a slit with varying *x*–*y* axes. The stereo structure of the ablation with a depth resolution of approximately 40 nm was also demonstrated through controlling a single pulse with varying sizes of the square beam shaped femtosecond laser. Although femtosecond laser ablations on ITO thin films have been investigated previously, to the best of our knowledge, this is the first report of the ablation depth control with a 40 nm resolution. This process might be a useful tool for high precision machining on ITO thin films in electronic devices and display components using high-intensity femtosecond lasers.

2. Experimental

The experimental setup was presented in Fig. 1. In the experiments, a commercial regenerative amplified mode-locked Yb:KGW laser (Model no.: S-Pulse HR, Amplitude Systemes, France) with a central wavelength of 1030 nm, a pulse duration of 190 fs, a repetition rate of 30 kHz, and a maximum pulse energy of 66 uJ was used. The pulse energy was measured using a power meter. The beam had a diameter of 3 mm and the M^2 quality parameter was 1.2. The laser beam was focused using an objective lens with 0.42 NA (Model no.: M Plan Apo NIR 50x, Mitutoyo). The laser beam was focused at the front of the sample in order to avoid direct ablation on the ITO by the lens. Then, the propagating defocused, shaped laser beam was irradiated via the slit onto the surface of the ITO thin film as depicted in Fig. 1(b). The ITO thin film sample was fixed on a micro positioning stage controlled by a computer, and it could be moved in the directions of *x*-, *y*-, and *z*-axes. The pulse energy of laser was controlled using neutral density filters. The femtosecond laser beam had linear polarization and the beam profile of spatial Gaussian. As seen in Fig. 1, the Gaussian beam was shaped via the slit in order to have a flat top. The flat top beam had a square shape due to the slit control. In this study, the following laser ablation experiments were conducted in order to control the ablation depth of the ITO thin film on the glass substrate using the shaped flat top beam and to accomplish selective removal between the ITO thin film and glass substrate.

Information regarding the sample was presented in Fig. 2. ITO thin films with a nominal thickness of 150 nm and a transmittance of 90.5% (In_2O_3:SnO_2 = 90:10) were deposited on the glass substrates (20 × 20 × 1.1 mm) using a DC magnetron sputtering system. The six sides of the glass substrate were optically polished. The sheet resistance of 10–15 Ω was used in the experiments. The ITO thin film was a commercial sample provided by WOOYANG GMS Korea (www.solaronix.co.kr).

The surface characteristics of the ablated ITO thin films were observed using an optical microscope (MM-20, Nikon), and the three-dimensional data and cross-section samples perpendicular to the ablated ITO thin film patterns were prepared using a scanning probe microscope (XE-100, Park Systems). Finally, the energy dispersive spectroscopy (Shrion, FEI) was used to identify the remained elements at the selective ablation area between the ITO thin film and glass substrate.

3. Results and discussion

In this study, experiments were conducted to control a single pulse using the flat top beam shaped by a slit in order to control the ablation depth. The well-defined localization of the photon energy is crucial for removing the thin layers from the substrate

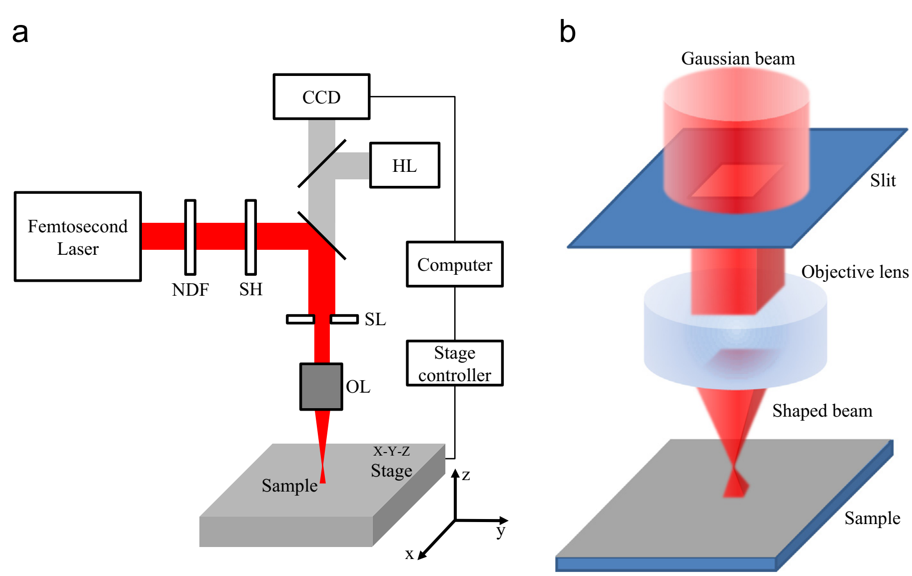

Fig. 1. (a) Schematical representation of the femtosecond laser system with a slit used in the experiment (NDF: Neutral density filter, SH: Shutter, HL: Halogen lamp, SL: Slit, OL: Objective lens). (b) Basic concept of the shaped beam using the slit.