Doctoral Thesis

A study on the quality improvement of transparent electrode micromachining using beam shaped femtosecond laser for advanced AMOLED repair process

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NANOMECHATRONICS

August 2018

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A Dissertation Submitted in Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy

May 2018

UNIVERSITY OF SCIENCE AND TECHNOLOGY
Major of Nanomechatronics

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ACKNOWLEDGEMENT

2012년 3월 이 곳에 처음 와서, 2018년 8월에 제 인생이라는 여정의 조그마한 하나의 막을 내리려 합니다. 현실로 다가오니 만감이 교차합니다. 과정을 뒤돌아보고 이루어진 결실을 다시 되새기며, 부족한 모습에 매우 창피하기도 하지만, 그래도 '결실'이라는 단어에 진심 어린 감사의 마음을 깊게 가지게 됩니다.

하나하나 생각해보니 매우 감사한 분들이 많은 것 같습니다. 드리지는 못하고 항상 받고만 살아왔던 것 같습니다. 먼저, 정말 긴 시간 동안 언제나 학업적인 지도와 조언, 그리고 인생의 조언까지 아끼지 않으신 저의 지도박사님 조성학 박사님께 깊은 감사를 드립니다. 그리고 바쁘신 와중에도 저의 심사에 시간을 내어주신 제태진 박사님, 최두선 박사님, 김재구 박사님, 김주한 교수님께도 머리 숙여 깊이 감사 드립니다. 항상 든든한 거목과 같이 따뜻함을 주셨고 힘들 때마다 유쾌한 술 동무가 되어주셨던 진우형님, 나에게는 백과사전과 같은, 무엇을 물어보아도 그리고 부탁해도 언제나 불평 없이 길잡이가 되어준 내 지식의 스승이자 친구 원석이 에게도 매우 감사 드립니다. 마음을 닫고 살았던 초반에 마음의 위안이 되어주고 즐거움이 돼주었던 이제는

형제와도 같아진 석영이, 대경이, 영관이, 충우도 정말 고맙다. 지금은 같은 곳에 있지 않지만, 든든한 지원군이 되주셨던 지욱이형, 그리고 두 아이의 엄마가 된 고마운 주희누나, 가끔은 오히려 형 같았던 인성좋은 준수, 예의 바르고 항상 명랑하고 밝았던 다솜이도 생각이 납니다. 아마 이 글을 읽지 못할테지만 항상 매일이 행복하길 기도하겠습니다.

힘들 때마다 힘이 되어주었던 우리 신상도 머스마들, 현수, 성무, 기웅아 대건아. 고맙다. 또 각지에서 열심히 살아가고 있는, 자주 인생의 낙이 되어 주었던 그리고 낙이 되어 줄 태준이, 윤표, 현호, 천호, 성완이도 정말 고맙다.

나의 미래의 아내 현지야, 이 곳에서의 시작부터 끝까지 함께해주어서 고맙다. 항상 곁에서 그늘이 되주었기에 정말 힘든 시간도 그리고 지친 내 모습도 너의 믿음을 벗삼아 살아 갈 수 있었다. 말로 다 표현할 수 없지만 정말 고맙다. 마지막으로 저의 부모님. 감사드립니다. 어찌 말로 형용할 수 없을 정도로 감사드립니다. 그리고 죄송합니다. 항상 존경하고 사랑합니다. 오래오래 사셨으면 좋겠습니다.

초록

극초단 레이저는 이전의 레이저와 비교하여 극히 짧은 펄스폭으로 인해 재료 가공 시 생기는 열이 가공부 주위에 전달 되기 전에 가공이 완료되어 비열적 가공이 가능하다는 이점을 가지고 있기 때문에 마이크로 크랙과 데브리와 같은 손상에서 자유로울 수 있다. 이로 인해 높은 가공 정밀도를 가질 수 있으며, 초미세가공의 유리한 특성을 가진다. 또한, 극초단 레이저가 가지고 있는 비선형 광학현상에 의해 이론적으로는 파장에 상관없이 모든 재질의 가공이 가능한 재료 무의존성의 큰 특징이 있다. 하지만, 기본적으로 레이저광 방출 시, 가우시안 분포를 갖는 빔을 그대로 가공에 사용하면 빔의 중심부와 주변부의 인텐시티가 크게 다르기 때문에 가공패턴의 균일도가 낮고, 가공 깊이의 조절이 어려울 뿐만 아니라 고종횡비의 가공이 어렵다.

본 연구에서는 유리 기판 위에 증착되어있는 ITO에 대하여 펨토초 레이저 빔의 경로에 슬릿을 구성하여 가우시안 분포를 갖는 레이저 빔을 사각형모양의 quasi-flat top 형태로 쉐이핑 하고, 쉐이핑 된 빔과 펄스 수 조절을 이용하여 가공 패턴의 균일도를 높이고 가공 깊이를 조절하기 위한 연구를 수행하였다. 2.8 TW/cm^2 의 Peak intensity에서 펄스 한

발로 40 nm 의 가공 깊이 조절이 가능함을 보았으며, 슬릿을 이용하여 정사각형 뿐만 아니라, 직사각형 및 스테레오 구조의 입체형상을 구현하였다. 또한, 1.3 J/cm^2 의 플루언스에서 가우시안 빔과 준 플랫탑 빔을 이용하여 가공성 연구를 진행하였다. 두 빔 프로파일을 이용한 가공에서 모두 6 발의 펄스가 조사되었을 때, 유리기판에 손상없이 선택적 가공이 진행되었음을 확인하였다. 가우시안 빔을 이용하였을 때에는, 1발에서 6발까지 패턴의 폭이 9.17 ㎛ 에서 9.99 ㎛ 까지 점차 증가하였으나, 준 플랫탑 빔을 이용하였을 때에는, 10 ㎛ 의 패턴 폭이 고정됨을 확인 할 수 있었다.

ABSTRACT

Femtosecond laser ablation has interesting characteristics for micromachining, such as non-thermal interaction with materials, high peak intensity, precision, and flexibility. Thin films based on application are of interest in many industrial fields. The laser selective patterning of thin films is often used to create certain functions. The interaction of ultra-short laser pulses with thin films is now an important area of research on laser material interaction. The interaction between the laser pulse and the thin transparent conductive oxide is important for the manufacture of touch panel sensors, light emitting devices and optoelectronic devices. This thesis presents the results from a study of thin transparent conductive oxide (TCO) micromachining using the femtosecond laser. The experiments were performed on indium tin oxide (ITO), and ITO remains an important element in many applications of TCO in the industry sector.

We report 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 (λp = 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 is obtained using the single pulse irradiation at a

peak intensity of 2.8 TW/cm2. The morphologies of the ablated area are 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 are 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 is also fabricated successfully using the irradiation of single pulses with different shaped sizes of femtosecond laser.

Therefore, we compares the ablation morphologies obtained with a femtosecond laser of both Gaussian and quasi-flat top beam profiles when applied to indium tin oxide (ITO) thin films for the purpose of OLED repair. The laser fluence is optimized for patterning at 1.38 J/cm2. With the Gaussian beam, the pattern width of the ablated area is shown to range from 9.17 to 9.99 ㎛ when the number of irradiation pulse increases from one to six. In contrast, when slit control is used to obtain a quasi-flat top beam, the ablated pattern width remains constant at 10 ㎛, despite the increase in the number of pulse. The improved surface roughness is correlated with the quasi-flat top beam through measured Ra values. Furthermore, when using the Gaussian beam, the minimum resolution of the controllable ablation depth on the ITO thin film is found to be 60 nm. In contrast, when the quasi-flat top beam is used, the minimum ablation depth decreases to 40 nm.

Keywords: Femtosecond laser, Beam shaping, ITO thin films, Ablation, Morphology

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*A thesis submitted to committee of the University of Science and Technology in a partial fulfillment of the requirement for the degree of Doctor of Philosophy conferred in August 2018.

Contents

1. Introduction

Femtosecond lasers have opened a new era in micromachining. Its precision, high peak power, flexibility, and non-thermostatic interaction provide many benefits in the micromachining of applications for optoelectronic devices. Femtosecond lasers with a pulse duration of ~ 100fs are widely used in micromachining as most of the secondary damage to the dielectric material is removed and the metal has a smaller heat affected area [1,2]. The key characteristics of a femtosecond laser pulse are its very high peak strength (> 10^{16} Wcm^{-2}) and its rapid deposition of energy into the material.

The benefits of femtosecond laser pulses are due to the advantage of pulse duration τ ~ 150fs to being shorter than the equilibrium τ_{ei} 1–10ps between electron and lattice ion subsystems. Moreover, the time τ_h required to reach the depth of the optical penetration for the electron thermal energy diffusion is several times longer than that of τ [3]. A short duration can eliminate the influence of material hydrodynamic motion during laser irradiation. In addition, the short pulse can prevent the shielding of the laser beam by the plasma from the cut surface, which can maximize the absorption efficiency [4].

Because of these benefits, femtosecond lasers provide a very flexible way to manufacture devices made of virtually all types of materials. Femtosecond lasers have proven to be a very effective treatment tool for such difficult materials for machining and also for a wide variety of others.

1.1 Laser micromachining

Since the invention of lasers in 1960, materials processing using pulsed lasers have become a subject of much study. Today, lasers are used as an efficient and validated tool in many industrial processes, such as heavy industry cutting, curing and welding. However, lasers are not yet a universal tool in the micro and nano manufacturing industries. In general, special lasers are required for certain microstructure applications. For example, excimer lasers are used for micromachining of ceramics and polymers, and ND:YAG lasers are used for micro-drilling and marking. In addition, the use of lasers with a pulse duration ranging from nanoseconds to micro-seconds, especially for metal materials of precision microstructure, is limited by thermal or mechanical damage. These restrictions have stimulated extensive research activities to minimize additional damage and thermal diffusion in the field of irradiation with ultrashort laser pulses, including investigations into the ablation of dielectric materials and metallic materials and attempt to make sub-micrometer structures. Femtosecond lasers are an excellent and universal tool for micro processing. Metal, semiconductor, genetic, polymer, transparent, and opaque materials can be micro-structured with femtosecond pulses to eliminate post treatment. Moreover, the surrounding area is not affected or damaged, opening possibilities for new applications.

Femtosecond laser micromachining is the process of using the femtosecond laser pulse to induce a micro-sized structure to the surface or to the volume of solid materials. The most common laser system used for micromachining is the Ti:Sapphire laser. This type of laser uses a titanium-doped sapphire crystal that has been poisoned by titanium as a gain medium and has a center wavelength near 800 nm. Other fiber-based and solid-state femtosecond lasers have also recently become a good source of micromachining. Ti:Sapphire Laser was been extensively studied for the interaction of femtosecond pulse using absorptive and transparent materials. Ablation is demonstrated in both absorptive and transparent materials, bulk modifications are mainly indicated by refractive index changes, and are widely represented as transparent materials. Micromachining of absorbing materials has been applied to drilling, surface defect removal and photolithographic mask repair [5-7]. The bulk refractive index change of transparent materials has been mainly used to fabricate optical waveguides and waveguide based optical devices [8-10]. In addition, micromachining of the transparent material has found application in the manufacture of microfluidic channels [11-13].

In recent years, micromachining by nanosecond, picosecond, and femtosecond laser has been extensively studied and has been successfully accomplished to various degrees [14-16]. Compared to nanosecond and picosecond lasers, femtosecond Lasers are considered an ideal tool for precision micromachining. The femtosecond laser deposits energy in the material in a very short time, securing a very small heat-affected zone (HAZ) and minimizing the energy loss for the bulk material [17]. On the other hand, in the case of nanosecond and picosecond laser machining, heat relaxation waves propagate in bulk to produce a relatively large layer of molten material, some of which are not removed but are fixed again to form recast layers, debris, burrs and craters [18-21].

1.2 State of study in laser ablation on ITO thin films

For most applications, the ITO layer must be configured with a special pattern. Wet etching, plasma etching, and laser direct writing are the main adopted methods in the industry. Wet etchings provide high yields on the process but require complex steps such as high equipment investments and resist coatings, optical lithography, developing, and etching [22,23]. In the case of large area devices such as solar cells, in addition to isotropic etching and selective grain-boundary etching, the tendency to generate different etch rates depending on the deposition method tends to be difficult [24]. Alternatively, plasma etching provides high resolution but may require corrosive gases and photolithography [25]. Laser direct writing for high speed, mask-less and environmentally friendly properties, has earned intensive research attention.

The earliest research on laser patterns for ITO thin films used KrF excimer lasers with a pulse length of 248 nm. The authors showed the possibility of laser selective removal of ITO film on glass and noted that thermal evaporation was the cause of film loss [26,27]. Yavas and colleagues used pulse DPSS lasers with different wavelengths at 1047 nm, 532 nm, 349 nm and 262 nm at 15 ns pulse duration to perform the processing of ITO thin films [28-30]. In the experiment, the shoulder was observed around the etching zone, which is about 100 nm higher than the original surface of this layer. The formation of these shoulders was considered a property of the surface tension gradient of the molten liquid flange in the situation of the Gaussian beam. On the surface, thermal evaporation has been identified for the film removal for all wavelengths.

Askhenasi et. al. has experimented with 800nm wavelengths with various pulse lengths from 150ps to 5ps on glass samples coated with 150nm ITO film [31]. Raciukaitus presented the results of the ITO pattern experiment using Picosecond lasers at visible wavelengths of 532 nm, 355 nm and 266 nm [32]. Risch reported a similar patterning process using picosecond lasers [33]. Harrison et. al. and Chen et. al. analyzed the ITO thin film pattern with a spatial laser beam shaping from the Gaussian beam to the top-hat beam to reduce the shoulder line [34,35]. Most investigations to date show that thermal evaporation is a major cause of this film removal.

However, with some exceptions reported, Szorenyi et. al. removed the ITO film from the glass substrate using a 248 nm excimer laser [36]. They found that thin films were more likely to be removed by mechanical delamination in a cleaner way, as observed for the studied 70nm and 160nm processes. The thick film was considered to be removed by thermal evaporation, e.g. from the experiment, with 400 nm and 500 nm films. Thermal elasticity showed that ITO thin film was isolated from the glass substrate by a spatially modified pulse Nd:YAG laser beam with a wavelength of 1064 nm and a pulse width of 6 ns [37].

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