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Nanosecond pulse laser scribing using Bessel beam for single shot removal of transparent conductive oxide thin film

Byunggi Kim [a,*], Ryoichi Iida [a], Duc Hong Doan [b,*], Kazuyoshi Fushinobu [a]

[a] Department of Mechanical and Control Engineering, Tokyo Institute of Technology, Mail Box I6-3, Ookayama 2-12-1, Meguro-ku 152-8552, Japan
[b] Advanced Materials and Structures Laboratory, University of Engineering and Technology, Vietnam National University, Hanoi, 144 Xuan Thuy, Cau Giay, Hanoi, Viet Nam

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ABSTRACT

Nanosecond laser Bessel beam scribing on the TCO thin film was investigated to improve processing precision and robustness of optical system. Fundamental wave (1064 nm) of Nd:YAG laser was shaped into high-quality Bessel beam by using novel optical system consisting of axicons and convex lens. Spatial FWHM of the beam was only 1.5 μm in the present context, and significantly precise scribing with minimum width of 2.3 μm was achieved on 600–700 nm-thick FTO film with electrical isolation. Furthermore, due to the critically deep focal length of millimeters-order, robustness on sample positioning was greatly improved. Additionally, experimental results showed that single shot removal of entire film can be achieved using film side irradiation unlike conventional Gaussian beam. Temperature distribution during the process was calculated by a numerical model in which we have taken into account beam propagation inside the film to give comparison with a Gaussian beam irradiation. The calculation results showed that only Bessel beam is self-reconstructed behind plasma shielding so that entire film can be removed by single shot. Our findings suggest that Bessel beam can be used for efficient IR scribing with significantly high quality without selecting substrate material.

1. Introduction

Recent spread of opto-electronic devices in various industrial field has boosted increasing use of transparent conductive oxide (TCO) thin films such as indium tin oxide (ITO), zinc oxide (ZnO), and fluorine doped tin oxide (FTO). Its one of the most representative applications is thin film photovoltaics (TFPV). Because of large size of TFPV, nanosecond pulse laser scribing, which can be implemented easily with significantly low cost and fast fabrication speed, has been used widely for patterning process of thin film layers [1–5]. However, scribing width less than several tens of micrometers cannot be obtained by traditional Gaussian beam irradiation. As scribed area of TFPV devices cannot generate electricity with sunlight irradiation, narrow scribing is a key technology to high energy conversion efficiency. In 2014, few micrometers wide femtosecond laser scribing was reported by Krause et al. [6]. Their findings showed that real cold ablation of fs laser, which is governed by interaction between material's electrons and laser, will lead to remarkable progress in thin film scribing industry. However, implementation of fs laser still require too large cost compared to ns laser. Therefore, we have focused on improving ns laser processing by controlling optical parameters such as spatial profile of the beam [7–9].

In general, it is known that optically thick film is removed with substrate side irradiation which leads to stress-assisted ablation induced by steep temperature gradient at film/substrate or film/film interface [1,10,11]. On the other hand, we experimentally demonstrated that under near-IR laser irradiation optically thin film such as the TCO is removed thermally from its surface in our previous study [12]. Irrespective to irradiation direction, surface temperature of the TCO film increases considerably because of heat conduction to the substrate. For ns laser processing, as plasma shielding accompanied by thermal ablation at the TCO thin film surface interrupts absorption of laser beam, substrate side irradiation has great advantage on complete film removal process with single shot. However, use of substrate side irradiation is limited to the cases that substrate material is rigid and transparent. As plasma shielding is less significant with short wavelength [13], film side irradiation of ultraviolet laser can be used in the case that film thickness is several tens of nanometer. However, film removal process using UV laser is strongly dependent on film thickness and sensitive to substrate damage.

In the present study, we report experimental achievements of Bessel beam scribing of TCO thin film, taking advantage of narrow

* Corresponding authors.
E-mail addresses: kim.b.aa@m.titech.ac.jp (B. Kim), doan.d.aa.eng@gmail.com (D. H. Doan).

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beam width and deep focal depth to improve precision of scribing and robustness of optical system. In addition, propagation of Bessel beam wavefront generated by axicon was of interest, reconstruction of beam intensity behind obstacle [14] is expected to help avoiding plasma shielding to some extent. Experimental data was analyzed numerically with the thermodynamic model with consideration of beam propagation inside the film. The experimental and theoretical investigations in this article will demonstrate advantages of Bessel beam in the TCO thin film scribing process.

2. Experimental setup

Fig. 1 shows schematic illustration of experimental setup. The near-IR wavelength of 1064 nm was used from Nd:YAG laser with pulse width of 5.5 ns (FWHM). Original spatial beam profile was nearly top-hat. In order to increase quality of the Bessel beam, the original beam was expanded and shaped into perfect circle by being passed into circular aperture. Plane wavefront can be obtained by this manipulation. Demagnifying telescope consisting of axicon-convex-convex lenses (in order) is generally used to obtain narrow quasi Bessel beam [15–17]. In the present context, we replaced second convex lens with another axicon. Bessel beam generated by this method has slightly spherical wavefront so that beam width changes on the optical direction. Nevertheless, this transform is more advantageous with the extremely longer focal depth and easier optical adjustment free from using two convex lenses. Hence, we adapted this combination considering robustness of the optical system. For the Gaussian beam irradiance, conventional convex lens focusing with $f = 100$ mm was used instead of Bessel beam shaper.

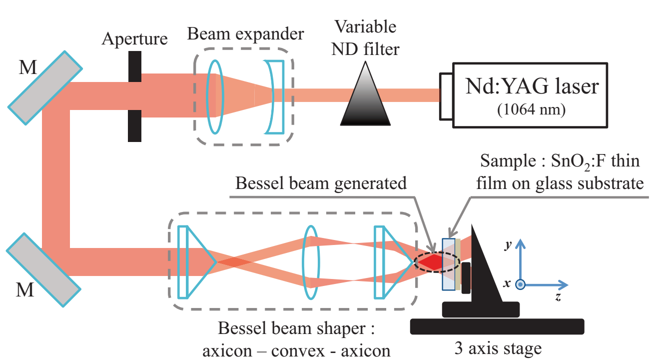


Fig. 1. Schematic illustration of experimental apparatus. A modified demagnifying telescope consisting of two axicons and a convex lens was used to shape narrow Bessel beam with crucially deep focal depth.

Table 1
Experimental conditions.

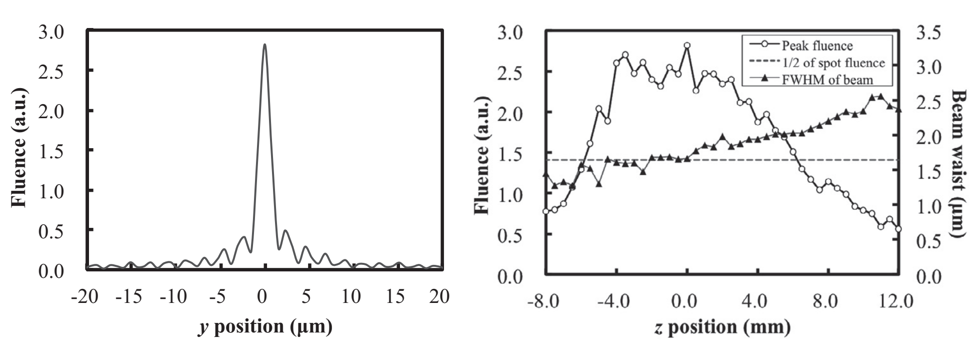
Parameter	Unit	Value
Wavelength, λ	nm	1064
Pulse width, t_p	ns	5.5
Focal length, f	mm	100
Bessel beam FWHM	µm	1.3–2.0
Gaussian beam waist	µm	24
FTO thickness, h	nm	600–700
Substrate thickness	mm	1.8

Fig. 2 indicates Bessel beam profile and change of beam waist and peak fluence along the optical axis. Spot with the largest peak fluence was determined as a focal spot. As experimentally obtained Bessel beam has imperfect separation between 0th order peak and 1st order lobe, we used FWHM instead of 13.5% width for Bessel beam. FWHM of generated Bessel beam was 1.3–2.0 µm, and focal depth (determined based on the area with fluence larger than half of the peak fluence) was measured as 11.5 mm. On the other hand, beam waist and focal depth of the Gaussian beam in this study were 24 µm and 1 mm. Therefore, Bessel beam had crucial advantages with extremely narrow beam width and deep focal depth compared to conventionally focused Gaussian beam.

The FTO thin film with 600–700 nm thickness on the glass substrate (Asahi VU type) was used as a sample. Grooves were fabricated by scanning of single shots, while irradiation increment was changed as an experimental parameter. By adjusting z-position of the sample, effective working distance of the optical system was investigated. Scanning electron microscopy (SEM), and confocal optical microscopy were used to evaluate the surface and shape of grooves. Also, electrical insulation of grooves was checked. All the experiments are performed under room condition. Experimental conditions are tabulated in Table 1.

3. Numerical method

In our previous study [12], temperature distribution was investigated using a thermal model considering plasma shielding, and it was found that melting depth has a critical relationship with crater depth. Therefore, influence of plasma shielding on source term of the heat equation was investigated using beam propagation method in this study. As influence of beam profile on temperature distribution during film side irradiation was of interest, only the numerical analysis in the case of film side irradiation, in which mechanism of material removal can be considered simply as vaporization and melt-ejection, was performed.



(a) Bessel beam profile at focal point (b) Beam waist and peak fluence along optical axis

Fig. 2. Spatial profiles of the Bessel beam in the present context. Spatial FWHM and focal depth of the beam were measured as 1.3–2.0 µm and 11.5 mm respectively.