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【Short Paper】

# Bessel beam laser-scribing of thin film silicon solar cells by ns pulsed laser

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**Abstract**

The thin film solar cells have attracted wide attentions for its low implementation cost and representative flexibilities such as selectivity of materials and fabrication conditions. On the thin film solar cells, width of the grooves of pattern 1, 2 and 3 are important factors to determine its efficiency and cost. In this study, as P1 fabrication process, ablation experiments of Transparent Conductive Oxide (TCO) coating on glass substrates of thin film solar cells are conducted using Bessel beam nanosecond laser pulse. The purpose is to assess the capability of the Bessel beam in laser scribing of thin film solar cells from the glass side. In order to fulfill this purpose, a Gaussian beam of 1064 nm nanosecond Nd:YAG was shaped into Bessel beam with few-micrometers beam width, using fluidic optical device. The Bessel beam, is used to backside laser ablation of a thin film. The function of the optical system and products fabricated with Bessel beam are compared with those of Gaussian beam. Experimental results show that: in the single pulse ablation, the vias ablated by Bessel beam have smaller variations in diameter and depth than those of Gausian beam at the same laser spot and peak fluence level. Furthermore, a few micrometer wide, perfectly isolated groove could be fabricated with Bessel beam. The paper concludes with suggestions for future research and potential application.

***Key words***: Bessel beam, Back-side scribing, TCO, Solar cell

## 1. Introduction

Laser ablation of TCO ($SnO_2$: F) coating on glass substrates is of special interest as these films are used as a transparent front contact for the thin film solar cells (TFSC). On the TFSC, in order to archive suitable current voltage characteristic and to reduce the ohmic losses, the panel is separated into multiple cells, which are connected in series. This fabrication process involves multiples coating and 3 steps patterning named P1, P2 and P3. During the P1 process, the TCO coating is scribed in line structure and perfectly isolated for the monolithic serial interconection. On the TFSC, width of the grooves of power-generating thin film layers is one of the most important factors to determine its efficiency because size of dead area, where cannot generate electricity, critically depends on it. Traditionally, mechanical scribing is used to fabricate a channel with typical width of hundreds of micrometer and a typical death zone of ~500 micrometers. Compared with mechanical scribing, laser scribing is able to fabricate a smaller channel width, typically ~ few tens of micrometers, so the dead zone can be much smaller, ~240 micrometers, and therefore higher efficiency (Booth et al. 2010 and Burn et al. 2012). However, traditional scribing process with nanosecond laser pulse, which is governed by heating, melting and vaporizing of TCO, has been show to leave a heat affect zone (HAZ) with poor isolation. In order to reduce the HAZ, ultra-short laser pulse, sub-picosecond pulse, is introduced with an optimization of laser parameters. However, industrial adoption is limited due to the immature process and higher cost of ownership which is typically 2x a typical nanosecond laser scribing process (Booth (2010) and Burn (2012)).

Backside scribing, which was first introduced by Avagliano et al. (1994), shows great advantages of HAZ free, recast free, shape edges and perfectly isolated (Avagliano et al. 1999 and Heise et al. 2011). In the backside laser ablation process, laser beam is induced from the glass side and is focused on the surface between glass and TCO coating layer. And the TCO layer is removed by thermal stress induced fracture (Heise et al. 2011). As material is removed without melting and evaporation processes, the fabrication is carried out at the small laser energy, without

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recast and debris. However, backside scribing technique also has an disadvantage of high complexity of the setup the optical system. As the smaller laser spot size, the shorter focal depth. Therefore, fabrication of a channel with a few micrometer wide is challenge work. The purpose of this study is to assess the capability of the Bessel beam in laser scribing of thin film solar cells from the glass side to fabricate a few micrometer groove in P1 process.

## 2. Experimental details

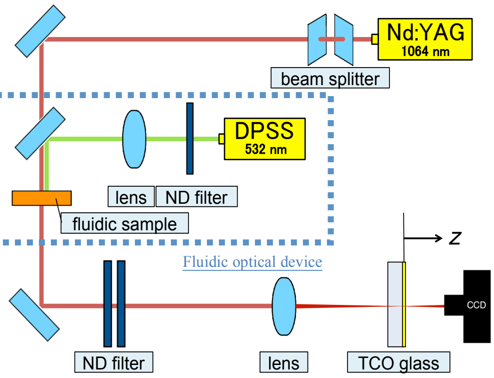


Fig. 1 Schematic illustration of the experimental set up for shaping the processing laser to Bessel beam and using it for P1 fabrication process in TFSC

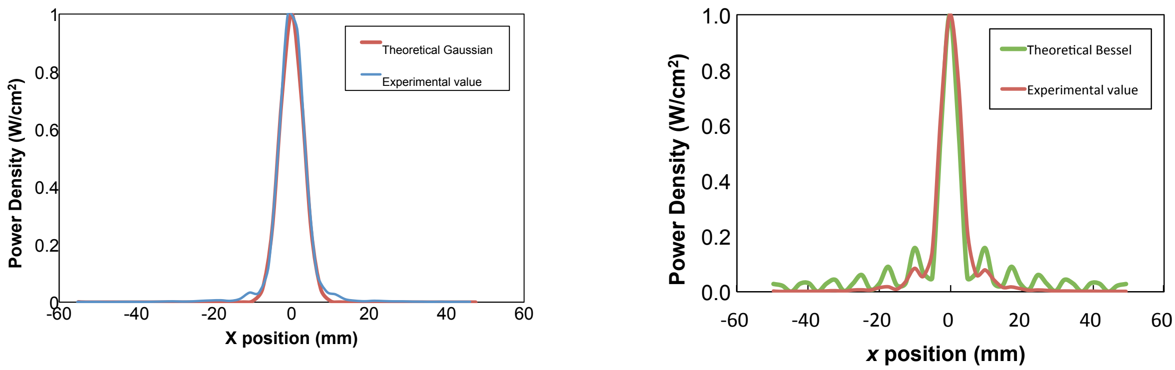


Fig. 2 Cross-section intensity profile of processing laser captured by the CCD camera:(a) left picture: a profile of a Gassian beam without FOD; (b) right picture: a profile of a Bessel beam within FOD. Both of intensity profiles are normalized by the peak intensity.

Figure 1 shows the experimental set up geometry including of two main parts: (i) processing laser and (ii) fluidic optical device (FOD). The fluidic optical device consists of the DPSS laser and the cuvette with a dye solution, as shown in Fig. 1. DPSS laser ($P_{max}$ = 100 mW, λ= 532 nm, TEM $_{00}$) emits CW light of 532 nm wavelength, and is aligned with the YAG laser beam with the dichroic mirror. The pump power of DPSS laser is the parameter to change the beam shape. The shaped processing laser beam profile is measured with a CCD camera (BeamStar FX 50) using a 4x beam expander with the spatial resolution of 2.5 µm × 2.5 µm. For more discussions on the functional of FOD, refer to author's previous works (Doan et al. 2012 and Doan et al. 2013). The processing laser (λ= 1064 nm, $M^2$=2~3) has pulse width of 5 ns; pulse energy, *E*, is controlled by using an external attenuator including a variable beam splitter and a correction plate. The spatial profile of the Nd:YAG laser beam, referred to as "beam shape" in the following descriptions, is controlled by using the fluidic laser beam shaper (FLBS). After propagating through the FOD processing laser is reduced again by a ND filter and focused using a 25 mm focal length convex quartz lens. Here, the ND filter is introduced to reduce the laser pulse energy again under the threshold energy value of CCD camera. The cross-section intensity profiles of processing laser captured by the CCD at the focal plane are shown in Fig. 2 for two cases of Gaussian beam (original beam profile of the processing laser) and Bessel beam (shaped by FOD). In Fig. 2, both of intensity profiles are normalized by the peak intensity. It is worth mentioning that the sub-peak intensity around

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the peak intensity, observed in the left picture of Fig. 2, is due to diffraction of solid lens.

It's worth noticing that FOD is used to make a fair comparison between a Bessel beam and a Gaussian beam. Actually, Bessel beam can be made with an axicon lens, however with a certain axicon lens (with a certain apex angle), the shape of Bessel beam (spot size, number of side lobes…) should be fixed. The comparison with a Gaussian beam in mean of same spot size and energy is difficult. Therefore, the FOD is used to control the optical parameter of the Bessel beam for the fair comparison with a Gaussian beam.

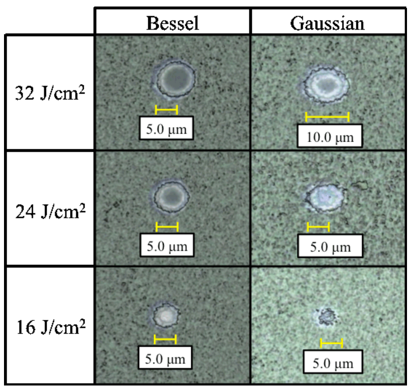
## 3. Results and discussion

After confirming the intensity profile of the processing laser, the CCD camera and ND filter is replaced by a sample for the drilling process. The sample consisting of a 600~700 nm thin TCO layer ($SnO_2$:F) on top of a 1.8 mm glass substrate. The quality of processing was evaluated with an optical microscope (KEYENCE VF7500) and a scanning electron microscope (KEYENCE VE8800). The detail of experimental parameters for drilling process is shown in Table 1.

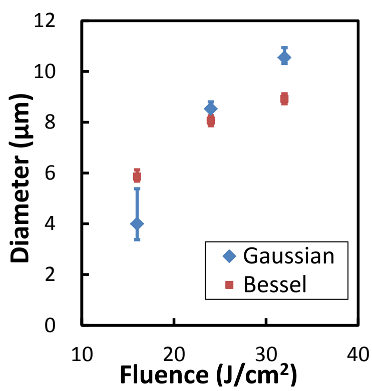
Table 1 Experimental conditions

| | |
|---|---|
| Wavelength | 1064 nm |
| Pulse width | 5-7 ns |
| Beam spot size | 12 µm |
| Beam profile | Gaussian, Bessel |
| Peak fluence | 16, 24, 32 J/cm$^2$ |

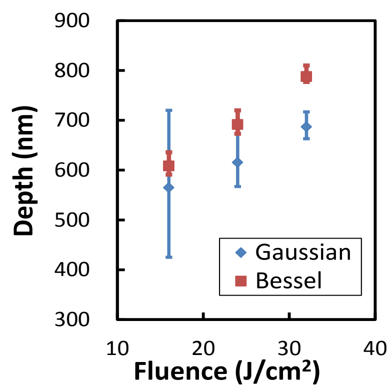
### 3.1 A single pulse ablation



(a) Optical microscope image of vias



(b) Via diameter



(c) Via depth

Fig. 3 Experimental results of single pulse ablation at several fluence levels for both of Gaussian and Bessel beam: (a) shows the image of vias taken by a optical microscope; (b) and (c) show the diameter and depth of vias ablated at different fluence levels. In (b) and (c), red and blue points show the measurement values of vias ablated by Bessel and Gaussian beam respectively.

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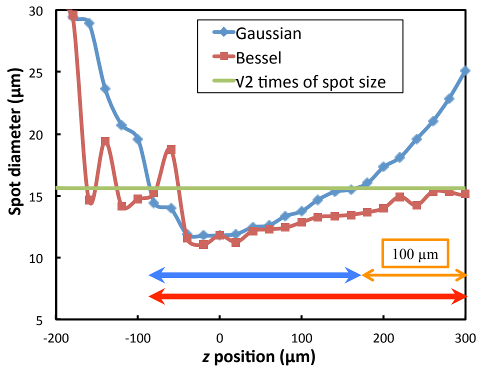


Fig. 4 Spot diameter of Bessel and Gaussian beam measured by a CCD camera at different positions around a focal point. Red and blue lines show the measurement values of Bessel and Gaussian beam respectively. Green line represents the 1.41 times of spot size

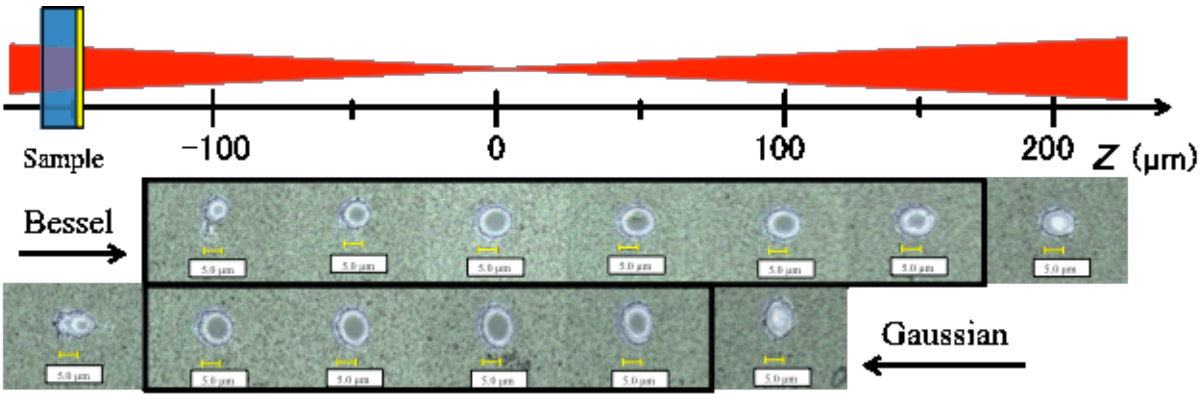


Fig. 5 Experimental results of single pulse ablation at different positions around a focal point for both of Gaussian and Bessel beam at the fluence of 24 J/cm$^2$

Figure 3 shows experimental results of single pulse ablation at several fluence levels for both of Gaussian and Bessel beam. Here, the fluence is peak fluence, which is measured and scale at the center of each beam. The values in Fig 3(b) and (c) are the average values; the error bar shows the maximum and minimum values of 5 measurements. Except in the case of the lowest fluence, the vias ablated by Bessel beam show smaller diameter and deeper depth compared with those of Gaussian beam. With increasing of fluence, diameter of vias ablated by Gaussian beam increase faster than those of Bessel beam. From error bar in Fig. 3(b) and (c), it is worth mentioning that the vias ablated by Bessel beam have smaller variations in diameter and depth than those of Gausian beam.

The different results obtained with Bessel and Gaussian beam could be explained by the depth of field focused by two types of beams. In order to study the characteristics of focusing, the spot diameters of Bessel and Gaussian beam around the focal point were measured by CCD camera and plot in Fig. 4 as a function of distance from focal point. In Fig. 4, the 0 value of z-position is the focal point; red and blue points show the measurement values of Bessel and Gaussian beam respectively. Green line represents the 1.41 times of spot size. Suppose that the depth of focal field is measure by the distance along the laser propagation axis where the spot diameter is smaller than 1.41 times of the spot size. The depth of focal field of Gaussian beam is measured about 220 µm. This value is almost same with which calculated for Gaussian beam with spot size of 12 µm. As shown in Fig. 4, the depth of focal field of Bessel beam was 100 µm longer than those of Gaussian beam.

To study the effect of depth of focal field in fabrication process, a single pulse ablation experiment was carried out at different distant from focal point. The optical microscope images of vias are shown in Fig. 5. The vias outside of the black rim, have a white color are at the vias center as the evidence of non-removable coating layer. These non-removable areas could increase the conductivity of the groove. Therefore, only the vias inside the black rim is considered as good quality vias with the coating layer is perfectly removed at the vias center. Let us call the distance along the laser propagation axis, where the good quality vias can be fabricated, as "work distance". As shown in Fig. 5,

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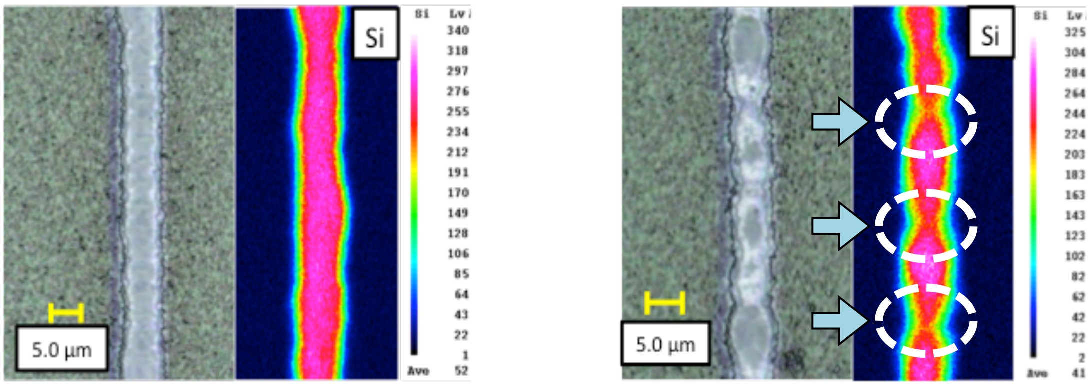
the Bessel beam shows a longer work distance than Gaussian beam. And the difference of work distance between Gaussian and Bessel beam is almost same with the difference of focal depth between two beams. Bessel beam with longer work distance would be a reason for the stable fabrication process compared with Gaussian beam at the same laser spot and fluence level.

### 3.2 P1 scribing

Table 2 Electrical conductivity of each groove

| Beam profile | | Bessel | | |
|---|---|---|---|---|
| Irradiation interval (μm) | | 3 | 5 | 7 |
| Peak fluence ($J/cm^2$) | 32 | ○ | ○ | ○ |
| | 24 | ○ | ○ | ○ |
| | 16 | ○ | × | × |

(○: isolated , ×: conductive)




(a) Irradiation interval of 3μm (b) Irradiation interval of 5μm

Fig. 6 Grooves scribed by a diameter of 12 μm Bessel beam with repetition of 10 Hz, peak fluence of 16 $J/cm^2$, and irradiation interval of (a) 3 μm and (b) 5 μm. In each picture, the left side is the optical microscope image of a groove; the right side shows the spatial distribution of Si on the surface of the laser line.

In this section, Bessel beam (a diameter of 12 μm and repetition of 10 Hz) was applied to scribe of P1 at difference of fluence levels and irradiation intervals. The dielectric characteristic of the P1 was assessed and shown in Table 2. At almost conditions of peak fluence and irradiation interval, the grooves show a good quality of geometry (as shown in Fig. 6(a)) and perfectly isolated (except in the case of peak fluence of 16 $J/cm^2$ and irradiation interval of 5μm and 7 μm.) The analysis of spatial distribution of Si on the surface of groove by secondary ion mass spectrometry was carried out and the results are shown in Fig. 6. It is clearly shown that, at fluence of 16 $J/cm^2$, the scribing with irradiation interval larger than 5 μm could make non-removable areas of TCO film as shown in Fig. 6(b) which could be a reason for the conductive characteristic of groove. However, the scribing process with irradiation interval of 3 μm, shows a very good quality of groove width of 6μm and perfectly isolated. This quality can be compared with the P1 fabricated with femtosecond laser, which reported recently by Krause. et al. (2014). It is also worth mentioning that, in this study, in order to compared with Gaussian beam in means of spot size and fluence, the fluidic optical device is used to make Bessel beam with a depth of focal field just longer than those of Gaussian beam. In the future work, the axicon lens, which can focus beam with spot size 1~2 μm and focal depth of tens of mm, will be used to make Bessel beam. The use of this Bessel beam should improve the fabrication quality.

### 4. Conclusion

In this study, the application of the Bessel beam in laser backside scribing of P1 for TFSC is demonstrated. In order to assess the capability of the Bessel beam in laser scribing of TFSC, both of single pulse ablation and scribing

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experimental were carried out. In the single pulse ablation experiment, the Bessel beam shown the stable fabrication process compared with Gaussian beam at the same laser spot and fluence level due to its long work distance. Furthermore, a few micrometer wide, perfectly isolated P1 groove were fabricated with Bessel beam, which can be compared with those were fabricated by femtosecond laser. The paper also concludes with the use of axicon lens to improve the fabrication quality in our future research.

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