Journal Pre-proof

Two-dimensional Detection of Subsurface Damage in Silicon Wafers with Polarized Laser Scattering

Jingfei Yin (Conceptualization) (Methodology) (Investigation) (Software) (Data curation) (Writing - original draft), Qian Bai (Conceptualization) (Methodology) (Visualization) (Supervision), Han Haitjema (Writing - review and editing) (Visualization), Bi Zhang (Writing - review and editing) (Supervision) (Project administration) (Funding acquisition)

PII: S0924-0136(20)30160-6

DOI: <https://doi.org/10.1016/j.jmatprotec.2020.116746>

Reference: PROTEC 116746

To appear in: *Journal of Materials Processing Tech.*

Received Date: 4 January 2020

Revised Date: 5 May 2020

Accepted Date: 11 May 2020

Please cite this article as: Yin J, Bai Q, Haitjema H, Zhang B, Two-dimensional Detection of Subsurface Damage in Silicon Wafers with Polarized Laser Scattering, *Journal of Materials Processing Tech.* (2020), doi: <https://doi.org/10.1016/j.jmatprotec.2020.116746>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier.

Two-dimensional Detection of Subsurface Damage in Silicon Wafers with Polarized Laser Scattering

Jingfei Yin¹, Qian Bai¹, Han Haitjema², Bi Zhang^{3*}

¹ School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China;

² Department of Mechanical Engineering, KU Leuven, Leuven 3001, Belgium;

³ Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, China;

*Corresponding author: zhangb@sustech.edu.cn

Graphical abstract

Highlights

- Polarized laser scattering can detect subsurface cracks without the influence of residual stress and surface roughness.
- A polarized laser scattering signal is determined by both the depth and density of the grinding-induced subsurface cracks in a silicon wafer.
- Compared to crack density, the depth of subsurface cracks is a dominant factor that influences the crack detection by polarized laser scattering.

Abstract

This study proposes a polarized laser scattering (PLS) method for detection of the two-dimensional distribution of the grinding-induced subsurface damage (SSD). This study also uses two destructive methods to observe the distribution of SSD in the ground silicon wafers by cross-sectional microscopy and by layer-by-layer microscopy. An experimental investigation is arranged for detecting the two-dimensional damage from diamond wheel grinding of silicon wafers through wafer sample preparation and SSD observations with the cross-sectional and layer-by-layer microscopy. It also includes PLS detection of the ground silicon wafers for SSD information. The results show that both the depth of SSD and the crack density contribute to the PLS detection signals. The study reveals the characteristics of the PLS detection, which illustrates the potential application of the PLS method to in-process detection.

Keywords: Silicon wafer; Grinding; Crack; Polarization; Laser scattering

1 Introduction

Silicon wafer has wide applications, as addressed in the paper of Lai et al. (2019). Xiao et al. (2019) stated that silicon was an important substrate material in photovoltaics. Luo et al. (2016)

believed that silicon is of a great value to the integrated circuit application. Zuo et al. (2017) claimed that silicon is an excellent optical material in the near and mid-infrared due to its broad mid-IR transparency and mechanical stability. Being a hard and brittle material, a silicon wafer generally suffers from subsurface damage (SSD) during a machining process, such as wire sawing studied by Kumar et al. (2016) and grinding studied by Li et al. (2017). Although Bifano et al. (1991) proposed that a hard and brittle material could be machined in a ductile regime to avoid SSD, they only observed the machined surface without any inspection on the subsurface condition of the material. Yan et al. (2009) suggested that ductile-regime due to phase transformation could be achieved on a silicon wafer surface at a considerably low cutting speed. However, ductile-regime machining requires the depth of cut be small enough, generally in the order of few nanometers, which obstructs the practical application of the ductile-regime machining for the sake of low productivity. Therefore, in the practical machining of silicon, it is inevitable to induce SSD into a machined surface.

SSD is detrimental to the performance and lifetime of the final part made of a silicon wafer. Zhou et al. (2016) found that residual stresses resulted in warpage which increased the possibility of the wafer breakage and failure. Zhang et al. (2018) suggested that the phase transformation in silicon were intolerable to the application of the integrated circuits and photovoltaics; Yin et al. (2018b) informed that subsurface cracks (SSCs) degraded the fracture strength of the wafer and indicated that among the different forms of damage, SSC is the most detrimental. Therefore, SSD detection is important to the subsequent processes practiced in the machining of a silicon wafer.

Currently, there are two types of the methods for detecting SSD, namely, destructive and non-destructive methods. In terms of the destructive methods, Gao et al. (2010) used the angle

polishing method to obtain depth of SSD; Yin et al. (2018b) used the cross-sectioning technique to study the configuration of subsurface cracks; Zhou et al. (2016) revealed the microstructure in the wafers with the transmission electron microscopy; and Sekhar et al. (2018) carried out the chemical etching to elucidate the asymmetry to the depth of SSD induced in the wire sawing. Various destructive methods are alternative for different demands. Although a destructive method offers a direct observation of damage in the sample, opening up the sample is needed. Yin et al. (2018a) have addressed that the destructive methods are time-consuming and only provides local information of SSD. Therefore, destructive methods are inapplicable to the in-process detections.

Non-destructive methods may enable fast scanning over the whole sample surface and detect the global distribution of SSD, which provides a more comprehensive estimation of SSD. They are promising for in-process detection and can greatly increase the overall production efficiency. Sun et al. (2016) proposed a model of grinding force in the self-rotating grinding of silicon. Based on the grinding force model, the distribution of subsurface damage depth in the whole wafer could be revealed. However, the grinding force model was built under a specific and ideal condition. In practical machining, many influential factors are ever-changing, for example, machining tool condition. Kumar et al. (2016) claimed that the influence of tool wear to the subsurface damage cannot be ignored. Therefore, the prediction model is unable to precisely detect the subsurface damage depth in a ground silicon wafer.

Geiler et al. (1999) and Geiler et al. (2002) used the scanning infrared depolarization (SIRD) technique to detect SSD distribution on a whole wafer of a diameter up to 300 mm. The SIRD technique is based on photoelasticity and has been used to detect the distribution of residual stresses induced in different processes. However, the two principal stress components cannot be

resolved. Su et al. (2015) employed a hybrid method by micro-infrared photoelasticity and finite element simulation for stress component isolation of the Through-Silicon-Vias. The stress distribution can be used to estimate SSC because the stress evolution within a silicon wafer is associated with SSC. However, the explicit relationship between stress and SSC remains unclear. Therefore, photoelasticity cannot be applied to quantitatively detecting SSC, neither can micro-Raman spectroscopy which was conducted by De Wolf (1996). Dallas et al. (2007) and Belyaev et al. (2006) developed the resonance ultrasonic vibrations (RUV) to detect cracks in the full-size silicon wafers. However, RUV is also a qualitative detection method.

Balogun et al. (2011) applied a laser-based acoustic microscopy to detecting the subsurface artificial features in the micrometer scale in silicon. However, SSD in a machined wafer is sophisticated, which is an obstacle for the laser-based acoustic microscopy. Fine et al. (2005) used confocal laser scanning microscopy to detect SSD in the polished and fine ground optical glasses and achieved a resolution as high as 150 nm. However, the method is inapplicable to detecting SSD beneath a roughly ground surface because surface roughness disturbs the detection signals. Takahashi et al. (1998) and Miyoshi et al. (2001) in Osaka University developed an annular illumination system to detect defects on silicon wafers. Experimental results showed that the system is highly sensitive to the surface microdefects with sub-micrometer scale. However, the light source they used was a laser with the wavelength of 488 nm. Zhang et al. (2004) have revealed the optical transmission properties of silicon wafer. They reported that the light penetration depth in silicon increased with the wavelength of the incident light. The laser beam of a wavelength of 488 nm cannot penetrate deep into a silicon wafer. Therefore, Takahashi et al. (1998) and Miyoshi et al. (2001) focused on detecting surface defects instead of subsurface

damage. In addition, the light scattering from surface grinding grooves and asperities is generally much stronger than the scattering from subsurface damage, the surface scattering would mask the weak scattering from subsurface damage, which thereby disturbs the detection of subsurface damage. Therefore, similar to the acoustic microscopy and confocal laser scanning microscopy, annular illumination system cannot be applicable to detecting subsurface damage because of the disturbance and masking from the surface scattering.

Zhou et al. (2019a) applied the three-dimensional digital image correlation (3D-DIC) technique to studying the fracturing behavior of the rock-like materials with different brittleness values in the uniaxial compression. They obtained the successive evolution of the fracturing process which helped understand the sensitivity of the fracturing behavior to the brittleness of the materials. The 3D-DIC technique is effective for studying surface fracture, however, it is not applicable to the detection of SSD. Zhou et al. (2019b) integrated the digital imaging and acoustic emission (AE) techniques in the investigation of the cracking of granite under the uniaxial loading. Based on the analyses of the acousto-optic-mechanical characteristics, the six stages of the cracking process were identified. However, neither digital imaging nor AE techniques could quantitatively determine the size of the internal cracks. Therefore, the integration of the digital imaging and AE techniques is not suitable for detecting SSD in the ground silicon wafers.

In laser scattering, Trost et al. (2013) suggested that the disturbance of surface roughness can be avoided by exploiting the polarization effects of the laser beam. Zhang and Sun (2005) proposed a polarized laser scattering (PLS) method, i.e. cross-polarization confocal microscopy (CPCM), to detect the SSD of the ground silicon wafers, excluding the influence of surface roughness. However, in PLS, Yin et al. (2019) found that the residual stress-induced

photoelasticity interfered with the detection of subsurface cracks. They proposed that aligning the polarization direction of the incident laser beam with the grinding marks could eliminate the inference of residual stress so as to directly detect SSC.

In order to provide a more comprehensive estimation of the grinding-induced SSD, this study investigates the two-dimensional distribution of SSD. For this purpose, the PLS method is used in the study. During the PLS detection, the influence of residual stress is excluded. On the other hand, SSD distributions are also detected with the traditional destructive methods in a control group. Based on the study, the distribution of SSD on a ground wafer is revealed. Meanwhile, the detection characteristics of the PLS method are investigated, which enables the exploration of the application of the PLS method.

2 Experimental procedures

In this study, a PLS system was installed to detect SSD. The schematic configuration of the PLS system is shown in Fig. 1. The working principle is described as follows. A laser emits a light beam with a wavelength of 914 nm which ensures the laser penetrating deep into silicon to detect SSD, based on the study by Zhang et al. (2004). The light beam passes through a polarizer with an extinction ratio of 1:100 and becomes linearly polarized. This linearly polarized beam is reflected by a polarized beam splitter (PBS) with an extinction ratio of 1:3,000 and focused on the surface of a ground silicon wafer by a lens. A part of the beam is scattered by the surface of the wafer, while the rest penetrates into the wafer and is backscattered by SSD. The surface scattering light preserves the same polarization as the incident light and is reflected back to the laser by the PBS along the incident light path. However, the SSD backscattering light is partly depolarized, goes through the PBS and is then collected by a detector. A Glan-Taylor polarizer is placed in front of

the detector to further ensure that the detected light is purely from the SSD scattering. A data acquisition (DAQ) system (PCIe-6320, NI, USA) is arranged to record the detected signal. A translation stage of a positioning uncertainty of 5 μm is used to position the silicon sample and realize the two-dimensional detection of SSD.

Fig. 1. The schematic configuration of the polarized laser scattering system

Four (100) wafers with a diameter of eight inches were ground by a commercial grinding machine. The wafers were polished before grinding to ensure there are no pre-existing cracks in the subsurface. Two cup-type diamond wheels were used to grind the wafers. These were a vitrified bond wheel and a resin bond wheel with abrasive grain sizes of #400 and #600 respectively. The grinding parameters are listed in Table 1. Each wafer was thinned by 50 μm . For each wheel grinding, one wafer was ground with a spark-out (SP) process and another with no spark-out (NSP) process, as shown in Table 2.

Table 1. Grinding parameters of the wafers

Parameters	Values
Spindle speed	2400 rpm
Worktable speed	120 rpm
Feed rate	90 $\mu\text{m}/\text{min}$
Spark-out duration	10 s
Coolant	Deionized water

Table 2. Specifications of wafers

Wafers	Grinding wheel	Spark-out or not
A	#400	No
B	#400	Yes
C	#600	No
D	#600	Yes

Before studying the two-dimensional distribution of SSD, the influence of surface roughness to the PLS detection was examined. Four ground silicon samples were selected from the ground wafers for the examination of the surface roughness influence. As shown in Table 3, sample 1 and sample 2 had the same level of the depth of SSD but two different levels of surface roughness, sample 3 and sample 4 had the same level of surface roughness but two different levels of the depth of SSD. Then, the four samples were subjected to the detection by the installed PLS system. By comparing the PLS signals of the samples, the influence of the surface roughness can be distinguished.

Table 3. Specifications of the samples for the examination of the surface roughness influence

Samples	Depth of SSD/ μm	Surface roughness Ra/nm
1	5.8	437
2	5.3	312
3	11.3	346
4	5.5	339

To study the two-dimensional distribution of SSD with the PLS system, three chips of an area of 8 mm×8 mm were diced from each wafer along the radial direction. The center of each chip was respectively approximately 25 mm, 55 mm, and 85 mm away from the center of the ground wafer. In the PLS detection, a chip was raster-scanned over an area of 5 mm×5 mm with a step size of 0.5 mm. The scanned area on the chip was 1.5 mm away from the dicing edge of the chip to avoid the influence of the damage induced in the sample dicing. In the scanning, to eliminate the influence of the residual stresses, the polarization direction of the incident laser beam was aligned with the grinding marks.

As to the application of the destructive methods for SSD detection, the study adopted two methods: the cross-sectional microscopy and the layered polishing. The cross-sectional microscopy to detect SSD depth is described in more detail in the study of Yin et al. (2018b). It was used to detect SSD in the sections of 20 mm, 40 mm, 60 mm, and 80 mm from the wafer center. The layered polishing was used to detect the two-dimensional distribution of SSD. To realize the detection, the chips were polished layer-by-layer to facilitate an easy detection. Each polished layer thickness was about 1 μm . The two-dimensional distribution of cracks was

observed with a laser confocal microscope (OLS4000, Olympus, Japan). The density of cracks in the subsurface was determined by a transverse-line measurement method after each layer was removed. The schematics of the transverse-line measurement method is shown in Fig. 2. Four measurement lines were perpendicular to the grinding marks, the length of each line was 200 μm and the interval between the lines was 50 μm . The total number N of the cracks which crossed the measurement lines was calculated. The crack density was defined as the ratio of the total number N of cracks to the total length of the measurement lines, and is expressed as cracks/mm.

Fig. 2. Schematics of the transverse-line measurement method

By comparing the PLS detection with the detection by the destructive methods, the characteristics of the PLS measurement were investigated. The PLS detection was compared with the detection by the destructive methods. Through the investigations, this study is able to reveal both the depth distribution and the lateral two-dimensional distribution of SSD in the ground wafers.

3 Results and analysis

The PLS signals of the samples for examination of ground surface roughness are shown in

Fig. 3. As shown in Fig. 3(a), the detected signals of sample 1 and sample 2 have no notable difference. The difference between sample 1 and sample 2 is surface roughness, therefore, surface roughness cannot lead to an observable change in PLS signal. Sample 3 and sample 4 have similar surface roughness but two levels of depth of SSD, as shown in Fig. 3(b), sample 3 with a larger depth of SSD represents a larger signal than sample 4. Therefore, comparing with the depth of SSD, the influence of surface roughness of ground silicon wafers can be neglected in the detection with the installed PLS system.

Fig. 3. Signal variation of the samples for examination of ground surface roughness detected with the installed PLS system

The depths of SSD in the wafers are summarized in Fig. 4. As shown in Fig. 4, generally, the wafers ground with the #400 wheel have a larger depth of SSD than the wafers ground with the #600 wheel. In the wafers without the spark-out process during grinding, the depth of SSD increases with the distance from the center of the wafers. SSD is caused in the grinding process. In the wafer self-rotating grinding, the depth of cut a_c of the abrasive grains can be calculated by Eq. (1), referring to the model in the study of Sun et al. (2016).

$$a_c = 2.44 \cdot R_e \left[\frac{rfN_w}{nN_s^2 \left(1 + \frac{r^2}{8 \cdot R_s^2} \right)} \right]^{0.4} \quad (1)$$

where r is the distance away from the wafer center, R_e , n , f , N_w , N_s , and R_s are the radius of the abrasive grain, the number of the grains, feed rate, worktable speed, spindle speed, and the radius of the grinding wheel, respectively. It is easy to infer that depth of cut a_c increases with the distance r and grain radius R_e . A larger depth of cut results in a larger grinding force, and therefore a larger depth of SSD. In the wafers with the spark-out process, the depth of SSD tends to be uniform at different distances from the center of the wafers, the wafers with the spark-out process have smaller depth of SSD, which is in accordance to the study by Gao et al. (2010).

Fig. 4. The radial distributions of the depth of the grinding-induced SSD in the wafers

Figure 5 shows a two-dimensional distribution of the PLS detection of the silicon chips. It is obvious that the PLS signals of the wafers ground with the #400 wheel are larger than those with the #600 wheel, which can be explained from the depth of SSD, as shown in Fig. 4. A larger depth of damage means that more incident laser beam is scattered and depolarized. Therefore, the depolarized light intensity is higher in the wafers ground with the #400 wheel. In the wafers prepared without the spark-out process, the detected signal intensity is larger in the chips near the periphery than near the center of the wafers. This can be explained by considering that SSDs of a larger depth is formed during the grinding process in the area close to the wafer periphery.

Fig. 5. The two-dimensional distribution of the PLS detection signal of the silicon chips

If the PLS signal intensity would be merely dependent on the depth of SSD, the distribution of the detected signal intensity should be coincided with that of the depth of SSD. As shown in Fig. 4, the wafers with the spark-out process have smaller depths of SSD, however, the PLS detection signal intensity is larger than the wafers without the spark-out process. This indicates the PLS signal is not just dependent on the depth of SSD. The detail analysis is addressed as follows.

The incident light beam penetrates into silicon wafer and is multi-scattered by SSC and the polarization of scattered light is depolarized. Therefore, more SSC leads to more depolarized

scattering light, i.e., a higher light intensity of the detection signal. Following this logic, the detected light intensity should also be related to the crack density.

Figures 6 and 7 show the two-dimensional distribution of subsurface cracks at different depths. The depth of SSD in the wafer ground with the #400 wheel is over 8 μm (Fig. 6) which is larger than 5 μm of the #600 wheel ground wafer (Fig. 7). This result is consistent with the detection result by the cross-sectional microscopy. In grinding with the #400 wheel, the depth of cut per abrasive grain is larger than with the #600 wheel. Accordingly, a larger depth of cut results in a larger grinding force and leads to a deeper damage. At low depths, the crack size is larger with severer surface chipping in the wafer ground with the #400 wheel than with the #600 wheel. From the photographic observations shown in Figs. 6 and 7, it is clear that the crack density decreases with an increase in depth. During the self-rotating grinding, the depth of cut per abrasive grain is not constant because the protrusion height of the grains is statistically distributed. Only a small portion of the grains is loaded with the largest depth of cut, while most other grains are loaded with an average depth of cut. Therefore, most cracks are formed in the topmost layer of a ground wafer.

Fig. 6. Photographic observations of the crack distribution at different depths in the wafer ground by the #400 wheel (a) as-ground surface, (b)-(i) 1-8 μm below the surface, respectively.

Fig. 7. Photographic observations of the crack distribution at different depths in the wafer ground by the #600 wheel (a) as-ground surface, (b)-(f) 1-5 μm below the ground surface, respectively.

Crack density decreases in the depth direction, as shown in Fig. 8. The decreasing gradient of the crack density in the wafers with the spark-out process is larger than that in the wafers without the spark-out process. Within a small depth into the wafers, the crack density in the spark-out wafers is larger, but it decreases faster than that in the wafers without the spark-out process. When the depth is over a threshold, the distribution of crack density reverses. In the #400 wheel ground wafers, the threshold is around 4.2 μm , as shown in Fig. 8 (a). On the other hand, in the #600 wheel ground wafers, the threshold is around 2.5 μm , as shown in Fig. 8 (b). It can be inferred that more additional microcracks are induced into the wafers during the spark-out process. In the spark-out grinding process with the #400 wheel, the depths of microcracks are less than 4.2 μm , whereas in the spark-out grinding process with the #600 wheel, the depths of microcracks are less

than 2.5 μm . Although the maximum crack depth in the wafer with the spark-out process is slightly smaller than that in the wafer without the spark-out process, the total crack density is larger. Therefore, the wafers ground with the spark-out process show larger PLS signal intensities, as shown in Fig. 5.

(a) Grinding with the #400 wheel

(b) Grinding with the #600 wheel

Fig. 8. Crack density distribution determined by the transverse-line measurement method at different depths in the wafers

During the grinding process, the grinding machine is deformed elastically by grinding forces. When entering the spark-out process, the grinding wheel stops feeding, the grinding contact relies on the elastic spring back of the machine loop system. In this process, grinding force and depth of cut gradually decrease. There still exists material removal before the grinding wheel completely leaves the wafer surface. As shown in Fig. 9, during the elastic recovery in the spark-out process, the higher surface asperities are smashed to finer chippings and more microcracks are induced into the ground surface after the spark-out grinding. During the spark-out process, the depth of cut of the individual grains is smaller than that in a grinding process. Consequently, the depth of microcracks is smaller than that of cracks induced in grinding. Therefore, within a topmost layer of the wafers, the crack density increases after the spark-out grinding, as shown in Fig. 8.

Fig. 9. The schematics of the evolution of the wafer surface processed by the spark-out grinding

As shown in Fig. 5, in the wafers with the spark-out process, the PLS signal distribution of the #600 wheel ground wafer is uniform along the wafer radius direction. However, the PLS signal distribution of the #400 wheel ground wafer has the same distribution trend with that in the wafer without spark-out grinding, namely, the PLS signal intensity is larger in the area close to the wafer periphery. The reasons are discussed as follows.

The evolution of the subsurface crack density is schematically described in Fig. 10. The cracks induced by the #400 wheel are large. Although the cracks in the topmost layer are removed in the spark-out process, many cracks still remain and are joined by the microcracks induced by spark-out. The crack density is higher towards the wafer periphery than close to the wafer center. Accordingly, a larger PLS signal on the silicon chips is also close to the wafer periphery. However, as shown in Fig. 10 (b), the cracks induced in the #600 wheel grinding are generally small. Most cracks distribute in the topmost layer that are removed in the spark-out grinding process, only minority with large depths remains. After the spark-out grinding process, most cracks are spark-out induced microcracks, which makes the total crack density uniformly distributed along the wafer radius. Therefore, the PLS signal is uniform across the whole wafer that is endured the spark-out grinding by the #600 wheel.

Fig. 10. Schematics of the evolution of subsurface crack density in spark-out grinding

In the wafer without spark-out grinding, the crack density distributions are shown in Fig. 11.

Both the wafers represent the same variation tendency in the distribution of crack density along the wafer radius direction. At a shallow depth, the crack density in the position near the center of the wafer is larger than that in the position close to the periphery of the wafer. As the depth increases, the crack density decreases, the crack density near the center of the wafers decreases faster than those far away from the center. In the wafer ground with the #400 wheel, the crack density near the wafer center is the largest at a depth less than about $2.5\ \mu\text{m}$ but the smallest at the depth over $2.5\ \mu\text{m}$. In the wafer ground with the #600 wheel, the critical depth is around $1.2\ \mu\text{m}$ over which the crack density near the wafer center turns to be smaller than that close to the wafer periphery. Finally, the depth of SSD near the center is smaller than that close to the periphery. Therefore, the PLS signals near the centers are smaller than that close to the periphery of the wafer without spark-out grinding, as shown in Fig. 5.

(a) Grinding with #400 wheel

(b) Grinding with #600 wheel

Fig. 11. Crack density distribution along the radius of the wafers without spark-out grinding

4. Discussion

When the wafers are ground with the same wheel, i.e., the depth of crack is similar, the influence of crack density needs to be considered. In this situation, a higher crack density results in a larger PLS signal. On the other hand, the wafers ground with different wheels can be distinguished from the depths of SSD with the PLS method. Therefore, in a ground wafer, the depth of cracks is a dominant factor for the PLS detection which can be applied to the quantitative detection of SSD so as to optimize the subsequent process. During the spark-out grinding, the material removal and thickness reduction are small. When the depth of SSD in a wafer is large, the PLS signal distributions along the radial direction of the wafer before and after the spark-out grinding are similar. When the depth of SSD in a wafer is small, the PLS signal increases with the distance away from the wafer center before the spark-out grinding. After the spark-out grinding, the PLS signal is uniform. This indicates that once the PLS signal distribution is uniform across the wafer surface, the depth of SSD is small. The PLS method provides a more comprehensive

detection tool for the measurement of SSD in a machining process.

This study reveals that both the crack depth and crack density influence the PLS detection for SSD in the ground silicon wafers, which provides a guide for the future investigation of the PLS detection. In addition to the crack depth and crack density, there are other factors that could influence the PLS detection, for example, damage type, such as cracks, pores, phase transformation, residual stress. In addition, considerations should also be paid to the multi-scattering caused by the considerably large surface roughness, internal impurities, the incident angle of the detection laser beam, and the light scattering characteristics at different wavelengths. These influential factors are to study in the future.

It is interesting that both the PLS system and the annular illumination system proposed by Miyoshi et al. (2001) demonstrated the alignment effect from the orientation of a surface defect and the incident laser beam. In the PLS system, the polarization direction of the incident laser beam should be aligned with the grinding marks to eliminate the effect of residual stress on detection results, which was elucidated in another work by Yin et al. (2019). Miyoshi et al. (2001) also pointed out that the annular illumination system provided a higher performance if the incident laser beam direction was aligned perpendicular rather than parallel to the orientation of a surface defect. The commonality of the two methods implies that both surface and subsurface defects can be detected at the same time by aligning the orientation of the incident laser beam. The alignment effect has become a main issue in the optical detection of defects, which remains to be investigated.

5 Conclusion

In this study, the PLS method is proposed for the detection of the two-dimensional distribution of SSD. SSD depth and crack density are the two dominant factors that may give influences on the PLS detection. A larger depth of SSD leads to a larger PLS signal while crack density should be considered in the detection of the wafers of a similar depth of SSD. The characteristics of the PLS method enable the detection of SSD in silicon wafers. Therefore, this study provides a guide to the engineering applications of the PLS method.

CRediT author statement

Jingfei Yin: Conceptualization, Methodology, Investigation, Software, Data curation, Writing- Original draft preparation.

Qian Bai: Conceptualization, Methodology, Visualization, Supervision.

Han Haitjema: Writing- Reviewing and Editing, Visualization.

Bi Zhang: Writing- Reviewing and Editing, Supervision, Project administration, Funding acquisition.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The study was financially supported by the National Natural Science Foundation of China (Grants No. 51575084 and 51605077) and the Peacock Program of Shenzhen (KQJSCX20180322152221965).

References

Balogun et al., 2011 O. Balogun, G.D. Cole, R. Huber, D. Chinn, T.W. Murray, J.B. Spicer

High-spatial-resolution sub-surface imaging using a laser-based acoustic microscopy technique

IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 58 (2011), pp. 226-233.

<https://doi.org/10.1109/TUFFC.2011.1789>

Belyaev et al., 2006 A. Belyaev, O. Polupan, W. Dallas, S. Ostapenko, D. Hess, J. Wohlgemuth

Crack detection and analyses using resonance ultrasonic vibrations in full-size crystalline

silicon wafers

Applied Physics Letters, 88 (2006), pp. 111907. <https://doi.org/10.1063/1.2186393>

Bifano et al., 1991 T. G. Bifano, T. A. Dow, R. O. Scattergood

Ductile-regime grinding: a new technology for machining brittle materials

Journal of Manufacturing Science and Engineering, 113 (1991), pp. 184-189.

<https://doi.org/10.1115/1.2899676>

Dallas et al., 2007 W. Dallas, O. Polupan, S. Ostapenko

Resonance ultrasonic vibrations for crack detection in photovoltaic silicon wafers

Measurement Science and Technology 18 (2007), pp. 852-858. [https://doi.org/10.1088/0957-](https://doi.org/10.1088/0957-0233/18/3/038)

0233/18/3/038

De Wolf, 1996 I. De Wolf

Micro-Raman spectroscopy to study local mechanical stress in silicon integrated circuits

Semiconductor science and technology, 11 (1996), pp. 139. [https://doi.org/10.1088/0268-](https://doi.org/10.1088/0268-1242/11/2/001)

1242/11/2/001

Fine et al., 2005 K.R. Fine, R. Garbe, T. Gip, Q. Nguyen

Non-destructive real-time direct measurement of subsurface damage

Proc. SPIE, 5799 (2005), pp. 105-110. <https://doi.org/10.1117/12.602993>

Gao et al., 2010 S. Gao, R.K. Kang, D.M. Guo, Q.S. Huang

Study on the Subsurface Damage Distribution of the Silicon Wafer Ground by Diamond Wheel

Advanced Materials Research, 126-128 (2010), 113-118.

<https://doi.org/10.4028/www.scientific.net/AMR.126-128.113>

Geiler et al., 1999 H. Geiler, W. Kürner, O. Storbeck

Photoelastic Imaging of Process Induced Defects in 300mm-Silicon Wafers

MRS Online Proceedings Library Archive 591. <https://doi.org/10.1557/PROC-591-249>

Geiler et al., 2002 H.D. Geiler, M. Wagner, H. Karge, M. Paulsen, R. Schmolke

Photoelastic stress evaluation and defect monitoring in 300-mm-wafer manufacturing

Materials Science in Semiconductor Processing, 5 (2002), pp. 445-455.

[https://doi.org/10.1016/S1369-8001\(02\)00138-5](https://doi.org/10.1016/S1369-8001(02)00138-5)

Kumar et al., 2016 A. Kumar, S. Kaminski, S.N. Melkote, C. Arcona

Effect of wear of diamond wire on surface morphology, roughness and subsurface damage of silicon wafers

Wear, 364-365 (2016), pp. 163-168. <https://doi.org/10.1016/j.wear.2016.07.009>

Lai et al., 2019 S. Lai, P. Lorenz, M. Ehrhardt, B. Han, D. Hirsch, I. Zagoranskiy, J. Lu, K.

Zimmer

Laser-induced frontside etching of silicon using 1550-nm nanosecond laser pulses

Optics and Lasers in Engineering, 122 (2019), pp. 245-253.

<https://doi.org/10.1016/j.optlaseng.2019.06.012>

Li et al., 2017 H.N. Li, T.B. Yu, L.D. Zhu, W.S. Wang

Analytical modeling of grinding-induced subsurface damage in monocrystalline silicon

Materials & Design, 130 (2017), pp. 250-262. <https://doi.org/10.1016/j.matdes.2017.05.068>

Luo et al., 2016 X. Luo, Y. Cheng, J. Song, T. Y. Liow, Q. J. Wang, M. Yu

Wafer-scale dies-transfer bonding technology for hybrid III/V-on-silicon photonic integrated circuit application

IEEE Journal of Selected Topics in Quantum Electronics, 22 (2016), pp. 443-454.

<https://doi.org/10.1109/JSTQE.2016.2553453>

Miyoshi et al., 2001 T. Miyoshi, S. Takahashi, Y. Takaya, S. Shimada

High Sensitivity Optical Detection of Oriented Microdefects on Silicon Wafer Surfaces Using Annular Illumination

CIRP Annals, 50 (2001), pp. 389-392. [https://doi.org/10.1016/S0007-8506\(07\)62147-7](https://doi.org/10.1016/S0007-8506(07)62147-7)

Pei et al., 1999 Z.J. Pei, S.R. Billingsley, S. Miura

Grinding induced subsurface cracks in silicon wafers. International Journal of Machine Tools and Manufacture, 39 (1999), pp.1103-1116. [https://doi.org/10.1016/S0890-6955\(98\)00079-0](https://doi.org/10.1016/S0890-6955(98)00079-0)

Sekhar et al., 2018 H. Sekhar, T. Fukuda, Y. Kida, K. Tanahashi, H. Takato

The impact of damage etching on fracture strength of diamond wire sawn monocrystalline silicon wafers for photovoltaics use

Japanese Journal of Applied Physics, 57 (2018), pp. 126501.

<https://doi.org/10.7567/JJAP.57.126501>

Su et al., 2015 F. Su, T. Lan, X. Pan

Stress evaluation of Through-Silicon Vias using micro-infrared photoelasticity and finite element analysis

Optics and Lasers in Engineering, 74 (2015), pp. 87-93.

<https://doi.org/10.1016/j.optlaseng.2015.05.010>

Sun et al., 2016 J. Sun, F. Qin, P. Chen, T. An

A predictive model of grinding force in silicon wafer self-rotating grinding

International Journal of Machine Tools and Manufacture, 109 (2016), pp. 74-86.

<https://doi.org/10.1016/j.ijmachtools.2016.07.009>

Takahashi et al., 1998 S. Takahashi, T. Miyoshi, Y. Takaya, K. Saito

In-Process Measurement Method for Detection and Discrimination of Silicon Wafer Surface Defects by Laser Scattered Defect Pattern

CIRP Annals, 47 (1998), pp. 459-462. [https://doi.org/10.1016/S0007-8506\(07\)62874-1](https://doi.org/10.1016/S0007-8506(07)62874-1)

Trost et al., 2013 M. Trost, T. Herffurth, D. Schmitz, S. Schröder, A. Duparré, A. Tünnermann

Evaluation of subsurface damage by light scattering techniques

Applied optics, 52 (2013), pp. 6579-6588. <https://doi.org/10.1364/AO.52.006579>

Xiao et al., 2019 H. Xiao, H. Wang, N. Yu, R. Liang, Z. Tong, Z. Chen, J. Wang

Evaluation of fixed abrasive diamond wire sawing induced subsurface damage of solar silicon wafers

Journal of Materials Processing Technology, 273 (2019), pp. 116267.

<https://doi.org/10.1016/j.jmatprotec.2019.116267>

Yan et al., 2009 J. Yan, T. Asami, H. Harada, T. Kuriyagawa

Fundamental investigation of subsurface damage in single crystalline silicon caused by diamond machining

Precision Engineering, 33 (2009), pp. 378-386.

<https://doi.org/10.1016/j.precisioneng.2008.10.008>

Yin et al., 2019 J. Yin, Q. Bai, B. Zhang

Subsurface Damage Detection on Ground Silicon Wafers Using Polarized Laser Scattering.

Journal of Manufacturing Science and Engineering, 141 (2019), pp. 101012.

<https://doi.org/10.1115/1.4044417>

Yin et al., 2018a J. Yin, Q. Bai, B. Zhang

Methods for Detection of Subsurface Damage: A Review

Chinese Journal of Mechanical Engineering, 31 (2018), pp. 41. <https://doi.org/10.1186/s10033-018-0229-2>

Yin et al., 2018b J. Yin, Q. Bai, Y. Li, B. Zhang

Formation of subsurface cracks in silicon wafers by grinding

Nanotechnology and Precision Engineering, 1 (2018), pp. 172-179.

<https://doi.org/10.1016/j.npe.2018.09.003>

Zhang et al., 2005 J.M. Zhang, J.G. Sun

Quantitative assessment of subsurface damage depth in silicon wafers based on optical transmission properties

International Journal of Manufacturing Technology and Management, 7 (2005), pp. 540-552.

<https://doi.org/10.1504/IJMTM.2005.007702>

Zhang et al., 2004 J.M. Zhang, J.G. Sun, Z.J. Pei

Optical Transmission Properties of Silicon Wafers: Theoretical Analysis, ASME 2004

International Mechanical Engineering Congress and Exposition, pp. 17-24.

<https://doi.org/10.1115/IMECE2004-59195>

Zhang et al., 2018 Q. Zhang, Y. Fu, H. Su, Q. Zhao, S. To

Surface damage mechanism of monocrystalline silicon during single point diamond grinding

Wear, 396-397 (2018), pp. 48-55. <https://doi.org/10.1016/j.wear.2017.11.008>

Zhou et al., 2016 P. Zhou, S. Xu, Z. Wang, Y. Yan, R. Kang, D. Guo

A load identification method for the grinding damage induced stress (GDIS) distribution in silicon wafers

International Journal of Machine Tools and Manufacture, 107 (2016), pp. 1-7.

<https://doi.org/10.1016/j.ijmachtools.2016.04.010>

Zhou et al., 2019a X. Zhou, Y. Wang, J. Zhang, F. Liu

Fracturing behavior study of three-flawed specimens by uniaxial compression and 3d digital image correlation: sensitivity to brittleness

Rock Mechanics and Rock Engineering, 52 (2019), pp. 691-718.

<https://doi.org/10.1007/s00603-018-1600-4>

Zhou et al., 2019b X. Zhou, J. Zhang, Q. Qian, Y. Niu

Experimental investigation of progressive cracking processes in granite under uniaxial loading using digital imaging and AE techniques

Journal of Structural Geology, 126 (2019), pp. 129-145.

<https://doi.org/10.1016/j.jsg.2019.06.003>

Zuo et al., 2017 H. Zuo, D. Y. Choi, X. Gai, B. Luther-Davies, B. Zhang

CMOS compatible fabrication of micro, nano convex silicon lens arrays by conformal chemical vapor deposition

Optics express, 25 (2017), pp. 3069-3076. <https://doi.org/10.1364/OE.25.003069>