Application of laser speckle technology in solar wafer roughness inspection system

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An optical inspection system has been developed to study laser speckle technology which analyzes the solar wafer roughness. It can accurately measure the surface roughness, without contacting with the surface of the solar cells and increase the speed of measurement. The incident laser light on the surface of a solar wafer generates a reflected light, then, the variations in roughness of the speckle pattern can be observed for further analysis and judgement. According to the randomly-distributed bright spots, statistical methods are adopted to analyze the diffraction efficiency of computer-simulated surface relief gratings and calculate the surface roughness of solar wafers. The surface roughness of a solar wafer is determined by a CCD camera and the conveyor while using independently-developed software for rapid and continuous imaging as well as analysis through the image processing toolkit. In the future, this inspection technology can be utilized in industries related to solar wafer manufacturing.

Keywords: Optical inspection system, Laser speckle technology, Solar wafer, Roughness, Speckle pattern

1 Introduction

Solar energy has the potential to fulfill the major portion of sustainable energy demands of future generations1,2. The physical characteristic of solar cells is its photoelectron conversion reaction upon absorbing light energy3. The manufacturing of solar cells is based on the processing of semiconductor materials4. Solar cell applications attempt to create roughness on a wafer in order to trap as much sunlight as possible5. Irregular and zoomed images of a surface are measured by instruments, which are called a surface profile. When the stylus of the instrument scans along the surface, its motion in the vertical direction can be zoomed and plotted. The average mean of a surface roughness can be directly read out from such an instrument. The area curves of the surface profile comprise a roughness curve and an undulating curve. In general, the undulating curve falls within the scope of profile measuring and its value is much larger than that of the surface roughness. The two curves of a surface profile may be considered together or separately, thus, there are different definitions of surface roughness6,7. The surface roughness (Ra) refers to the mean deviation of the profile. The measurement of surface roughness must consider the consistency of Ra on a solar wafer which cannot be identified by the naked eye but through the contact inspection of a stylus. However, such contact may damage the surface. For instance, the contact measurement of a solar wafer by the surface roughness tester of Fig. 1 may scratch and damage the surface.

Due to the features of speckle, the inspection of surface roughness can observe bright spots around a reflected speckle as scattered light waves on the rough surface of a solar wafer interfere with each other at positions of reflection.

Laser speckle is the image of intensity distribution obtained by irradiating on a measured object which results in the interference effect8-10. It is related to the features of the laser transmitter and the surface...
properties of the measured object\textsuperscript{11,12}. The laser speckle is regarded as a measuring signal and is widely applied in various fields of engineering measurement as it has many advantages such as high sensitivity, easy mounting, detectable without any surface treatment and able to detect objects in high-speed motion\textsuperscript{13,14}. Therefore, laser speckle technology is utilized for the analysis and study of the surface roughness of a solar wafer as well as for measuring the surface roughness of solar cells.

The image of a solar wafer under a microscope shows that the distribution of a solar wafer has a periodic relief structure similar to that of grating. According to actual measurements as shown in Fig. 1(b), there are periodic relieves on the surface of solar wafer and the bright spots that interfere with a speckle are also periodic. Fig. 2 shows the surface structure of a solar wafer with different sized pyramid-shaped distributions whereas the surface of periodic relief has a similar distribution with the surface structure of surface relief grating. In this paper, the application of laser speckle technology in a solar wafer roughness inspection system is presented.

A screen is placed at the position of reflection, then the images of laser speckle on the screen are extracted by a CCD camera. Thus, the granular spots distributed around the reflecting light point can be observed. The reason for this phenomenon is that the scattered light waves on each part of an uneven solar cell interfere with other cells at the position of reflection. When the structural details of solar cells are in random arrangement, the speckles are also randomly distributed. For different surface roughness, the directions and phases of scattered laser light will vary with the distribution of light spots. According to the randomly-distributed spots, statistical methods are adopted to analyze the diffraction efficiency of computer-simulated surface relief gratings and calculate the surface roughness of solar wafers.

2 Theory of Laser Spot Analysis

The concepts deriving from the coupled wave theory noticed the relationship of the grating profile and diffraction efficiency, and many duties were undertaken to establish the outline of what process parameters influence the grating profile or diffraction efficiency. A general approach to solving the boundary problem of surface relief grating is to divide the grating into 3 areas (Fig. 3), which are free space (Region I), substrate (Region III), and the area (Region II) between the two\textsuperscript{15}.

Wave propagation in region II of the gratings is described by the scalar wave equation

\[ \nabla^2 E_{2,n} + k^2 \varepsilon_n(x,z_n) E_{2,n} = 0 \]  \hspace{1cm} (1)

where \( E_{2,n} \) is the electric field for the nth slab grating in region II; \( z_n \) is the z-axis coordinate of the nth slab grating; \( \varepsilon_n(x,z_n) \) is the relative permittivity for the nth slab grating;

\[ k = \frac{2\pi}{\lambda} \]

\( \lambda \) is the wavelength of the incident light.

The relative permittivity for the nth slab grating can be presented as follows:

\[ \varepsilon_n(x,z_n) = \varepsilon_i + (\varepsilon_{III} - \varepsilon_i) \sum_{h=-\infty}^\infty \tilde{\varepsilon}_{h,n} \exp(ihKx) \]  \hspace{1cm} (2)

where \( h \) is the harmonic index.

\[ K = \frac{2\pi}{\lambda} \]  \hspace{1cm} (3)

\[ \varepsilon_{h,n} = \left( \frac{1}{A} \right) \int_0^A u(x,z_n) \exp(-ihKx) \, dx \]  \hspace{1cm} (4)

![Fig. 2 — Surface structure of solar wafer](image)

![Fig. 3 — Boundary superposition of surface relief grating](image)
is the grating spacing and the function $a(x, z_n)$ is equal to either zero or unity depending on the shape of the grating.

According to the coupled wave theory, the sinusoidal wave and rectangular wave are utilized, and the irregular shaped function and the shape crater function are approaching to its boundaries. The distribution of refraction efficiency of the computer-simulated surface relief grating is as shown in Fig. 4. Similarly, the surface of a solar wafer is complicated and periodic with the brightness distribution of speckle and its diffraction efficiency can be deduced by the coupled wave theory. The boundary conditions have the superposition effect.

Then, the profile height $y$ of surface relief grating in a period can be composed as follows:

$$y = g_1 d \left[ \frac{g_2}{2} \sin \left( \frac{2\pi x}{A} + \frac{\pi}{2} \right) + 1 \right] + (1 - g_3) \text{rect} \left( \frac{2x}{A} \right) + g_4(x) + g_5(x)$$

when $|x| < \frac{g_2 A}{2}$

$$y = 0$$

when $|x| > \frac{g_2 A}{2}$

where $g_1$ is aspect ratio factor; $g_2$ is shape type factor which determines if the groove should be narrow or wide; $g_3$ is S-R ratio factor which determines if the grating should be similar to sinusoidal or rectangular type; $g_4$ is irregularity factor which concerns the irregularity of the groove margin; $g_5$ is pitch factor; $d$ is the height of grating.

Further analysis of the superposition effect considers the surface roughness based on the brightness distribution of speckle. If the surface structure of a substrate is known, the brightness distribution of reflected light spots can be calculated. In other words, if the brightness distribution is known, the surface relief of the substrate can be calculated.

The speckle is formed by laser light irradiating on the surface of an object and light waves scattered back from the surface interfere with each other within the space. The intensity of speckle varies due to different angles of incidence, surface structures, areas and wavelengths. The statistical magnitude of the light intensity distribution $I(X, Y)$ is as follows:

The correlation function of light intensity is:

$$C(X, Y) = \langle I(X, Y) I(X + X, Y + Y) \rangle$$

This function can obtain the distribution of speckles of solar wafer. When $X = Y = 0$, the maximum value can be gained, because the Fourier transformation of the function is:

$$P(S_x, S_y) = \int \int C(X, Y) \exp[i2\pi (S_x + S_y)] dx dy$$

The function after the Fourier transformation can represent the spatial frequency of the speckles. The probability density function of the intensity is presented in Eq. (3):

$$P(I) = (1/2\sigma^2) \exp(-I / 2\sigma^2)$$

where

$$\sigma^2 = \lim_{n \to \infty} \left( \frac{1}{2N} \right) \sum_{n=1}^{N} |A_n|^2$$

Hence, the mean value of the speckle intensities of solar wafer is:

$$<I> = 2\sigma^2$$

Because the mean value of speckle comparison is in direct proportion to the standard deviation of intensities:

![Fig. 4 — Distribution of diffraction efficiency of computer simulation](image)
The interdependent function of light intensity is:

\[ C_{12} = (\bar{X}, \bar{Y}) = (I_x(X, Y)I_y(X + \bar{X}, Y + \bar{Y})) \]  

This implies the variations in speckle due to the change of reflecting surface, \( I_1 \) and \( I_2 \) are intensity distributions before and after the change. The peak of this function reveals the motion of speckle and the change in the height of peak indicates the deformation of speckle.

The spot of the speckle image is of specified colour and can be separated from the background easily. The parameter of brightness of reflected light spots of solar wafer is defined, and thus, the surface structure of solar wafer can be estimated:

\[ R_b = \frac{I_r - I_s}{I_r + I_s} \]  

where

\[ I_r = \frac{1}{N_r} \sum_{i} (R_i + G_i + B_i) \]  
\[ I_s = \frac{1}{N_s} \sum_{i} (R_i + G_i + B_i) \]  

\( R_b \) is the brightness ratio of reflected spot to the spot nearby, \( I_r \) is the brightness of reflected speckle, \( I_s \) denotes the brightness of speckle nearby, \( N_r \) denotes the number of pixels in the reflected spot and \( N_s \) denotes the number of pixels in the light spots of the spot nearby. \( R_s, G_s, B_s \) are the intensity corresponding to red, green, and blue colour in the speckle image, respectively.

Let \( q(i) \) be the function of the center’s brightness and brightness near the center, \( a(i) \) be the function of the center area, \( e(i) \) be the number of interference points for speckles, \( l(e) \) be the function of space between the points of diffraction and \( n(e) \) be the ratio of brightness of the points of diffraction.

According to the experimental results, the empirical equation of the surface roughness of solar wafer is as follows:

when \( e(i) < 2 \)
\[ R_s = c_1 R_b + c_2 q(i) + c_3 a(i) \]  

when \( e(i) \geq 2 \)
\[ R_s = c_1 R_b + c_3 q(i)^2 + c_3 a(i)^{-1.5} + c_7 e(i) \]
\[ + c_8 l(e)^{-1.6} + c_9 n(e)^{1.65} \]  

where, \( c_1-c_9 \) is the correlation coefficients of the smoothening process of curve.

According to the empirical equation of the experimental results, the surface roughness of solar cells can be solved. The different numbers of inference points of speckle patterns are taken as the basis for division. When the number of inference points is less than 2, the surface roughness can be determined by Eq. (16) and when it is larger than 2, Eq. (17) is used.

3 Experimental Results and Discussion

For the application of laser speckle technology during analysis of the surface roughness of a solar wafer, the hardware architecture of this research included, linear automatic slide, CCD camera, PC, laser transmitter, reflectors, and solar wafer as shown in Fig. 5.

Regarding laser speckles on solar wafer surfaces of different roughness, the differences can be visibly

Fig. 5 — Hardware architecture of the inspection system
Fig. 6 — Laser speckle patterns of different surface roughness (a) Ra: 0.25 µm (b) Ra: 0.38 µm (c) Ra: 1.79 µm

<table>
<thead>
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<th>Surface Roughness (Ra-um)</th>
<th>Average (µm)</th>
<th>Program (Ra, Ave.)</th>
<th>Difference (µm)</th>
<th>Measured Profile</th>
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Fig. 7 — Comparison of speckle images and measurement by the surface roughness tester
observed on the interference images of speckles as shown in Fig. 6 in which the surface roughness of laser speckle patterns is 0.25, 0.38 and 1.79 µm, respectively. There are subtle variations in surface roughness of a solar wafer.

Since the surface of solar wafer is complicated, there is a small gap between the calculated roughness and the roughness measured by the surface roughness tester. Table 1 presents a datasheet listing measured roughness by a tester and the related data obtained after measurement according to a surface roughness inspection system.

Under the laser speckle, the subtle changes in the surface roughness of solar cells can be observed. The results show the comparison of speckle images and measurement by the surface roughness tester (Fig. 7).

The measured results of the roughness of the four sides of each solar cell indicate that the roughness differs by +/-0.15 µm and there are visible regular peaks and valleys from the roughness of 0.35 µm on the profile image as measured by the surface roughness tester. However, the speckle images reveal that the interference points scatter from the roughness 0.35 µm. The higher the surface roughness of solar cells, the greater the number of interference bright points in the speckle images and the greater the distance between these bright points. In other words, the larger the roughness, the greater the distance between the bright points of interference. When $R_a$ exceeds 20 µm in the surface roughness inspection, the products of solar wafer are regarded as defective products. However, even if the $R_a$ of the measured object is far lower than the threshold, the impacts of vibration during wire saw cutting can be determined from a contrast of the speckle’s brightness and that of interference points and the accuracy for inspection can be controlled within 3%. An atomic force microscope (AFM) is used for measurement. Surface measurement data of solar cells is 0.248 µm in Fig. 8(a). Figure 8 (b) shows the 3D images of the

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<th>$R_a$ (µm)</th>
<th>$q(i)$</th>
<th>$a(i)$</th>
<th>$e(i)$</th>
<th>$l(e)$</th>
<th>$i(e)$</th>
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Fig. 8 — (a)-Surface measurement data of solar cells with an atomic force microscope measurement, (b) 3D images of the surface of solar cells with an atomic force microscope measurement
surface of solar cells with an atomic force microscope measurement. KOSAKA ET3000 is employed to measure the surface roughness of solar cells which is 0.34 µm by means of contact measurement (Fig. 9). The surface periodicity is thus, obtained. The measuring results by various measuring instruments are compared with the measured result of the speckle pattern in order to verify its accuracy.

The roughness values of the four sides of solar cells are measured by the statistical table of measurement results of the speckle pattern and the surface roughness tester, and then, the average values are calculated in order to compare the measured results of the speckle pattern. The error between the two is less than 0.1 µm; thus, the practicability and accuracy of this system are verified.

4 Conclusions

Although there are many methods of measuring the surface roughness and characteristics, this study proposed an innovative method that uses the automatic inspection abilities of laser speckle, conducted by CCD and the linear-motion-driven XY-Table, in order to construct a simple automatic surface roughness inspection system for solar wafers. Surface roughness inspection by applying laser speckle technology can increase inspection speed and accurately conduct an inspection without contacting the surface. It can accurately calculate the surface roughness of solar wafer with less limitation than the other methods. The overall structure is simple and can be fabricated at a low cost. It can quickly and accurately conduct the surface roughness inspection
of solar wafers, which are so fragile that a stylus is not suitable for such measurements, and thus, the non-contact speckle technology can be applied. It is a field which the AOI system is well-adapted to, as the surface roughness inspection of solar wafers through laser speckle technology can be accurate within 3%. The range of roughness estimated from the proposed method can be from 0.1 to 30 µm. Therefore, it is a technology worthy of further popularization and application.

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References