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Roughness characterization of well-polished surfaces by measurements of light scattering distribution

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According to vector scattering and scalar scattering theory, the relationship of BRDF (bidirectional reflectance distribution function) of light scattering from micro-rough surface with TIS (total integrated scattering) is analyzed. Roughness statistical characterization such as RMS (root mean square), PSD (power spectral density) function are deduced by TIS of polished surface. Based on the light scattering measurement theory, an automatic measure system of light scattering with one dimensional scanning method is built, BRDF of two kinds of polished surfaces (silica surface and Ag reflector) have been measured. PSD of two surfaces has been given by light scattering measurements, roughness characterization of two surfaces has been compared with the data tested by profile meter. The results show that the light scattering measurement method has great application prospects as regards nondestructive measurement for polishing surfaces.

Keywords: light scattering, roughness, bidirectional reflectance distribution function (BRDF).

1. Introduction

In modern industry, there are growing needs for testing roughness of well-polished surfaces, such as metal, ceramic, glass, semiconductor wafer, and so on [1]. These polished surfaces are usually examined by using vision inspection method, comparing the surface examined with the sample of known roughness, or by using mechanical profile meter to examine the roughness. None of these methods is capable of fast, on-line, nondestructive, noninvasive measurement [2]. Hence, a non-contact and more speedy optical method would be attractive. Different optical non-contact methods for measuring surface roughness have been developed mainly based on reflected light detection, focus error detection, laser scattering, speckle and the interference method. Among these methods, the light scattering method has proven to be a useful one [3].

The root mean square (RMS) roughness σ of well polished surface is often far less than the inspection wavelength λ, $\sigma/\lambda \ll 1$; these well polished surfaces can been called micro-rough surfaces. Light scattering, caused by micro-rough surfaces, not only contains roughness information on the surface but also provides an on-line and nondestructive method for the demanding quality control in modern industry. Numerous experimental data have been accumulated and analytical methods including numerical solutions have been developed to explain and inspect the roughness of a well polished surface [4, 5]. However, practical tools based on laser scattering technique are relatively few.

In this paper, the relationship of bidirectional reflectance distribution function (BRDF) of light scattering from micro-rough surface with total integrated scattering (TIS) is analyzed. Also, roughness statistical characterization such as RMS (root mean square roughness), PSD (power spectral density function), *etc*., are deduced by TIS of polished surface. And, an automatic measure system of scattering with one dimensional scanning method is introduced. Based on the light scattering measurement system, BRDF of two kinds of polished surfaces (silica surface and Ag reflector) have been tested, and RMS, PSD of two surfaces have been given by light scattering measurements. The results show that the light scattering measurement system can be widely applied to on-line and nondestructive measurement for polishing surface.

2. Theoretical description

The theoretical background of light scattering from a micro-rough surface is based mainly on Beckmann and Spizzichino's rough surface light scattering model [6]. As shown in Fig. 1, a beam of laser is directed towards a micro-rough surface, the reflected light field consists of specular reflection beam and scattered light.

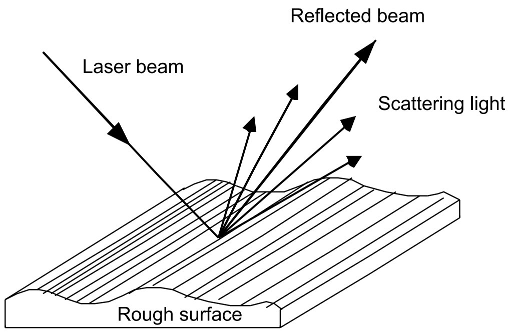

Fig. 1. Laser light scattering from rough surface.

According to Beckmann and Spizzichino's rough-surface light scattering model, for a well polished surface, the roughness of which is much smaller than the wavelength of the scattered light, the relation between the scattered light and surface roughness is as follows:

$$\mathrm{TIS} = 1 - \frac{R}{R_0} = 1 - \exp\left[-\left(\frac{4\pi\sigma\cos\theta_i}{\lambda}\right)^2\right] \tag{1}$$

where TIS is the total integrated scattering, R is the specular reflection ratio, R_0 is the total of reflection and scattering ratio, θ_i is the incident angle, λ is the laser wavelength, σ is the root mean square roughness. Equation (1) shows that TIS is the function of root mean square σ. So, the root mean square σ can be acquired by measuring the total integrated scattering light.

Under certain circumstances, total integrated scattering can be acquired by angular resolved scattering (ARS) method. NICODEMUS *et al.* [7] introduced the ARS method and BRDF was put forward, the latter being defined by:

$$\mathrm{BRDF} = \frac{\mathrm{d}\,L_s\,(\Omega_s)}{L_i\,\cos\theta_i\,\mathrm{d}\Omega_i} \tag{2}$$

In Equation (2), $\mathrm{d}\,L_s$ is the flux of light scattering, L_i is the total flux of incident light, Ω_i is the solid angle of incident light, Ω_s is the solid angle of outgoing direction. So, the angle resolved light scattering techniques (ARS) can be used to make maps of scattering as a function of position on a surface and to give the RMS roughness

$$\mathrm{ARS} = \mathrm{BRDF}\cos\theta_s$$

Thus, the total integrated scattering is the integral of the BRDF:

$$\mathrm{TIS} = \int \mathrm{BRDF}\,\cos\theta_s\,\mathrm{d}\Omega_s = \int_0^{\pi/2} \sin\theta_s\,\mathrm{d}\theta_s \int_0^{2\pi} \mathrm{BRDF}\,\cos\theta_s\,\mathrm{d}\varphi_s \tag{3}$$

The θ_s and φ_s are illustrated in Fig. 2.

Also, the surface power spectral density (PSD) function can be calculated from the measured bidirectional reflectance distribution (BRDF) function

$$\mathrm{BRDF} = \frac{16\pi^2}{\lambda^4}\cos\theta_i\,\cos\theta_s\,Q\;\mathrm{PSD} \tag{4}$$

The light wavelength is denoted by λ, and the angles θ_i and θ_s (measured from surface normal) are the incident and scattering angles, respectively, Q is the polarization coefficient (which is numerically close to the specular reflectance for many situations). This relationship has been investigated in great detail in the literature and has been proven to be very accurate for the case of smooth, clean, front surface reflectors. The PSD function is the frequency spectrum of the surface roughness

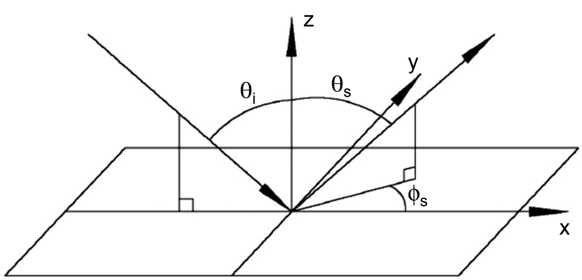

Fig. 2. The geometry angle used in the paper.

measured in units of spatial frequency. The PSD function provides information about both the amplitude and spatial wavelength of the surface. The most useful feature of the PSD function is that it relates information about the Fourier transform of the surface into a form that makes it possible to readily compare information generated from various instruments. The RMS roughness may be calculated directly as the square root of the integral of the one-dimensional PSD curve.

So, after the angle resolved light scattering (ARS) measurement instrumentation has been built, roughness characterization such as root mean square roughness and PSD of well polished surfaces can be acquired by light scattering measurement according to Eqs. (1)–(4).

3. Measurement system arrangement

An automatic measurement system of scattering has been developed to perform high-speed, accurate, non-contact measurements of surface roughness. Figure 3 shows the arrangement of measurement system which was made in Zhejiang University. A visible He-Ne laser emits a laser beam that passes through a splitter, one beam is encoded by a chopper and strikes the sample surface, and one beam is reflected by a splitter into detector for phase lock signal. The sample is put on an angular resolved plane. The light is reflected and scattered by the sample surface into a photomultiplier, decoded and amplified by phase-lock amplifier, then input and processed by a computer.

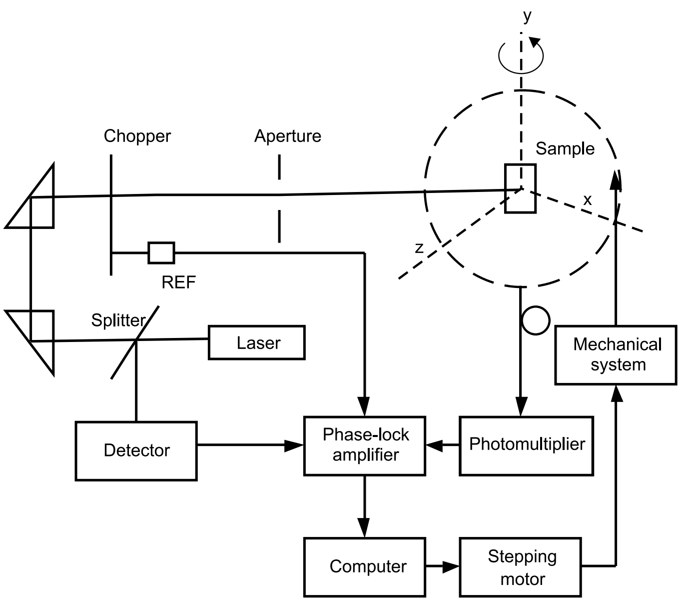

Fig. 3. Arrangement of measurement system.

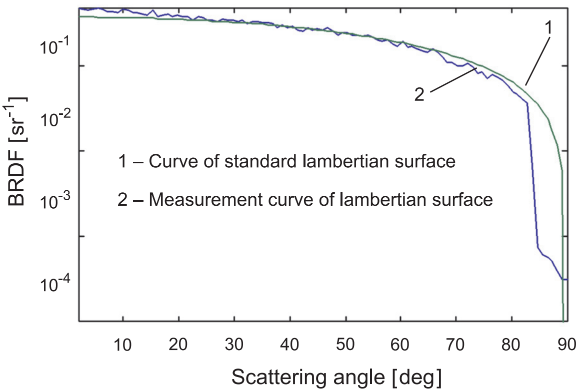

Fig. 4. Calibration curve of measurement system.

The intensity and angular distribution of the specularly reflected and scattered light are measured, the data are digitized, and the roughness characterization of surface sample is calculated at the position of the illuminated spot by the computer. The parameters of the system are as follows:

– Light source: He-Ne laser,10 mW;
– Sensor: photomultiplier tube (PMT);
– Angle range: form –90° to 90°;
– Angle step: 0.45°;
– Angular resolution: 0.5°;
– S/N ratio: > 40 dB;
– Size: 2000 mm×1200 mm×900 mm.

Calibration of measurement system is carefully established by standard lambertian surface. $BaSO_4$ powder was pressed in the plate as calibration plate, which was proved the scatter the radiation incident according to the Lambert law. Figure 4 shows the calibration curve. From Fig. 4, the calibration curve is well matched with the lambertian surface from 0 to 80°.

4. Measurement and experiment

The new automatic measurement system of scattering is used to measure the well polished surface. A well polished silicon wafer and an Ag-coated reflector have been used as an example.

Figure 5**a** shows tested BRDF data of Ag-coated reflector at a 9° angle of incidence, Fig. 5**b** shows tested BRDF data of well polished silicon wafer using measurement system at different incidence angles: 9°,18°, and 36°.

At the same time, profile meter was used to test the roughness characterization of two surfaces. This instrument has measurement length 80 μm and a height sensitivity of –0.1 nm RMS. Figure 6 shows the tested profile data of well polished silicon wafer

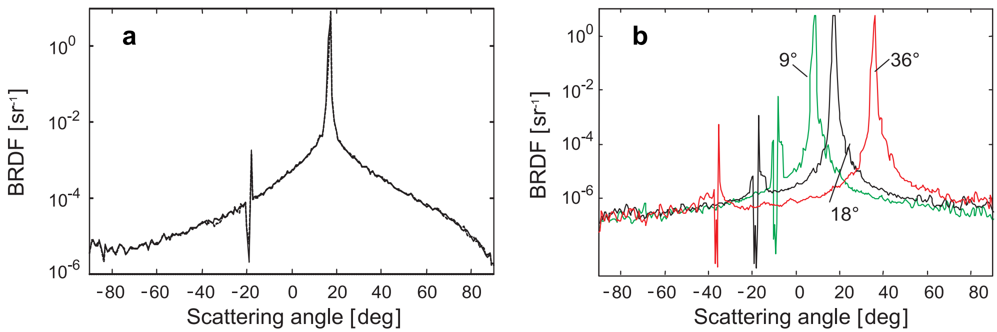

Fig. 5. Test BRDF of silicon wafer using measurement system: BRDF data of Ag-coated reflector at a 9° angle of incidence (**a**), BRDF data of polished silicon wafer at 9°, 18°, and 36° angles of incidence (**b**).

(Fig. 6**a**), of Ag-coated reflector (Fig. 6**b**), whereas Fig. 6**c** is the HDF (height distribution function) of well polished silicon wafer, and Fig. 6**d** is the tested HDF of Ag-coated reflector.

PSD of the sample surfaces can be calculated by Eq. (4). In Figure 7, curve 1 represents the PSD calculated by angle resolved light scattering method; another

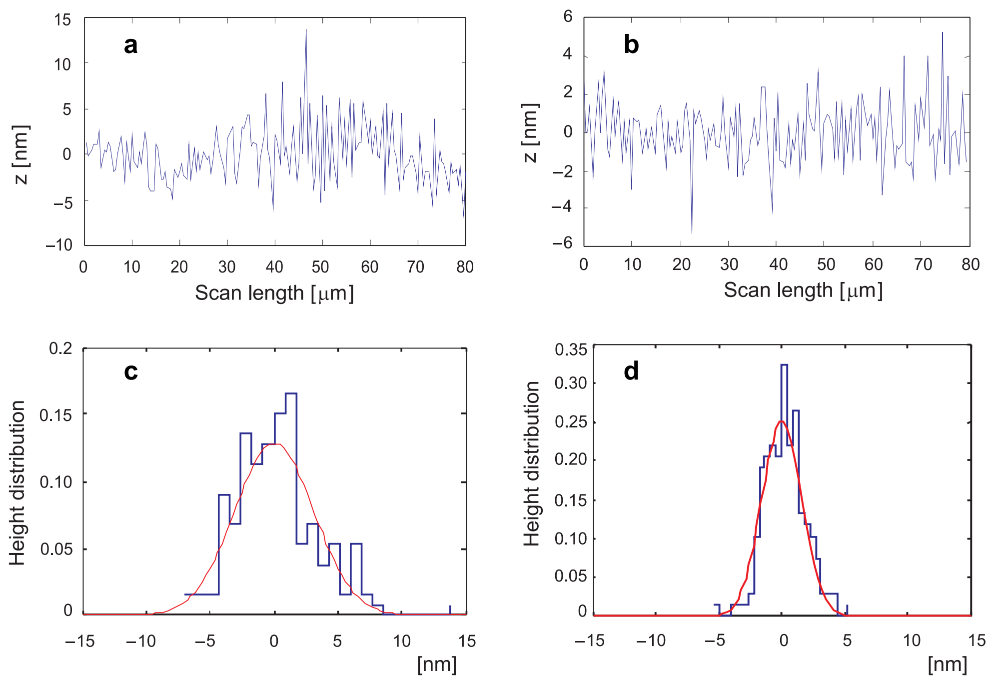

Fig. 6. Tested roughness data of silicon wafer and Ag-coated reflector using profile meter: surface profiler of silicon wafer (**a**), surface profiler of Ag-coated reflector (**b**), height distribution function of silicon wafer (**c**), height distribution function of Ag-coated reflector (**d**).

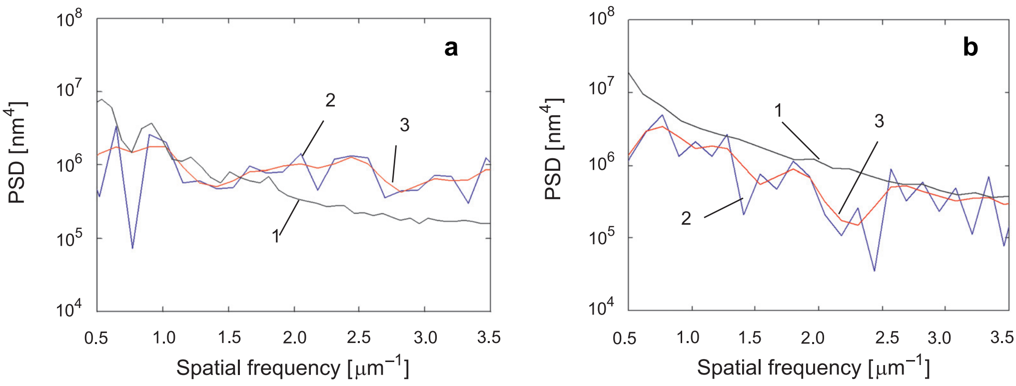

Fig. 7. PSD of two surfaces using different test methods: PSD curve of silicon wafer (**a**), PSD curve of Ag-coated reflector (**b**).

method is using height distribution function to calculate PSD; curve 2 (blue) and curve 3 (red) are two PSD curve which are calculated by height distribution function data using profile meter, with the measurement being repeated twice to improve the measurement precision. Figure 7**a** shows the PSD curves of silicon wafer, and Fig. 7**b** shows the PSD curves of Ag-coated reflector. Comparing the PSD curves which are calculated by different methods, we can see that the PSD curves match well, which means that the angle resolved light scattering method can be consistently used to measure the roughness of polished surface.

By Equations (1)–(4), the root mean square roughness σ can be calculated. The Table compares the tested RMS roughness of silicon wafer and Ag-coated reflector using light scattering method with the data tested using profile meter.

T a b l e. Comparison of tested RMS data using different method.

	RMS [nm]	
Surface	Profile meter	Scattering
Silicon wafer	2.044	2.981
Ag-coated reflector	1.581	2.648

By comparing the roughness test result using the method of light scattering with that of using profile meter, roughness data by scattering method is usually larger than that of using profile meter. There are many reasons for this; firstly, any pits or other surface defects that have large deviations from the mean surface level greatly influence the RMS roughness values, especially influenced by scattering derived method because of surface defects. Secondly, the roughness data derived by scattering method probably contain the particulate scattering effects, which would influence the result greatly in scattering method. So, individual dust particles are readily avoided in the light scattering measurement system.

5. Conclusions

In this paper, an automatic measurement system of scattering is introduced to test roughness by the relationship of BRDF of micro-rough surface with TIS. Roughness statistical characteristics are measured by TIS and BRDF of polished surface. The BRDFs of two kinds of polished surfaces (silica surface and Ag reflector) have been tested, and RMS, PSD of two surfaces have been given by light scattering measurements. Also, tested roughness characteristics are compared with test data using profile meter. The results show that light scattering measurement system has great application prospects in non-destructive testing for polished surface.

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