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The calculation of incident conditions by APSD analyzation in multiple-beam laser interference lithography

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Abstract
Laser interference lithography (LIL) is becoming a popular technique for fabricating functional surfaces on different materials, because of the low cost and high efficiency. By multiple beam LIL, hierarchical structures were fabricated and applicated in a variety of fields. Incident conditions determine the shape and size of the final patterns and a small change in incident condition can cause a great error. However, misalignment in incident conditions in LIL system was common. Periods of the final pattern have been used to calculate the incident angle in two beam LIL, but for patterns fabricated by multiple-beam laser interference lithography, which were more complicated, it was difficult to find the periods directly. This paper reported a novel method used for calculating the incident conditions in multiple-beam LIL, including incident angle and azimuthal angle using laser intensity distribution. The mathematical simulation result indicated that APSD (areal power spectral density) analyzation can be applied in incident conditions calculation. Silicon wafers were fabricated by three-beam LIL as samples and measured by stylus profiler. The result was analysed by the new arithmetic and the actual incident condition was given.

Laser interference lithography, incident conditions, average power spectral density, surface topography

1. Introduction

Laser beam machining is one of the major methods in functional surface fabrication. Compared with other laser beam machining techniques, laser interference lithography (LIL) is more effective and economical, for it can process perfect micro- and nano- structures with a single exposure. LIL fabricated surfaces were widely applicated in different fields, including data storage [1], hydrophobic surfaces [2, 3], and solar cells [4, 5].

The theory of interference had been studied during the past decades and the effect of different parameters had been analysed. C. Tan talked about the influence of incident angle on period of patterns [6]. M. Ellman investigated the effect of laser fluence on structure width and depth [7]. D. Wang studied the effect of incident angle in TE and TM polarization mode [8]. T. Tavera changed the azimuth angle of laser to generate quasi-periodic patterns [9]. Research on interference system set-up and phase control has also been done [10, 11]. However, the researches on incident angle and azimuth angle were based on the direct measurement of periods of periodic patterns. For the quasi-periodic patterns generated by multi-beam LIL, both the measurement of periods and the calculation of incident conditions became more complicated.

This paper presented a novel arithmetic to test the incident conditions in multi-beam LIL. By analysing the average power spectral density (APSD) of the surface profile, incident parameters including incident angle and azimuth angle can be calculated. Mathematic simulation was carried out to perform the process of incident condition analyzation. To verify the arithmetic, a three-beam LIL fabricated silicon wafer was measured, and the topography was analysed to calculate the incident parameters.

2. Theory of laser interference lithography

2.1. Intensity of interference pattern

Based on the theory of interferometry, the final laser intensity distribution in laser interference is the superposition of fringes generated by each two beams and a direct component, which can be expressed by

$$I = \frac{1}{2}\sum_{i=1}^{n} a_i^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j (\vec{p_i}\cdot\vec{p_j}) \cos(\mathrm{k}\cdot[(\vec{r_i}\cdot\vec{d}) - (\vec{r_j}\cdot\vec{d}) + \delta_i - \delta_j), \quad i,j \in \mathrm{N}^* \tag{2-1}$$

where I is the final intensity, n is the number of beams, a is the amplitude of each beam, $\vec{p}$ is the polarization vector, $\mathrm{k} = \frac{2\pi}{\lambda}$ is the wave number and λ is the wavelength of the laser, $\vec{r}$ is the propagation vector, $\vec{d} = x\cdot\vec{i} + y\cdot\vec{j} + z\cdot\vec{k}$ is the position vector and δ is the initial phase of the beam.

The sinusoidal components in the intensity distribution make up the interference pattern. The orientation and period of each interference component are determined by the incident angle and azimuth angle of the two beams. The amplitude of each fringe is determined by the laser intensity and polarization angles.

2.2. Orientation and period of each interference component

As two laser beams interfere with each other, if the incident angles are θ_1, θ_2 and the azimuth angles are ϕ_1, ϕ_2, respectively, the orientation of the interference fringe can be represented by the angle between the orientation and the coordinate axis, which is calculated by

$$\tan\alpha = \frac{\cos\phi_1 \sin\theta_1 - \cos\phi_2 \sin\theta_2}{\sin\phi_1 \sin\theta_1 - \sin\phi_2 \sin\theta_2} \tag{2-2}$$

and the period of the interference fringe can be calculated by

$$P = \frac{\lambda}{\sqrt{(\cos\phi_1 \sin\theta_1 - \cos\phi_2 \sin\theta_2)^2 + (\sin\phi_1 \sin\theta_1 - \sin\phi_2 \sin\theta_2)^2}} \tag{2-3}$$

where λ is the wavelength of the beams.

Hence,

$$\cos\phi_1 \sin\theta_1 - \cos\phi_2 \sin\theta_2 = \pm\frac{\lambda \tan\alpha}{P\sqrt{\tan\alpha^2+1}} \tag{2-4}$$

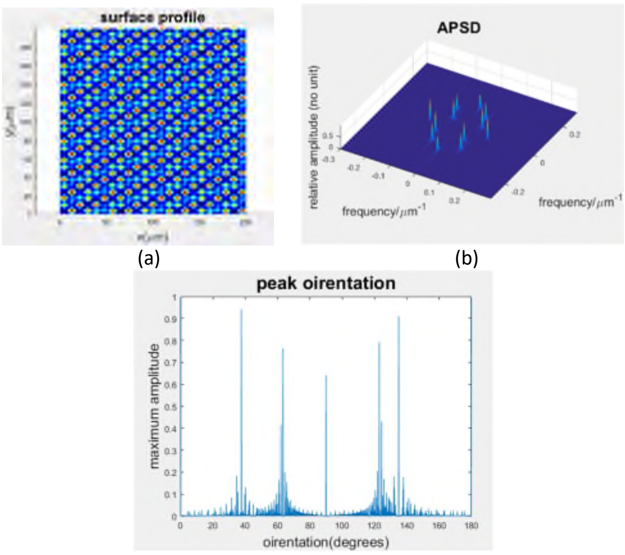
$$\sin\phi_1 \sin\theta_1 - \sin\phi_2 \sin\theta_2 = \pm\frac{\lambda}{P\sqrt{\tan\alpha^2+1}} \tag{2-5}$$

2.3. Calculation of incident angle and azimuth angle

By using the APSD function, the orientation and period of each sinusoidal component can be extracted. Each interference component will generate two equations from Equation (2-4) and Equation (2-5), which make up an equation set to calculate the incident angle and azimuth angle of each beam.

3. Mathematical simulation

A MATLAB program was designed to extract the interference components and calculate the incident parameters. First, the light intensity distribution of a 4-beam interference pattern was simulated, shown in Figure 1(a). The wavelength of laser was 1064 nm, the azimuth angles were set at 0°, 90°, 180°, 270°, and the incident angles were set at 3°, 3°, 4°, 6°, respectively. The polarization mode was TE-TM-TE-TM (TE refers to transverse electric and TM refers to transverse magnetic), which means each two beams interfere with each other and 6 interference fringes was generated. However, it was difficult to measure the period and orientation of each component directly from the quasi-periodic profile. The APSD image of the surface was shown in Figure 1(b). The orientation of each component is shown in Figure 1(c). It can be observed that the orientations were 0°, 37.6°, 63.4°, 90°, 123.0° and 135.0°. The periods were 8.6912 µm, 12.1879 µm, 8.9397 µm, 6.893 µm, 8.3802 µm and 14.1351 µm.



(a) (b) (c)

Figure 1. Simulated images

After calculation, the incident angles of the beams were 3.04°, 2.99°, 3.99°, 6.03°, the azimuth angles of the beams were 0.36°, 90.52°, 179.72°, 269.73°. The error of incident angle was smaller than 0.05° and the error of azimuth angle was smaller than 0.5°. In the real laser interference system set-up, the error of incident angle can vary from a friction of degree to a degree, the error of azimuth angle can be several degrees. Hence, this arithmetic can be used to calculate the incident parameters accurately.

4. Experiment

A silicon wafer was fabricated by three-beam LIL using a high-power pulsed Nd:YAG laser. The wavelength was 1064 nm. The incident angles were set at 5°, 5°, 5°, and the azimuth angles were set at 0°, 120°, and 240°. The profile of the sample was shown in Figure 2. Periodic structures can be observed on the surface. However, because of the irregular shape of the structures, it was difficult to measure the period and orientation of the components directly.

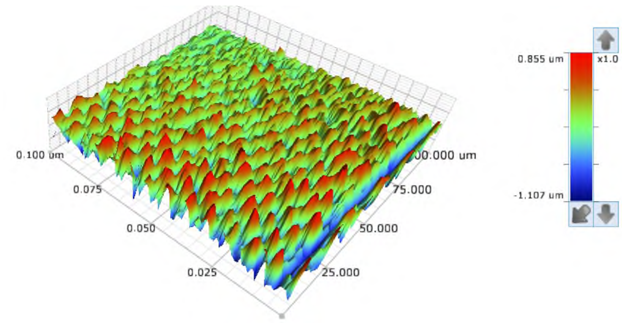


Figure 2. AFM image of three-beam LIL fabricated silicon wafer

After analysing the 3D profile of the sample using APSD function, the incident angles were calculated to be 4.92°, 4.85° and 4.57°, and the azimuth angles were 0.34°, 119.72° and 239.48°, respectively.

5. Conclusion

In this paper, a novel arithmetic was presented to calculate the incident conditions in multi-beam LIL. Mathematic simulation was carried out to verify the accuracy of the arithmetic, and the arithmetic was used to calculate the incident angle and azimuth angle of a three-beam LIL fabricated silicon wafer. For periodic or quasi-periodic structures generated by multi-beam LIL, this arithmetic can effectively test the incident conditions, which can be used in adjusting the incident parameters to obtain ideal interference pattern.

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