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Silicon wafer microstructure imaging using InfraRed Transport of Intensity Equation

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ABSTRACT

A novel quantitative 3D imaging system of silicon microstructures using InfraRed Transport of Intensity Equation (IR-TIE) is proposed in this paper. By recording the intensity at multiple planes and using FFT or DCT based TIE solver, fast and accurate phase retrieval for both uniform and non-uniform intensity distributions is proposed. Numerical simulation and experiments confirm the accuracy and reliability of the proposed method. The application of IR-TIE for inspection of micro-patterns in visibly opaque media using 1310 nm light source is demonstrated. For comparison, micro-patterns are also inspected by the contact scanning mode Taylor Hobson system. Quantitative agreement suggests the possibility of using IR-TIE for phase imaging of silicon wafers.

Keywords: infrared imaging; phase retrieval; defocused intensity; transport of intensity equation

1. INTRODUCTION

Silicon wafers are widely used in ultra-large-scale integration (ULSI) and micro-electro-mechanical system (MEMS), in quality control process it's very important to assess the yielding microstructure etched on or inside the wafer. The conventional mechanical probe processes may cause substrate scratch, moreover it costs more time due to mechanical movements. Non-invasive phase imaging techniques has gained more attractions. There are several main types of quantitative phase imaging (QPI): off-axis, phase-shifting, common-path and white-light where TIE can be considered of the fourth category [1]. This technique is based on the theoretical formalism developed by Teague [2]. TIE imaging relies on the derivatives of the wave equation in the paraxial approximation. It works under coherent illumination (usual laser) also capable with partially coherent field. Direct phase retrieval from intensity measurements using the TIE has begun to enter the actual application [3, 4]. Infrared (NIR) imaging plays a big role in non-destructive testing in medicine, aerospace and semiconductor industries. For silicon wafers normally visible light cannot pass through, whereas it's transparent in IR range. Existing 3D IR visualization systems are mainly based on interferometric methods such as optical coherence tomography (OCT) or time consuming measurement processes as in the case of IR confocal microscopy. In this paper we seek to develop a novel type of method for quantitative 3D IR imaging. Our new system can be an alternative for subsurface measurement applications such as non-destructive testing and medical imaging (eye biomedical diagnostic). This prototype is non-interferometric and inexpensive compared to existing solutions. Additionally, by using tunable lens [5] (electrically monitored) the system is capable for real time imaging at millisecond temporal resolution which broadened the spectrum of possible applications. With the vigorous development of the high-precision imaging industry, the whole setup can be mounted on a commercial inverted bright-field microscope [6], it lays the foundation for functionalization and industrialization.

2. THEORY

2.1 Basis

Assuming there is one paraxial beam is propagating along the z axis, the scalar wave field be written in terms of an amplitude and phase as $\sqrt{I(\mathbf{r})} \exp[ik\varphi(\mathbf{r})]$. Under the approximation of a slowly varying field along the z axis, the derivative of intensity in the light propagation implicates phase information that can be retrieved via:

$$-k \frac{\partial I(\mathbf{r})}{\partial z} = \nabla \cdot [I(\mathbf{r}) \nabla \varphi(\mathbf{r})] \quad (1)$$

Where k is the wave number $2\pi/\lambda$, and λ is the spectrally-weighted mean wavelength of illumination, $\mathbf{r}$ is the position vector representing the spatial coordinates (x, y) , $I(\mathbf{r})$ is the intensity at the image plane. ∇ is the gradient operator over $\mathbf{r}$ which is normal to the beam propagation direction. Eq. (1) indicates that knowledge of the intensity distribution and its axial derivative yields information about the phase distribution. Expanding the Eq. (1), we obtain

$$-k \frac{\partial I}{\partial z} = \nabla I \cdot \nabla \varphi + I \nabla^2 \varphi \quad (2)$$

On the right-hand side, there are two terms that contain phase gradient (first-order derivative) and phase curvature (second-order derivative) respectively. This indicates that the variations of light intensity are codetermined by phase slope and its curvature. The gradient performs beam shift (as a prism) while curvature is a drive for convergence and divergence of light (as a lens). So they are also known as prism term and lens term [7]. The intensity distribution can be directly measured at the image plane and its z -derivative is obtained by defocusing the image slightly in both the positive and negative z -directions.

Now we consider certain circumstances of the equation: firstly the phase is a constant, the right-hand side of equation is zero, and we cannot observe any changes on intensity in propagation, actually the performance is consistent with plane wave. There's another more meaningful case: when the irradiance of the light field is uniform, which is for pure phase object, Eq. (2) can be further simplified:

$$-k \frac{\partial I}{\partial z} = I \nabla^2 \varphi \quad (3)$$

This is a standard Poisson equation which indicates the light intensity distribution from a slightly defocus pure phase object is proportional to its curvature (second-order derivative) of phase.

2.2 Simulation

To verify the performance of TIE algorithm, we generate one complex light field. The intensity equation is set to be

$$I = \exp \left[\frac{-(x^2 + y^2)}{2\sigma^2} \right] \quad (4)$$

Which is a standard two-dimensional Gaussian function, here $\sigma = 0.2$, and the phase we stimulated as

$$\varphi = x^2 + 2x - 3y^2 - 4y + 0.5 \quad (5)$$

It has small fluctuation where can be considered from any real phase object. Here x and y denote pixel coordinates or pixels grid whose distribution is symmetric, and that can be calculated by multiplying pixel subscript and pixel pitch. This complex field is defined on a 256×256 grid and the pixel pitch is $2 \mu m$, wavelength is $632.8 nm$ (commonly used He-Ne laser). The field of view is 200×200 pixels which means leave a black margin around the region of interest (ROI), this technique is necessary in use of angular spectrum propagation method, this safe band keeps most of frequency signal inside the discrete grid, for TIE algorithm it also demand the energy should be equal when calculate derivative especially on the boundaries. Angular spectrum propagation is implemented to generate two defocused images, here called I_+ and I_- respectively, and shift distance $\Delta z = \pm 10 \mu m$. Derivative approximation equation is shown below:

$$\frac{\partial I(\mathbf{r})}{\partial z} \approx \frac{I_+(\mathbf{r}) - I_-(\mathbf{r})}{2\Delta z} \quad (6)$$

Substituting Eq. (6) into Eq. (1) gives us the phase, φ . The simulation results are shown in Fig. 1.

Fig. 1 (a) intensity images stack; (b) intensity axial derivative; (c) original phase; (d) retrieved phase; (e) phase residuals

The metric relative root-mean-square error (RMSE) of the residual map is 0.0048 rad. It proves that in this model the performance of the algorithm is accurate and reliable. Here in phase reconstruction test experiment, we directly calculate two images to get approximate axial intensity derivative. Based on equations, the smaller defocus distance is, the more accurate derivatives are obtained. However, in practice, there is a contradiction: under test beam with phase object information usually contains noise, distortion and position shift, which are produced from incorrect magnification and misalignment etc. in setup. Besides, when Δz is small enough in denominator, the variations of light intensity and distance shift will become equivalent infinitesimal. The unwanted high order error will behave more obviously. On the other hand, enlarging the distance would undermine the accuracy of the estimation on slope. In order to overcome this tradeoff, some new computational techniques are proposed [8-10]. The optimal frequency selection method efficiently solves the contradiction between low frequency components and high order nonlinearity errors, improving the signal-to-noise ratio (SNR) and accuracy.

3. EXPERIMENT

The actual silicon wafer microstructure imaging setup is shown in Fig. 2 (a) and its schematic diagram is illustrated in Fig. 2 (b).

Fig. 2 (a) actual experimental setup; (b) schematic diagram

In this experiment we use one super luminescent light emitting diode (SLED) broadband source (central wavelength 1310 nm and bandwidth of 30 nm) which has been expanded and collimated. Then it passes through the silicon wafer where microstructure exists. The object is reimaged onto IR-CCD camera with a magnifying 4f system. The IR CCD

camera has a resolution of 320×256 and $20 \mu\text{m}$ pixel size. The focal length of each lens is 5 cm and 10 cm respectively, and the object distance to the first lens is equal to its focal length. The camera is placed on a translation stage that can change axial distance, Δz to record the desired images. The phase object under test is a geometric pattern etched on silicon wafer substrate. Several images are recorded by IR camera and processed using the DCT TIE solver. Two datasets from image stack with defocus distance 7 mm was used. The two defocused images are located symmetrically on either side of the image plane ($\Delta z = 3.5 \text{ mm}$). Fig. 3 shows the through the focus intensity images with Fig. 3 (b) corresponding to the in-focus image, while (a) and (c) are images on either side of focus. Being a nearly pure phase object the in-focus image barely shows a recognizable shape of structure. Numerical solution of partial differential equations using the DCT solver is implemented to retrieve phase. The height is then delineated from phase or the optical path difference using the refractive index of silicon wafer as $3.5003 @ 1310 \text{ nm}$.

Fig. 3 Silicon wafer imaging intensity in different image planes (a) -3.5 mm from the focal plane; (b) at the focal plane; (c) 3.5 mm from the focal plane

To better assess the accuracy of the phase measurements, we use a high precision direct contact instrument (Taylor Hobson Talyscan 150, scanning area $5 \text{ mm} \times 5 \text{ mm}$ with spacing 5 microns) to independently measure the ROI surface profile. Comparison of the results from two measurements is illustrated in Fig. 4.

Fig. 4 (a) Taylor Hobson stylus contact measurement result; (b) TIE phase imaging result

Fig. 5 Profile comparison along the red line of thumbnail image (TH represents Taylor Hobson)

TIE phase imaging result Fig. 4 (b) retains all the edges from original microstructure, and moreover, the third 'L & I shape' can be faintly seen in its mesh while it disappears in direct contact result Fig. 4 (a). To have a better view on results, the values are extracted from the same line (red line on bottom image, Fig. 5). The offsets of the two curves were adjusted to the same level. The trends of two curves are accordance with each other, particularly in hopping transition places. The TH gives about $0.4\ \mu\text{m}$ average peak-to-valley height between bottom groove and flat top in central part, as a contrast, TIE can achieve the similar result. Although the good results are obtained, irregularities of TIE result on background and discrepancy of in-line curves still have drawn attention. Actually from Fig. 3 we can notice the raw images have those unwanted clutter and stripes, dirty dots on defocused image are more obvious. This non-object intensity information has actually undermined the true phase retrieval quality. Cleaner field of view with better imaging system will significantly improve the accuracy of results and the success rate when solving.

4. CONCLUSION

In this paper, we have introduced a new method to image silicon wafer microstructure quantitatively. The contrast results between Taylor Hobson and TIE have shown good accuracy and reliability. Quantitative phase imaging based on TIE presents more advantages than conventional methods, no interferometric fringe pattern, also works with partially coherent illumination, get recovered phase directly no need 2π unwrapping, due to relatively inexpensive components and easily assembled structure, all makes great promise in further applications.

5. ACKNOWLEDGEMENT

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