Digital holographic microscopy for silicon microsystems metrology

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ABSTRACT

We propose to use digital holographic microscopy (DHM) with an illumination in the near infrared spectrum bandwidth, where the silicon is known to have small absorption. With such an illumination condition, it is possible to observe a wider range of specimens than in the visible spectrum, providing a new metrology technique for 3D silicon micro-systems characterization. Suitability of DHM with near infrared illumination for micro-optical elements and wafer inspection is demonstrated. The intrinsic robustness and speed of the method place DHM as a valuable candidate for real-time quality check inside production chains, opening a wide field of applications in quality control.

Keywords: Digital Holography, near infrared

1. INTRODUCTION

Interferometric measurement techniques have been increasingly considered as a valuable approach for micro-systems quality check.[1] Repetto *et al.* reported on an infrared holographic setup for metallic films on silicon wafers inspection,[2] but structures embedded in silicon remain difficult to observe in 3D and constitute an increasing demand of engineers realizing 3D devices. DHM is a contact-free, non destructive full-field optical measurement technique with real-time capabilities enabling the access to both amplitude and phase of the field transmitted through the sample under investigation.[3] Moreover, numerical techniques can be applied to automatically compensate for aberrations.[4] When using the transmission configuration, the phase signal computed from the acquired hologram is proportional to the refractive index $n(z)$ integrated along the optical axis. Quantitative measurement on either the topology for a homogeneous specimen, or the refractive index for specimens of known topology can thus be achieved. For high aspect ratio samples, axial measurement range extension can be achieved with two wavelength illumination.[5]

Although using near infrared wavelength will induce a loss of maximum achievable lateral resolution, the fact that Silicon is almost transparent starting from 1.2 μm enhance the versatility of the holographic setup, allowing to measure both Silicon micro-structures and glass micro-structures, such as quartz micro-lenses arrays, that are usually measured with visible wavelengths.

In off-axis DHM, an object wave (O), diffracted by an object and collected by a microscope objective is interfering at the sensor plane with a reference wave (R),

$$I_{sensor}(x,y) = I_R + I_O + R^*O + RO^*. \tag{1}$$

As (O) and (R) arrive on the sensor plane with different angles, the zero-order term and the two interference terms can be clearly separated in the Fourier spectrum of the hologram, which allows for filtering of the real or virtual image term.

The filtered imaging term is then numerically propagated up to the focus plane, using a Fresnel convolution formalism. This is of great interest for the observation of thick sample, where we can digitally focus at a given depth inside the sample.

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2. SETUP

The Mach-Zehnder configuration sketched on Fig. 1 is used to acquire an hologram of the field transmitted through the sample under investigation. First, the light is separated in a reference arm (R) and an object (O) arm with the help of the beam splitter cube BS1. The light scattered by S is collected with a 10x 0.3NA microscope objective (MO), to observe a magnified version of the object. The beam splitter BS2 is used to recombine R and O, in order to acquire the hologram on the camera. The mirror M2 is placed so that there is an angle between the propagation directions of R and O, providing an off-axis configuration enabling Fourier-space filtering of the image term for phase signal reconstruction and further, for numerical propagation.

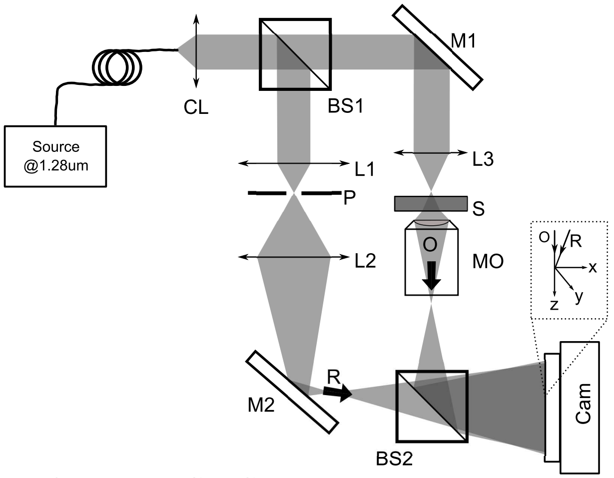


Figure 1: DHM transmission configuration. CL: Collimating lens. L1 + P + L2: reference beam cleaner. M: Mirrors. L3: Condenser. S: Sample. MO: 10x 0.3NA Microscope Objective. BS: Cube beam splitters. Cam: InGaAs/CMOS hybrid IR Camera with $30\mu m$ pixel pitch.

3. RESULTS

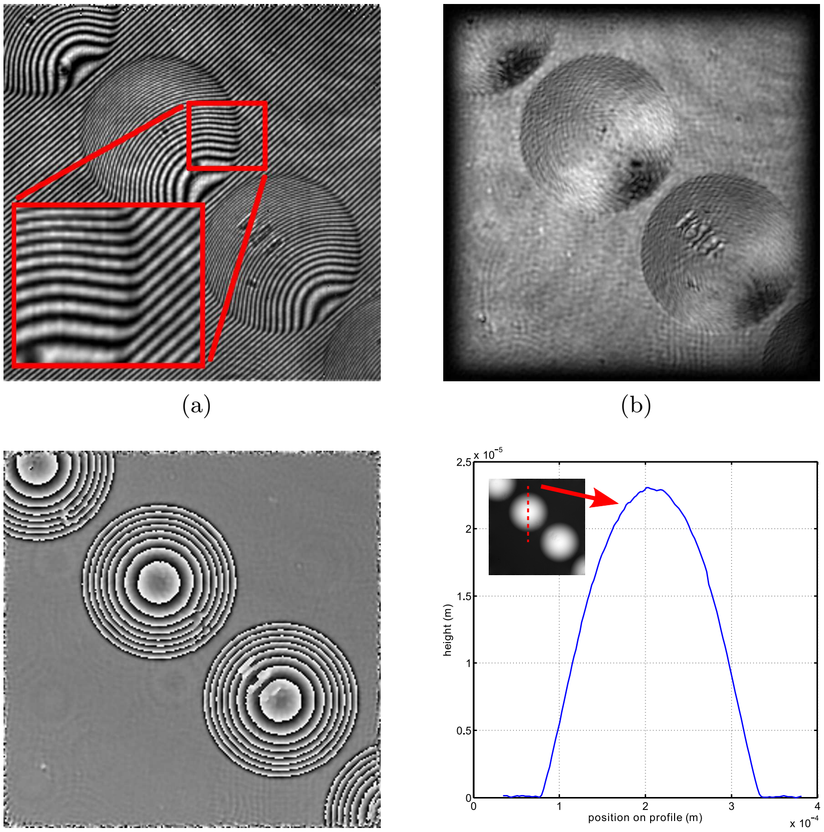
Micro-lenses measurement

Fig. 2 shows results obtained when measuring an array of micro-lenses made of fused silica. This sample has been used as a validation compared to data obtained with a calibrated DHM using visible wavelength, as fused silica is transparent both to visible and near infrared light.

The field of view is $600\mu m$. Fig. 2a is the acquired hologram, with an inset showing the carrier fringes deformation due to the lens under investigation. Fig. 2b and Fig. 2c are the reconstructed amplitude and phase of the measured diffracted field, respectively. Finally, fig. 2d represents a profile plot of the measured height of one micro-lens, obtained by first unwrapping the phase signal and then calculating the corresponding height with eq. 2,

$$h\left(x,y\right)=\frac{\varphi}{2\pi}\frac{\lambda}{\Delta n}. \tag{2}$$

Contrary to a measurement made with visible light, where CCD cameras with small pixel size compared to the numerical aperture and wavelength theoretically allows diffraction limited imaging, here the lateral resolution is limited by the large pixel size of the camera, which is mainly a technological limitation. On the other side, concerning the longitudinal resolution, it has to be noted that the use of a longer wavelength produces less 2π phase counts for the same object, and thus permits more robust phase unwrapping, which is a necessary step to obtain height profile.



(a) (b)

(c) (d)

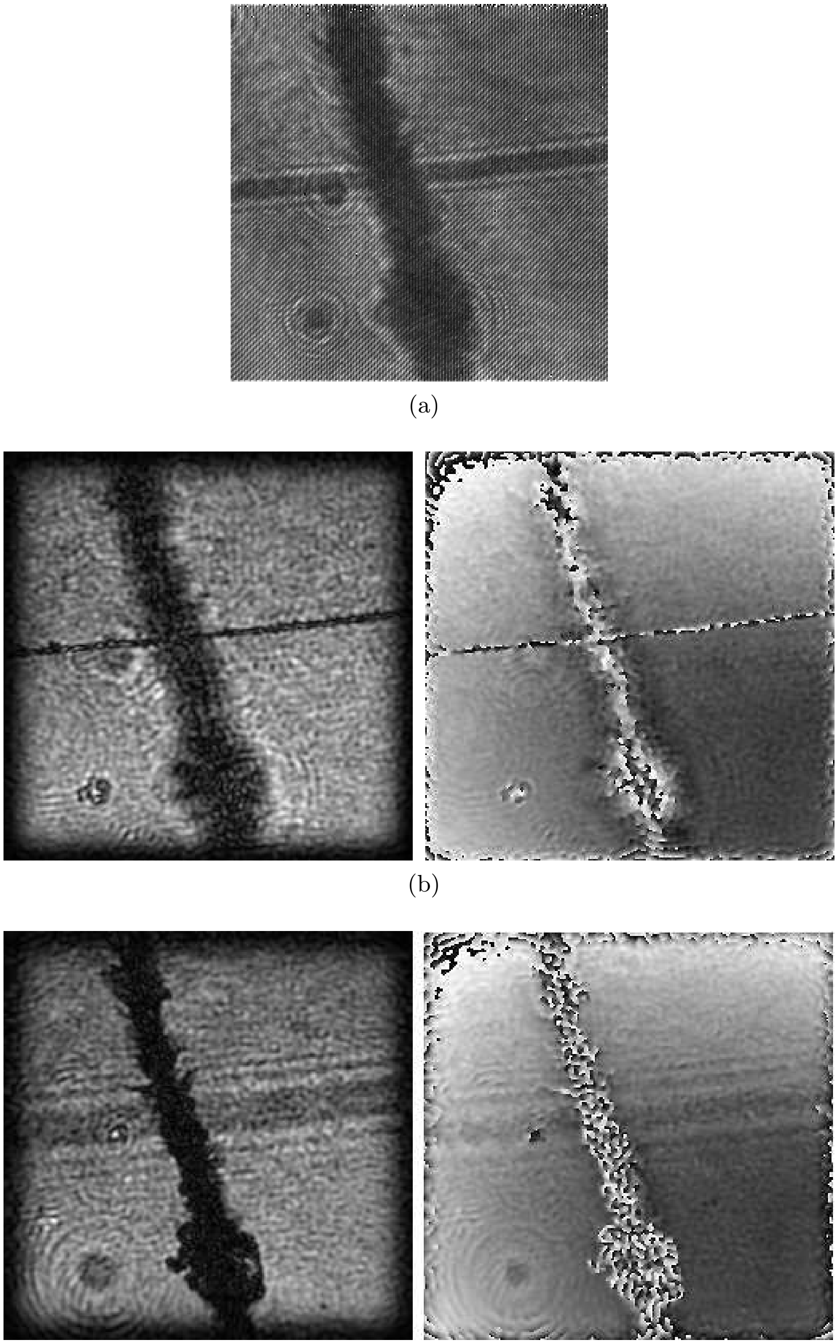
Figure 2: Fused silica micro-lens. (a): hologram, (b): reconstructed amplitude, (c): reconstructed phase, (d): unwrapped phase to quantitative height measurement.

Depth sectioning on thick samples

In order to demonstrate the ability to investigate features inside Silicon with near infrared DHM, a layered sample consisting of 2 polished Si wafers, separated by a cover-glass has been realized. Each wafer is scratched, with different pressure and orientation.

Fig. 3a shows the acquired hologram. Fig. 3b and Fig. 3c are the reconstructed amplitudes (left) and phase (right) obtained with 2 different distances d for propagation calculation. For $d = 5cm$, the image is focused on the light horizontal scratch, as for $d = -10cm$ the focus is on the heavy vertical scratch.

This demonstrates that it is possible to use DHM with near infrared illumination to investigate inside Silicon samples. Moreover, it is possible to obtain an extended depth of field based on only one acquisition with the use of numerical propagation to selectively focus at a the desired location.



(a)

(b)

(c)

Figure 3: 2 stacked Si wafers with scratches. (a): hologram, (b): amplitude and phase for $d = 5cm$, (c): amplitude and phase for $d = -10cm$.

4. CONCLUSION

Robustness and speed are undoubtedly two main advantages of DHM for quality control or non-destructive testing applications. With the unique advantage of focus adaptation given by numerical propagation, depth registration of features embedded in Silicon can be achieved with only one acquisition.

5. ACKNOWLEDGEMENTS

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