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Assembly and optimization of an infrared quantitative phase-contrast microscope for semiconductor inspection

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Method Article

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Abstract

Laser-induced permanent modification inside silicon has been demonstrated by using tightly focused short pulses in the infrared domain of the spectrum, and has a broad field of applications. These include the fabrication of devices in Silicon Photonics with for instance the writing of monolytic waveguides by changing the local refractive index with silicon modifications. In order to characterize very precisely and quantitatively the accessible refractive index variations, we designed and assembled a microscope associated with an interferometer to apply the so-called phase-shifting measurement method with an infrared wavelength. An interferometer close to a Mach-Zehnder configuration is first set. An arrangement of imaging lenses are then installed to operate the interferometer while imaging samples in transmission mode. The sample is placed on the way of one arm of the interferometer, meanwhile the second one is the reference path. The presence of modifications induces an optical path difference relative to the surrounding non-modified zone which can be quantitatively measured.

Introduction

Details of the quantitative phase measurement method are explained in [1]. Procedures and instructions for camera operation, image acquisition and numerical calculations for phase retrieval are not included in this protocol. To realize the experimental arrangement only basic knowledge about optics is necessary.

To study narrow bandgap semiconductors, it is necessary to choose a domain where the materials are transparent. In the case of silicon, the gap is 1.12 eV which corresponds to an absorption edge at wavelength of 1.11 μm . Therefore, the instrument must be developed for a wavelength above this limit in the infrared.

Light from infrared sources can be located using fluorescent cards but remains difficult with modest power sources. Accordingly, it is preferable to set approximately the optical system with visible light first (red light from a laser pointer for example), and next finish with infrared light to obtain the desired interference pattern with exact superposition of both beams coming from both arms. Figure 1 and Figure 2 show the setup to be progressively assembled to set the interferometer and Figure 3 the overall setup to image and study samples.

Here are now presented the protocol principles. We present the essential steps that can be hardly circumvented because the precision for the alignment of the interferometer affects the final image quality and measurement precision. (i) First, you assemble the interferometer setup with visible light (here a red CW laser source). Once this is done you implement the infrared source and with two well-separated

apertures placed previously on the optical path of the red light you align infrared light. (ii) Second, you obtain interferences. In practice you translate the moving mirror along the optical axis using a precision manual actuator (Vernier micrometer) until you observe interferences, normally a certain number of fringes. (iii) Then, you make adjustments to get less and less fringes and confirm collinear and superposed beams. This is done by observing the way fringes are moving when you adjust position and angle of one beam (the second one being the reference kept static). (iv) Finally, you add the mounts supporting the lens making up the microscope, and you align them with the beams, after that you can add the lenses so that the microscope is ready. Figure 4 shows a picture of the microscopy arrangement composed of a focusing lens, a tube lens and an infrared camera.

To assess performance and precision, a reference sample is needed. For example a thin layer of known thickness locally deposited on an infrared transparent material (e.g. <15nm of Gold on Si). When imaging the edge, a phase step is observed which must correspond to the film thickness. An example of images from such a test procedure is shown in Figures 5,6,7 and 8.

Reagents

Equipment

- 5 gold mirrors and their two adjuster kinematic mounts
- posts, postholders, clamps
- One mirror with a piezo actuator (here PI-721 from PI) on and a linear stage (range ~20mm) with its manual actuator (Vernier micrometer)
- Piezo controller
- 1 polarizing beam splitters (PBS) and a 1 non-polarizing beam splitter (BS) and their mounts.
- An infrared camera (here Bobcat-320-GigE from Xenics)
- A cage system to support the camera and tube lens on the same axis (adjustable separation)
- 1 tube lens
- Two imaging lenses (one for the reference path and the objective)
- Some adaptaters
- Mounts with x,y,theta,phi adjusters (and rotation for the second beam splitter)

- Magnetic base (for the removable mirror)
- Eventually infrared filters
- Infrared LED with appropriate coherence length (here SLD1018S by Thorlabs) and its mount (with x,y adjusters at least)
- A red laser
- Some iris diaphragms
- A white cardboard and holder to place it anywhere in the beam path
- A laser viewing card (here VRC from Thorlabs for fluorescence in the infrared)

Procedure

Procedure 1 : Setting the interferometer

1) Setting with visible light

Reference (called also first) path (or beam) will be the path with the mirror which has the piezo control (see fig. 1).

First (mirrors,apertures,etc), second and ordinal numbers are defined in the light's propagation direction.

(1.1)

-Set the removable mirror (which is on a magnetic base so if you have to put it again it comes back to its initial position), the first PBS and waveplates roughly (cf. fig 1).

-Choose the height wanted for the beam with respect to camera height for example. You can use a post with a horizontal metallic rod to have the reference height. You can write a thin line on a white cardboard across the width to have another height reference (Write also a line longitudinally on the center of the card). The post with the rod shall be used to set height of the optical elements added after, meanwhile the card will be useful to see the red laser and control its height.

(1.2)

- Put the laser red source and block its position totally. It must not move after.

- Before PBS, put an aperture to work with a small beam. Alternatively, you can choose an iris aperture which does not totally close (so if you open the iris aperture you can come back to the reference settings defined by the aperture closed as much as possible).

- Lock aperture's position.

(1.3) Then, proceed optical element by optical element, in the order of light propagation :

- Set the PBS so it sends the reference beam alongside the optical table. To have a good alignment, screw a post on the same line (line drawn by the holes in the table) as far as possible and place the white card in front of it to see the beam and set alignment.

- To fix the eventual tilt, use two movable apertures placed on the line (or look manually with the white card in two different points on the line). *Generally*, red beam may be hard to observe due to optics not designed for visible wavelengths. In this case try to work in the dark room and after opening the aperture until it is visible.

- Add the mirror with its piezo and set alignment with the same procedure at the other side.

- Set mirrors of the other path with same procedure.

- Add the second BS, and set it in a way beams from both paths are superposed.

This step is critical, this BS has to have adjusters so that it can be rotated and translated (3 degrees of freedom) because we need to assure two beams intercepting at the same location on the BS and an orientation to obtain rigorous colinearity. Try to be very precise.

2) Setting with infrared light

(2.1)

- First, add an aperture on the path you want, far of the first one, centered on the red light beam. Now, both installed apertures will be used to align infrared beam.

- Set the infrared source and block its position. Put a lens with a short focal length to collimate the beam (with the goal to minimize energy losses). An infrared card is needed to see if the beam after the lens is not divergent and to set the system. Working in the dark is preferable to perform the adjustments with good conditions.

- Put the two mirrors which will serve to align infrared beam with the path of red light, as in fig 2.

- Now repeat the following procedure until it converges : (step 1) Aim the first aperture center with the first mirror

(step 2) Aim the second aperture center with the second mirror. It converges since distance between first mirror and first aperture is smaller than distance between second mirror and second aperture.

- Put the camera after the second PBS and get interference translating the piezo mirror with the manual actuator.

(2.2) Now the goal being is to have only one disc on the screen, meaning we have two colinears and superposed beams, the following step aims to do that.

- Rotate a little bit (it is very sensitive) the second BS searching for the optimum (bigger fringes that can be seen).

- Next, adjust carefully the last mirror before the BS (on the second path), trying to have bigger fringes. You should not forget that fringes orientation indicates tilt orientation. You can try to set vertical direction and horizontal direction independently (firstly get totally vertical fringes and after that fix horizontal tilt for example)

If on the image, the spot of the second beam is getting away from the reference beam, it means beams are becoming collinear but less superposed. With the PBS only, superpose the second beam with the reference beam.

During this manipulation reference path should not be changed (if you do that it becomes very hard to go back to red light settings if you need it after).

Procedure 2 : making the microscope

- In our setup (see fig. 4) camera is mounted on a cage system with the tube lens on it and the lens for magnification of the reference beam.

- Block the second beam (placing an object on the path) and align the cage system with the reference beam. Then, mount an aperture on the extremity of the cage system and repeat the following procedure until it converges: (step 1) center the reference beam on the camera moving the post which carries the camera side (step 2) center the aperture with the beam moving the other post (other extremity). Direction where it has to be moved is visible closing the aperture as much as possible.

- Lock position of the cage system. Normally tube lens and the lens of the reference path are aligned and centered on the reference beam.

- Ensure that the second lens will be approximately at the same distance of the tube lens than the first one, and use a base mount with a micrometer screw.

- Take the mount of the second lens (the 'objective') and install an aperture on it to center the beam on it.

- Put the lens (or a longer focal length lens if it is needed for the first settings because it is easier), and with the Vernier micrometer find interferences in the image.
- Using the adjusters on the lens mount, try to have bigger fringes and finally rings.
- Due to the fact that the beam is a little bit diverging and it has not exactly the same profile everywhere on the path crossed (curvature can change a little bit, something we don't see normally but we can see with interferences), we see rings and not only one spot evidencing longitudinal interferences between two strictly identical beams (same wavefront). With the Vernier micrometer, adjust the distance objective-tube lens to get finally the largest possible interference rings. In practice one ring observed on the camera corresponds to acceptable conditions for measurements without complex procedure for phase reconstruction. At this stage, the microscope is ready for measurements (see fig.3 for schematic of the final setup)

Procedure 3 (optional) : calibration measurement for performance validation

A thin gold sample with modifications or defaults on it (typically local removal of the film) is good to verify the performance of the assembled system. Modifications can be measured with an AFM microscope, and knowing its refractive index, we can evaluate if consistent results are obtain by both methods.

Troubleshooting

Step : Implementing the source

Problem/reason: At the infinity, diffraction patterns are observed due to the source itself

Solution : Check the mount does not diffract the source output and change the source/mount if possible.

Step : Implementing lenses

Problem : Some lenses including the 'objective' leads to the formation of a bright point at the center of the image

Solution: Try other lenses with more appropriate coating and/or different mounts. In the current setup the illumination is relatively large and may be diffracted by the imaging lens. It might be also relevant to investigate other illumination conditions (for instance where only the imaged zone is illuminated)

Time Taken

Procedure 1 : 1 day to one week

Procedure 2 : half of a day

Anticipated Results

References

1. Q. Li, M. Chambonneau, M. Chanal, and D. Grojo, "Quantitative-phase microscopy of nanosecond laser-induced micro-modifications inside silicon," Appl. Opt. **55**, 9577-9583 (2016)

Figures

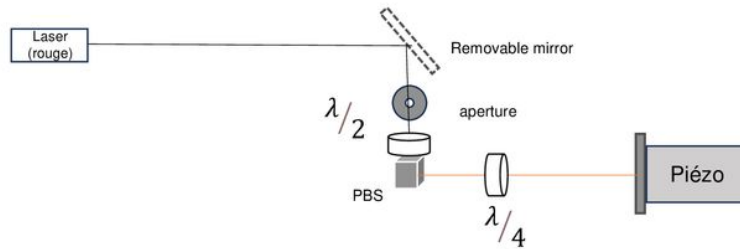


Figure 1

Reference path

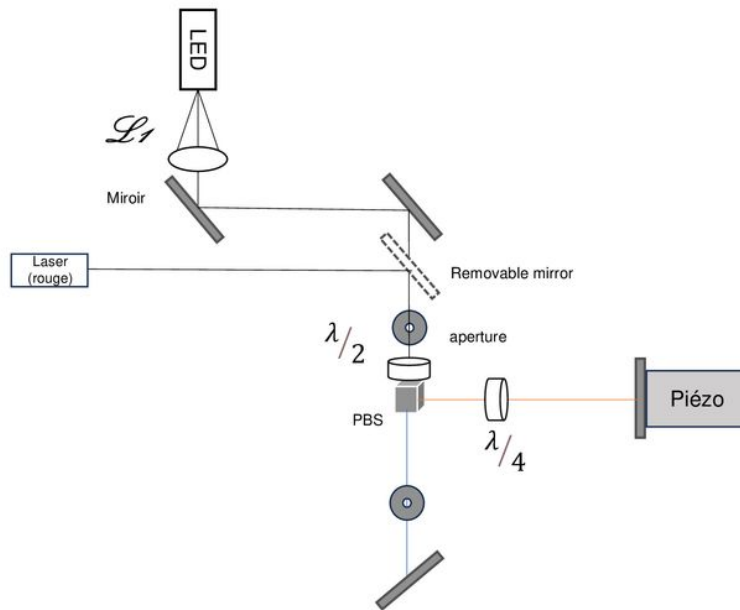


Figure 2

Intermediate setup to align infrared path with red light path

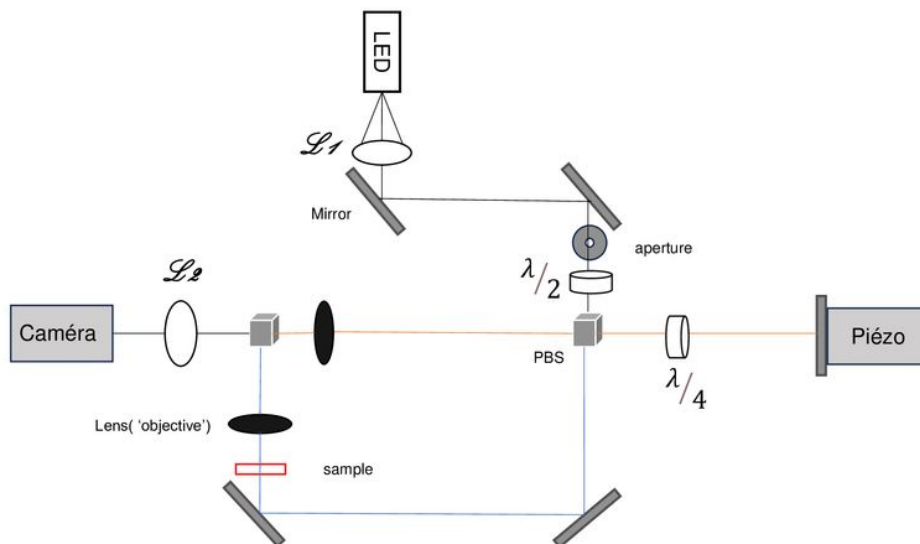


Figure 3

Final setup

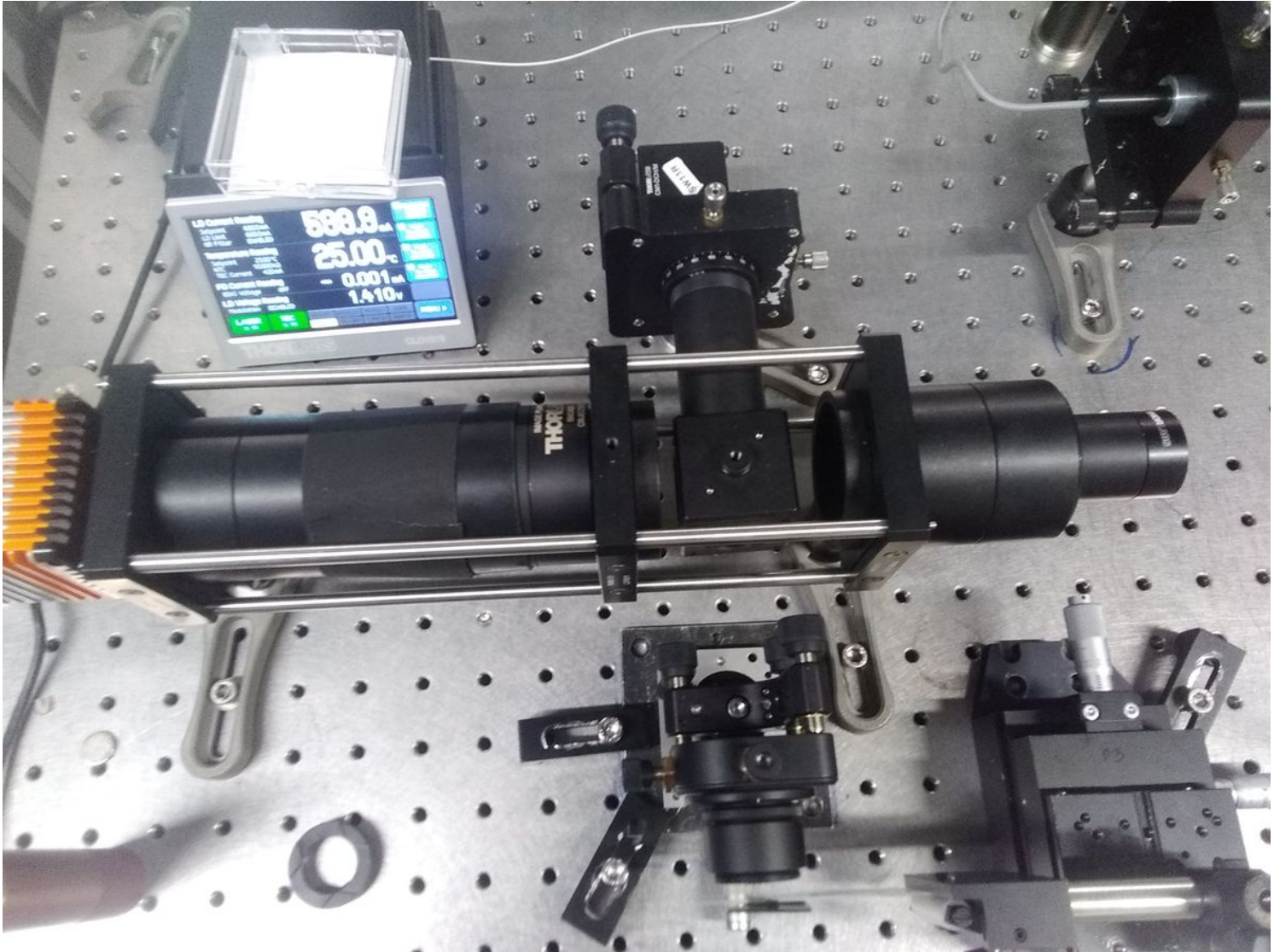


Figure 4

Camera cage (camera at the left,lens tube inside, pbs in the middle, lens at the right)

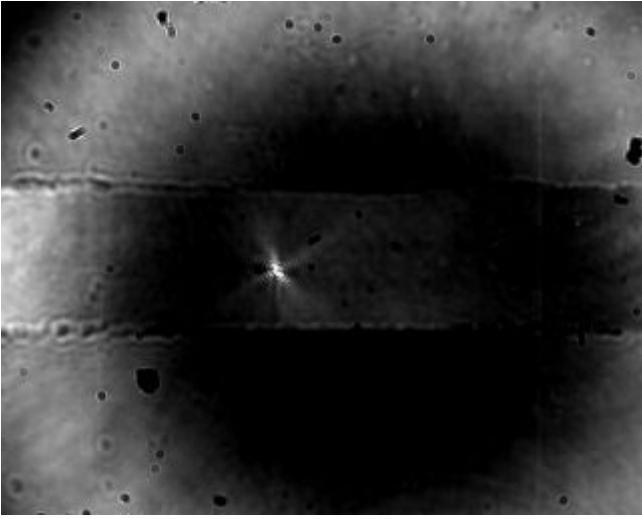


Figure 5

Gold thin layer pict 1

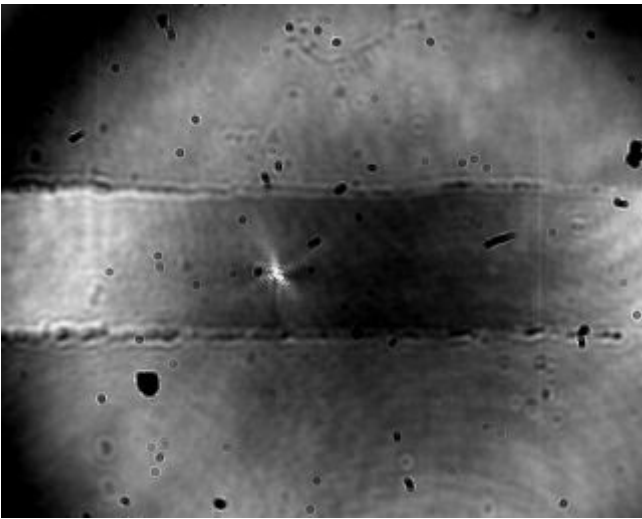


Figure 6

Gold thin layer after moving piezo by $\lambda/4$

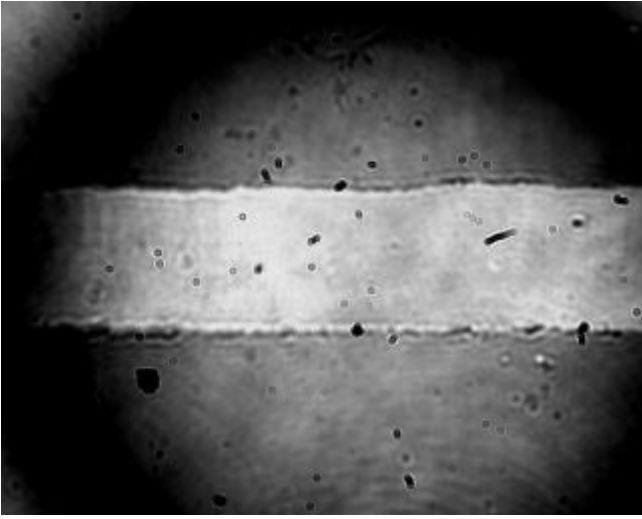


Figure 7

Gold thin layer after moving piezo by $\lambda/2$

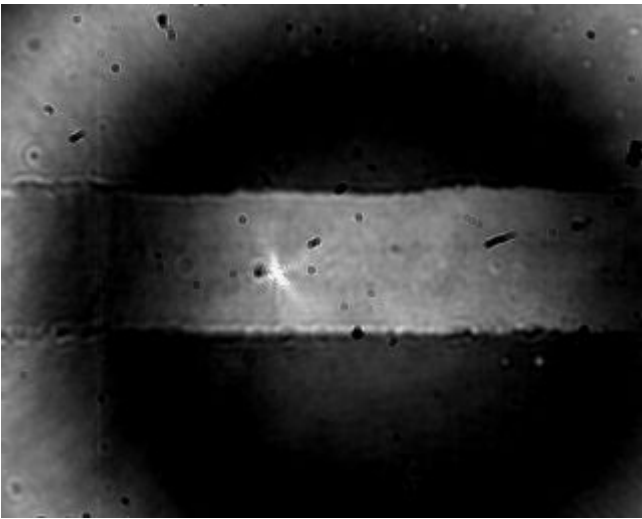


Figure 8

Gold thin layer after moving piezo by $3\lambda/4$