White-light interference microscopy: a way to obtain high lateral resolution over an extended range of heights

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Abstract: A problem with conventional techniques of interference microscopy, when profiling surfaces with an extended range of heights, is that only points on a single plane are in sharp focus. Other points, which are higher or lower, may be out of focus, with a consequent loss of lateral resolution. We show that white-light interference microscopy, with an achromatic phase-shifter, makes it possible to produce a three-dimensional representation of such surfaces with high lateral resolution over the entire range of heights.

OCIS codes: (180.3170) Interference microscopy; (110.4500) Optical coherence tomography; (180.6900) Three-dimensional microscopy; (120.3180) Interferometry; (170.1650) Coherence imaging; (110.6880) Three-dimensional image acquisition.

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1. Introduction

Conventional techniques of interference microscopy using monochromatic light offer excellent vertical resolution. However, their use for profiling surfaces with an extended range of heights (typically, more than a few wavelengths) presents two major problems.

The first problem is 2π ambiguities, which arise at discontinuities and steps with a height greater than half a wavelength. One way to overcome this problem, which can be applied over a limited range of heights, is by making measurements of the phase differences at two wavelengths. The difference of these values yields the phase difference that would have been obtained with a longer synthetic wavelength, and measurements can be made without ambiguities over a correspondingly longer distance [1-3].

However, another problem which presents itself with profilers using monochromatic light, or with the two-wavelength technique, is that since the image of the object is recorded at a single focus setting, only points on a single plane in the object are in sharp focus. Other points, which are higher or lower, may be out of focus, with a consequent loss in resolution. This problem is more serious with objects exhibiting a greater range of heights and with microscope objectives having a higher NA, which have a very limited depth of focus.

An alternative way to overcome the problem of 2π ambiguities is white-light (low-coherence) interference microscopy. In this technique, the object is scanned in height, using white light, and the visibility of the interference fringes (the degree of coherence) at each pixel in the image is measured. The location of the visibility peak along the scanning axis gives the height of the surface at that point.

Digital filtering techniques can be used to recover the fringe visibility curve and locate the visibility peak, but they require measurements with increments of the optical path that are less than a quarter of the shortest wavelength and are also numerically intensive [4, 5]. In addition, the resolution in depth that can be obtained is limited.

A more direct approach is based on phase shifting, using a phase shifter operating on the geometric (Pancharatnam) phase to obtain phase shifts that are independent of the wavelength [6]. With this technique, high resolution in depth, equivalent to that attainable with monochromatic light, can be obtained [7, 8]. In addition, it is possible to acquire a set of phase-shifted images at each height setting without changing the optical path difference.

We show that this technique also yields high lateral resolution over the entire range of depths, due to the optical sectioning property of low-coherence interference (LCI) microscopy, which effectively exploits coherence effects to maximize lateral resolution. Since the final image is built up using information at each point on the object acquired from a single plane very close to it, points at different depths are imaged with a minimal loss of resolution.

2. Loss of resolution due to defocus

Figure 1 shows the variation of the diameter of the circle of confusion with the distance from the plane of best focus for microscope objectives with NAs of 0.80 (50× magnification), 0.65 (40× magnification), and 0.25 (10× magnification). As can be seen, even with a medium-power microscope objective (40× magnification, 0.65 NA), there is a significant loss of resolution at a distance of 2.0 μm from the plane of best focus. With a 50× magnification objective (0.80 NA), there is a noticeable loss of resolution for a change of height as small as 1.00 μm. At a plane at a distance of 2.0 μm from the plane of best focus, the diameter of the circle of confusion would be approximately 5.3 μm, resulting in a serious loss of resolution.

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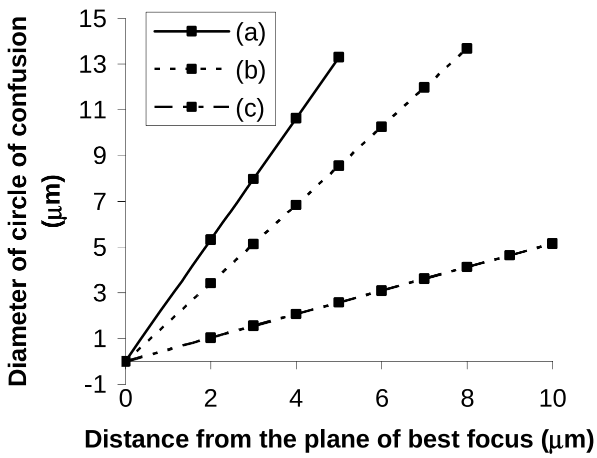

Fig. 1. Variation of the diameter of the circle of confusion with the distance from the plane of best focus for microscope objectives with: (a) 0.80 NA (50× magnification), (b) 0.65 NA (40× magnification) and (c) 0.25 NA (10× magnification).

2.1 Experimental arrangement

We used an LCI microscope based on a Linnik configuration with a tungsten-halogen lamp as the source for our measurements [8]. The linearly polarized beam transmitted by the polarizer was divided at the polarizing beam-splitter into two orthogonally polarized beams which were focused onto a reference mirror and the test surface by two identical infinity-tube-length microscope objectives. After reflection at the reference mirror and the test surface, these two beams returned along their original paths to a second (nonpolarizing) beam-splitter, which sent them through an analyzer to a CCD array camera.

The phase difference between the two beams was varied by a system operating on the geometric (Pancharatnam) phase featuring two identical switchable phase-shifters, one in each beam [9, 10], located between the beam splitter and the corresponding microscope objective. Each phase shifter consisted of a quarter-wave plate, with its principal axis at 45^0 to the plane of polarization of the beam, followed by a ferro-electric device with a retardation of a quarter wave and a switching angle of 45^0. This system produces phase shifts of 0^0 and $\pm 90^0$ that are almost independent of the wavelength over the range of visible wavelengths, even with simple quarter-wave plates made of PVA (polyvinyl alcohol).

2.2 Experimental procedure

Measurements were made with a pair of 50× magnification (0.80 NA) objectives. We used as a test sample an integrated circuit which was tilted so that 13 interference fringes were seen across a selected area (lateral dimensions 59 μm × 44 μm). The left edge of this area was then approximately 1.8 μm above the center of the sample, while the right edge was approximately 1.8 μm below the center of the sample. From Fig. 1, the diameter of the circle of confusion at this distance from the plane of best focus would be 4.7 μm.

To make measurements, the sample was moved along the height (z) axis, by means of a piezoelectric translator, in steps Δz=0.33 μm over a range of 10 μm centered approximately on the zero-order white-light fringe. At each step, three values of the intensity were acquired

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at each point in the fringe pattern, corresponding to no additional phase shift and additional phase shifts of 90° and -90°. The visibility of the interference fringes at each step could then be calculated, from these three sets of intensity values, using the formula

$$V = \left[\frac{\left(I_{90} - I_{-90}\right)^2 + 2\left(I_0 - I_{90} - I_{-90}\right)}{I_{90} + I_{-90}} \right]. \tag{1}$$

An initial estimate of the surface height at each point was obtained by fitting a curve to the visibility data for each pixel and finding the position of the peak of the visibility curve along the scanning axis. Final values of the surface height were then obtained by processing the intensity data at the step nearest to the visibility peak to obtain the corresponding values of the phase [7], using the relation

$$\tan\phi = \frac{I_{90} - I_{-90}}{2I_0 - I_{90} - I_{-90}} \tag{2}$$

3. Experimental results

Figure 2 is a three-dimensional image of a section of the surface of the tilted test sample (lateral dimensions $59\mu m \times 44\mu m$) obtained with white light by achromatic phase-shifting. As can be seen, there is no loss of resolution due to the effects of defocus over the entire area, and fine details on the surface, with lateral dimensions less than $1.0\mu m$, are clearly resolved over the whole range of depths ($3.6\mu m$) covered by the image.

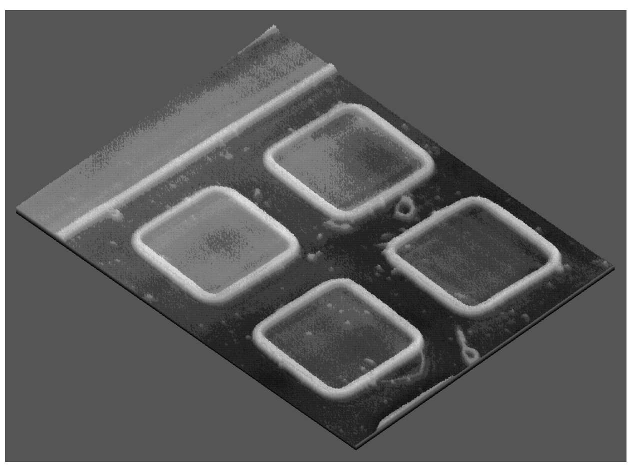

Fig. 2. Three-dimensional image of the surface of a section of an integrated circuit (lateral dimensions $59\mu m \times 44\mu m$) tilted so that the left edge was approximately $1.8\mu m$ above the center of the sample, while the right edge was approximately $1.8\mu m$ below the center of the sample.

This result is confirmed by Fig. 3, which shows profiles of the surface of the test sample along two lines running across the test sample, one in the plane of best focus and the other near its lower edge in a plane 1.8 μm below the plane of best focus.

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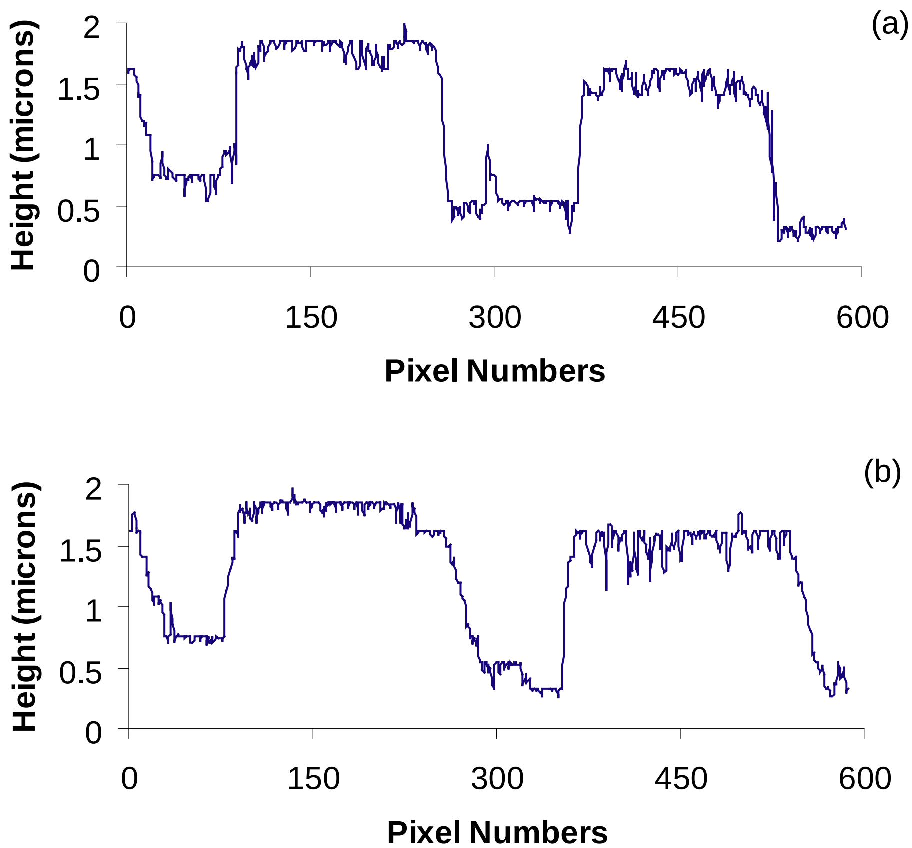

Fig. 3. Profiles of the surface of the test sample: (a) along a line in a plane of best focus, and (b) along a line in a plane 1.8 μm below the plane of best focus.

These results can be compared with Fig. 4, which is a photograph of the tilted test sample recorded under the same conditions. The loss of lateral resolution near the upper left edge and the lower right edge, due to the effects of defocus, can be seen clearly.

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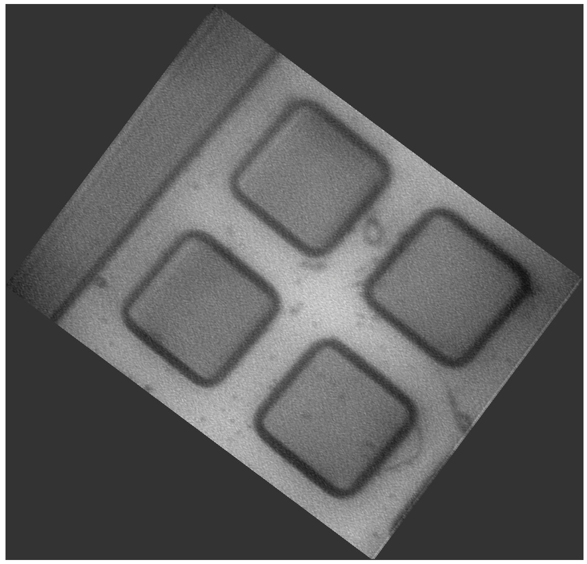

Fig. 4. Photograph of the tilted test sample recorded under the same conditions.

4. Conclusions

We present results which show how white-light phase-shifting interference microscopy using an achromatic phase-shifter makes it possible to profile surfaces with a range of heights of several wavelengths, with little or no loss in lateral resolution over the entire range of heights.

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