Document version 1.2 17th May 2010

Optical reflection mode imaging with the Virtual Lens®

The Phase Focus Virtual Lens® technology is as applicable to reflection geometries as it is to transmission. In this technical brief we describe in detail the principle behind optical reflection mode imaging with the Phase Focus Virtual Lens® and discuss what physical properties of the sample can be obtained from measured data. These include quantitative measurement of topographic features, film thickness, refractive index and reflectivity. As with other Virtual Lens® measurements it is also possible to refocus the images after acquisition.

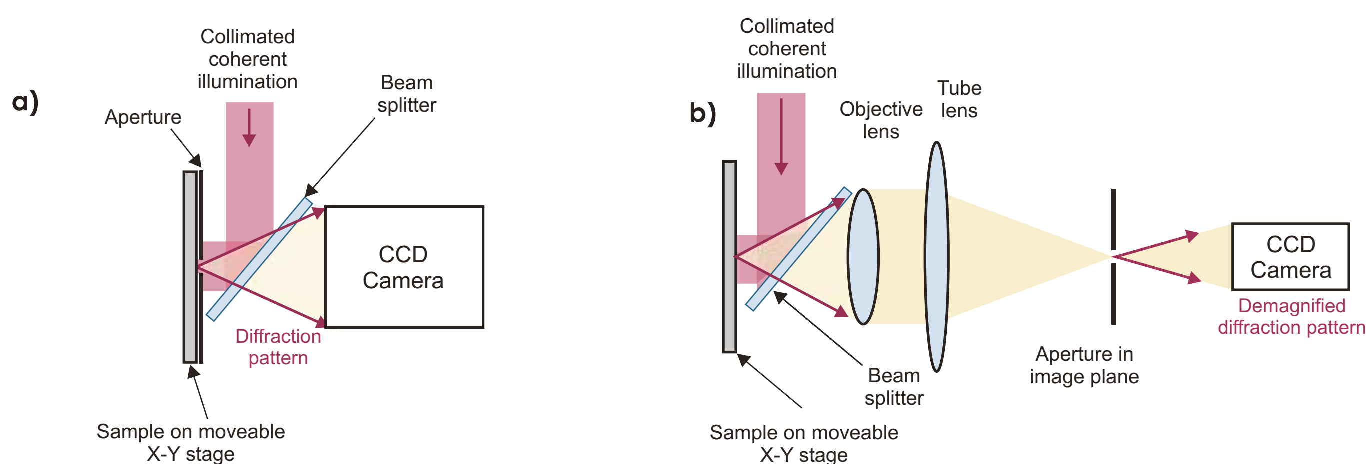

Figure 1: *Lensless vs lens-assisted geometries. a) Fully lensless reflection geometry. b) Lens-assisted configuration*

A conventional microscope forms an image either from light transmitted through a transparent sample, or from light reflected from the surface of an opaque sample. The operation of the microscope is identical in both cases; it is simply the path of light prior to leaving the sample that changes. Similarly, the Phase Focus Virtual Lens® can be used in a transmission or reflection geometry since the physics of the system is the same. The reflection geometry can be visualised as simply a transmission set-up with the illumination optical path "folded" back onto itself, as shown in Figure 1. Figure 1a) shows a completely lensless configuration, conceptually the simplest arrangement. Figure 1b) shows a lens-assisted arrangement that can be incorporated into a standard optical microscope. The purpose of the beam splitter shown in the diagram is to enable normal incidence of illumination on the sample. As an alternative, illumination at an angle would eliminate the need for the beam splitter.

In both the arrangements in Figure 1, light diffracted from the sample is recorded as a diffraction pattern on the CCD camera. An aperture is placed in, or near, the image plane of the optical system to define a localised area of illumination, or "probe" region of the sample. The sample is moved laterally to an array of positions and a diffraction pattern is collected at each location. The positions are chosen such that each "probe" region overlaps its nearest neighbours, as

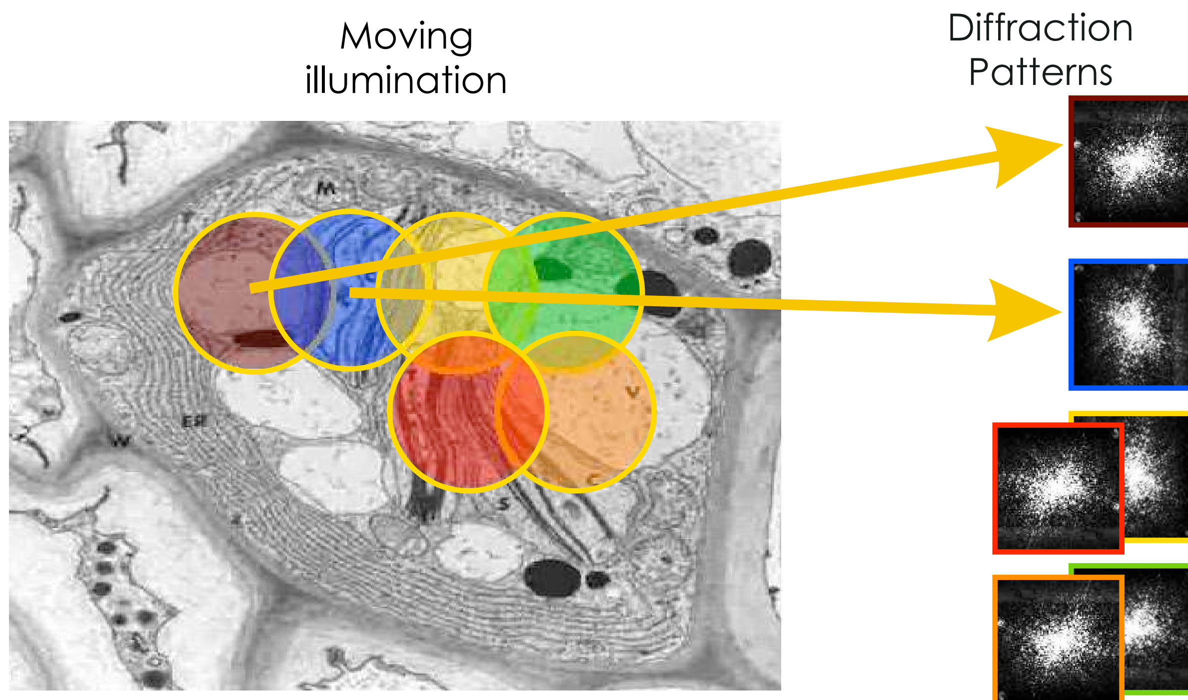

Figure 2: *Image data collection; a series of overlapping regions are illuminated and the corresponding diffraction patterns recorded.*

shown in Figure 2. Once all the diffraction patterns have been collected, the Phase Focus Virtual Lens® algorithm is used to reconstruct a phase and amplitude image of the sample. The reconstructed images can be focussed to any plane, allowing post-acquisition re-focussing and the ability to take measurements at multiple depths from a single set of data. For a more detailed description of how the Phase Focus Virtual Lens® algorithm works, see Technical Brief TB01. Note that the lenses shown in Figure 1 are not strictly required; they simply reduce the size of the CCD sensor needed for a given lateral resolution. The resulting images provide a range of quantitative measurements of sample properties, each of which will be discussed below.

Reflectivity measurements

For a perfectly flat sample with variations in reflectivity across its surface, the generated diffraction pattern would be of the same form at every probe position: a diffraction pattern created by the aperture. As the probe is moved, the only change would be a change in the amplitude of this pattern. In reality such an ideally flat sample is impossible; the surface topographic structure adds higher order features to the diffraction pattern that will change with the position of the probe. Since the Phase Focus Virtual Lens® separates reflected amplitude and phase information, the resulting amplitude image represents a map of surface reflectivity.

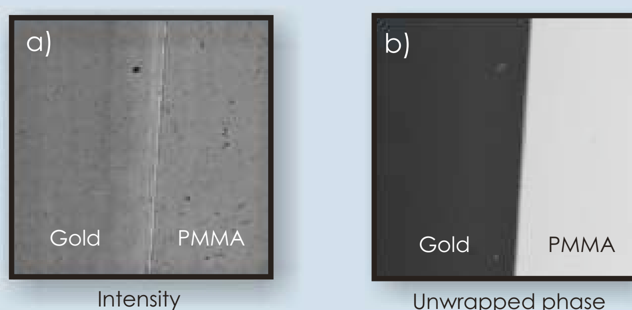

Figure 3: *A 1μm thick layer of PMMA on a gold substrate. Note that there is very little contrast in the intensity image, but a very clean step is observed in the phase data.*

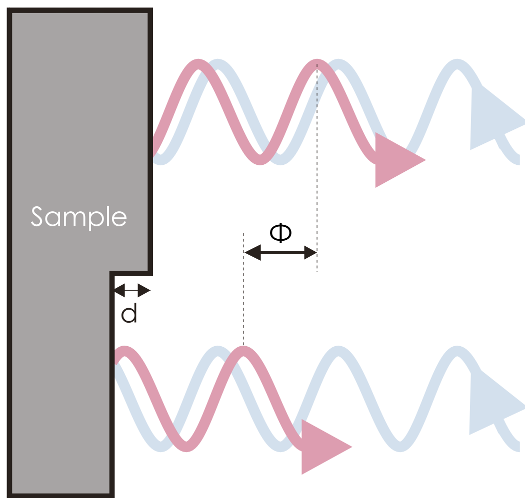

Figure 4: *Phase shift due to a step of height d on the surface of a sample. The lower wave travels a distance 2d further than the upper wave.*

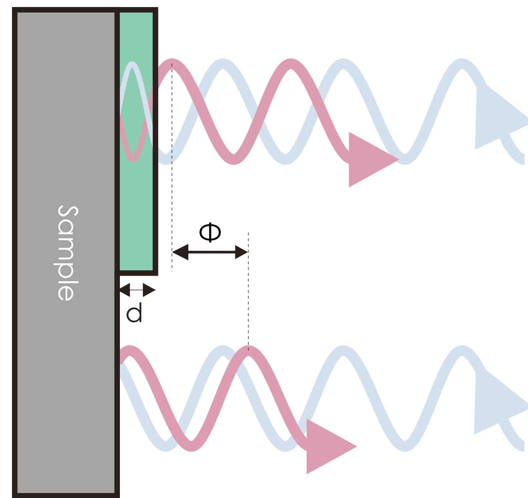

Figure 5: *Phase shift due to a transparent film of thickness d on the surface of a sample. The lower wave travels a distance 2d further than the upper wave.*

Topographic measurement

Direct measurement of topographic features on a surface can be made from the recorded phase image in reflection mode. Consider the situation shown in Figure 4. A reflective sample contains two parallel planar regions with a step between the two regions of height *d*. If we compare points away from the step edge, we can consider the reflections from each region by taking two identical waves (representing two parts of the same incident wavefront) reflected at each region. The reflected wave shown in the lower part of Figure 4 will have travelled a distance *2d* further than the upper reflected wave, resulting in a phase shift, Φ, relative to the upper wave.

This relationship can be turned around to provide quantitative measurements of topographic features from a phase map with the following formula:

$$d = \frac{\Phi\lambda}{4\pi} \qquad \text{Eqn (1)}$$

Where d is change in height, **Φ** is the observed phase change in radians, and **λ** is the wavelength of the illuminating light. An important point to note from the equation above is that calibration of the system is only dependent on the wavelength of the illuminating light. Consequently, calibration errors are likely to be very small, due to the high degree of accuracy to which wavelength can be measured. This also provides a simple route to traceable, calibrated measurements*.

* Material changes may cause uncertainties in measured height values due to different phase changes on reflection from different materials.

Film thickness & refractive index measurement

The topography measurement method in the preceding section assumed that the sample was purely reflective. Here, we consider a uniform transparent film on a flat reflective surface, as shown in Figure 5.

If a film of thickness d and refractive index n is deposited on a surface, a phase shift, Φ, will be observed relative to an area where no film is present. A directly equivalent formula to Eqn 1 can be written that takes into account the refractive index of the film:

$$d = \frac{\Phi\lambda}{4\pi(n-1)} \qquad \text{Eqn (2)}$$

Assuming that the film refractive index is known, it is simple to calculate film thickness from phase measurements, as in the topographic case. Alternatively, if the film thickness is known then the refractive index can be calculated.

Note that in order to measure film thickness a reference surface is required with no film covering it, as shown in Figure 5. Without this reference there is no reference phase from which a relative shift can be measured.

Conclusion

Using the Phase Focus Virtual Lens® in optical reflection mode it is possible to directly measure topography, reflectivity, film thickness and refractive index of opaque samples. The technique requires no physical contact with the surface.

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