Application Note

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Surface characterisation by reflection imaging with the Phase Focus Virtual Lens®

In this application note, we present a brief summary of the principles of reflection imaging with the Phase Focus Virtual Lens®, and discuss its application to surface characterisation of patterned semiconductor wafers. We demonstrate that topographic features can be obtained from phase information with 30nm steps clearly resolved with an accuracy of <1nm. We also discuss the technique's use in measuring surface properties such as reflectivity.

There is an increasing need for the characterisation of large areas of surfaces with sub-nanometre vertical resolution. From semiconductor wafers to engine components, the texture of a surface has a critical effect on the overall performance of the product. Previously it has been sufficient to measure a single line profile along a surface and extrapolate this to estimate the overall surface texture, however this is no longer considered to be reliable enough since it represents such a small sample of the total surface. There is now strong demand for techniques that can measure surface properties over complete areas rather than single lines; so-called areal metrology. Consequently, a number of surface mapping techniques have been developed in recent years that have <1nm resolution in the Z axis and yet can cover mm^2 areas. Scanning White-Light Interferometry (SWLI), Scanning Confocal Microscopy and Atomic Force Microscopy (AFM) are all examples of such techniques. In this application note we present a new non-contact areal metrology technique using phase information obtained with the Phase Focus Virtual Lens®.

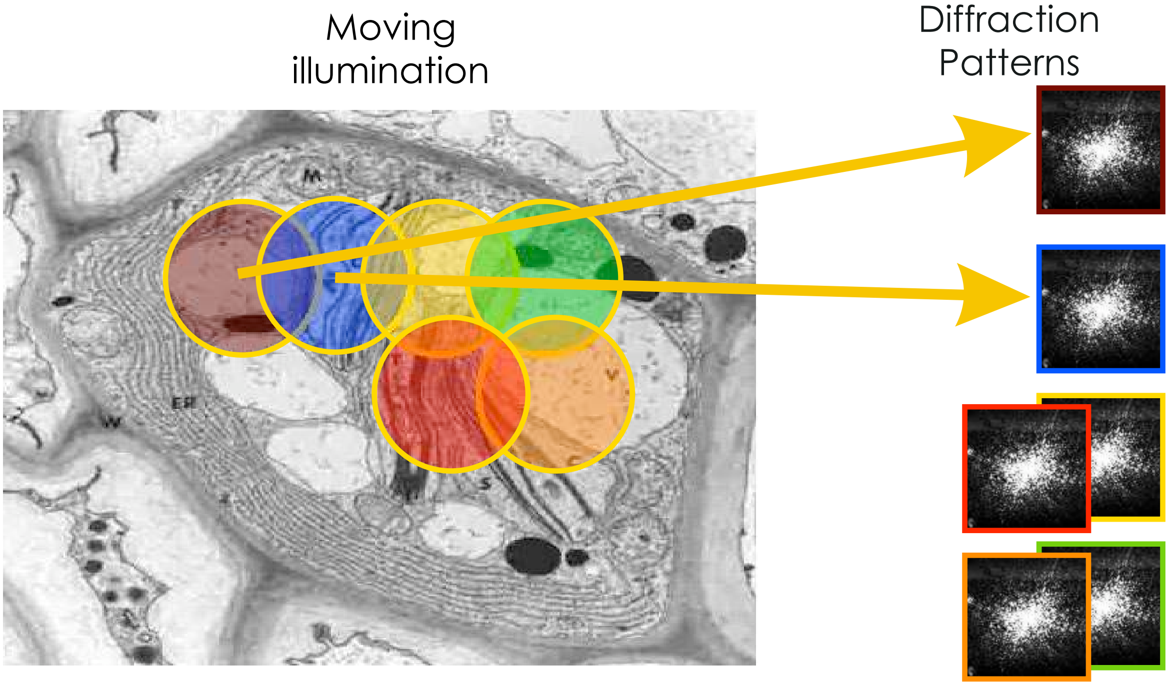
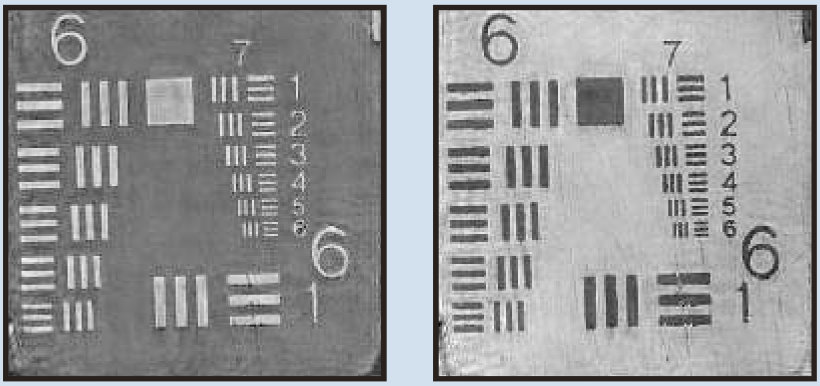


Figure 2: Image data collection; a series of overlapping regions are illuminated and the corresponding diffraction patterns recorded.

The Phase Focus Virtual Lens®

Phase Focus has developed a technology that replaces or complements a microscope conventional lens system with a computer algorithm: The Phase Focus Virtual Lens®. It makes the physical set-up inherently simple; in its simplest form just a light source, sample and detector. The algorithm calculates the complete optical wavefront leaving a sample from the diffraction created by coherent illumination of the sample. An optical wavefront consists of amplitude and phase information, yet conventional imaging techniques only record amplitude; the phase information is lost. In addition, because the entire wavefront is known, it is possible to refocus the image to any point after data acquisition. In this application note we make use of the phase information obtained by the virtual lens to characterise surfaces. For a more detailed explanation of the Phase Focus Virtual Lens®, please refer to "TB01 - The Phase Focus Virtual Lens®".



Amplitude

Phase

***Figure 3:**Typical reflection mode images. The sample was a transmission calibration target, showing high reflectivity on the marks and low signal between the marks. The phase image shows inverted contrast due to phase changes related to height and material changes .*

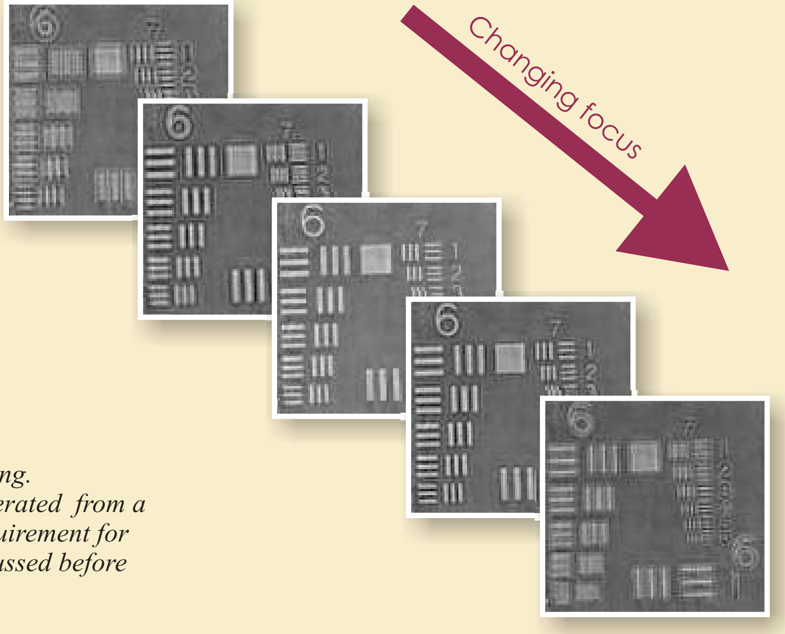


Figure 4: *Post-acquisition focussing. This through-focal series was generated from a single dataset, eliminating the requirement for the microscope to be perfectly focussed before data collection.*

Reflection Imaging: Experimental Methodology

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.

To perform reflection imaging, a standard commercial microscope (Olympus BX41) was adapted to operate in Phase Focus Virtual Lens® mode, without losing the ability to perform conventional imaging. The experiment was set up as shown in the schematic diagram on the next page in Figure 5. For safety reasons the usual eyepieces were replaced by a CCD camera streaming real-time images to a PC. A second, identical, CCD camera was also added, to which light could be directed via a beam-splitter. This second camera was not placed in the image plane; a 1mm aperture was placed in the image plane with the CCD camera positioned a fixed distance above.

A second beam-splitter cube was located inside the reflection arm of the microscope to direct light from the back illumination port down through the microscope objective lens onto the sample. The sample was mounted securely onto a computer-controlled X-Y positioning stage (Physik Instrumente M-686), with 0.1µm positioning accuracy. Standard Olympus plan achromat10x (0.25NA) and 20x (0.4NA) lenses were used. The region of interest was located using the conventional imaging camera, then a virtual lens image was collected by scanning the stage to an array of probe positions (typically a 10x10 grid) and collecting a diffraction pattern at each point. Typically the total acquisition time per probe position was 0.25 seconds, including movement between position and collection of the diffraction pattern data. Therefore a complete dataset was collected in ~25 seconds. After data collection, the Phase Focus Virtual Lens® algorithm was used to reconstruct the complete optical wavefront leaving the sample, and subsequently amplitude and phase images at a specified plane. This stage took an average of 30 seconds to process the diffraction patterns and reconstruct the phase and amplitude images. Both acquisition speed and image reconstruction can be sped up by using a faster camera and more processing power.

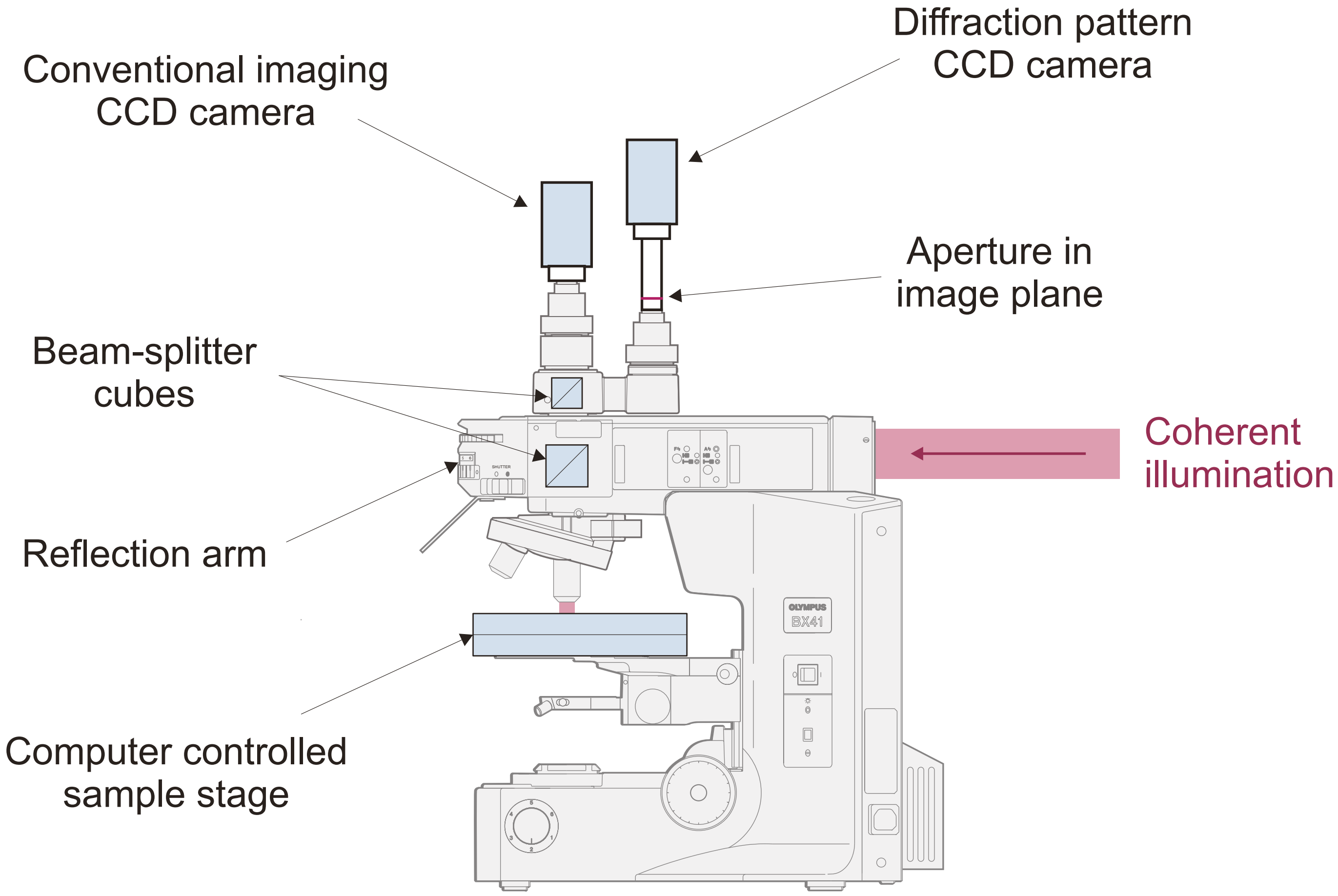


Figure 5: *Schematic of the experimental configuration. The addition of a computer-controlled stage, aperture and CCD camera outside the focal plane enable Phase Focus Virtual Lens® reflection imaging.*

Imaging surface features

When light is reflected from a surface, the wavefront that forms will depend on the reflectivity of the surface, its topographic features and material properties such as dielectric constant. The amplitude of the wavefront represents the reflectivity of the surface. This is the only information shown by conventional brightfield reflection images. The phase of the wavefront depends on variations in the height of the surface, along with material properties such as dielectric constant. In this application note we focus on using the phase data to generate topographic maps of surfaces. In Technical Brief "TB03 - Optical reflection imaging" we consider in detail the analysis of reflection phase data and its use to measure topography, material properties, film thicknesses and refractive indices. A future application note will provide examples of these measurements.

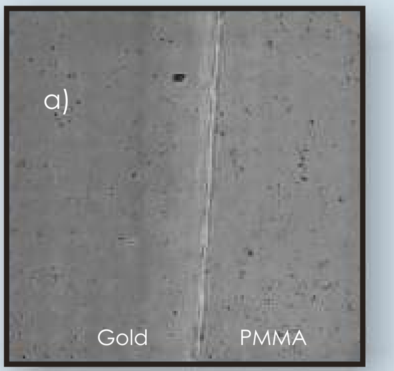
To demonstrate topographic imaging, a test sample was made by evaporating a thick gold film onto a standard microscope slide. A 1μm thick layer of PMMA was then formed on one half of the slide, with the other half remaining un-coated gold. The images in the panel to the right show data collected from the sample. The amplitude image a), equivalent to a conventional brightfield image, shows very little contrast, with the step between the gold and PMMA barely visible. Image b) shows the raw phase data from the sample. At the step edge between the two layers, a series of bright/dark fringes can be seen. These fringes are where the phase signal has gone through a full 2π radians and has "wrapped" around due to the size of the step. We can unwrap the phase, summing up each fringe, to produce the image shown in c).

The unwrapped phase data can be converted to height using the equation below, where d is the relative height, Φ is the change in phase and λ is the wavelength of the illumination:

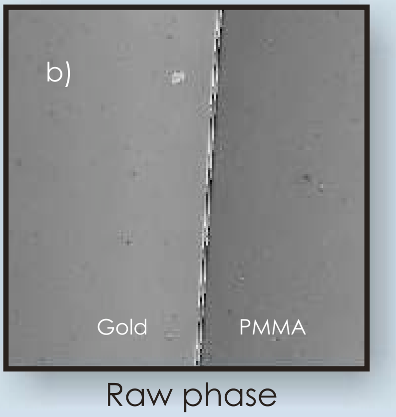
$$d = \frac{\Phi\lambda}{4\pi}$$

It is clear from the equation that measured phase will change by a full 360° (black-to-white in raw phase image) when the height changes by half the wavelength of illuminating light (~317nm for the 635nm laser used in this experiment).

For a more detailed discussion of the origin of this equation, please refer to Technical Note TB03.

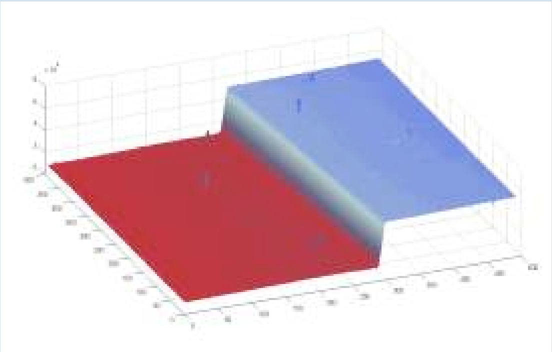


Amplitude



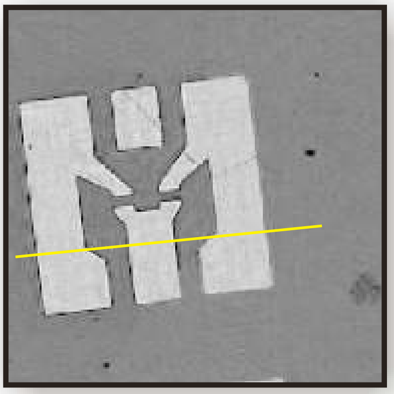
Raw phase

Unwrapped phase



3D representation

Figure 6: *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.*



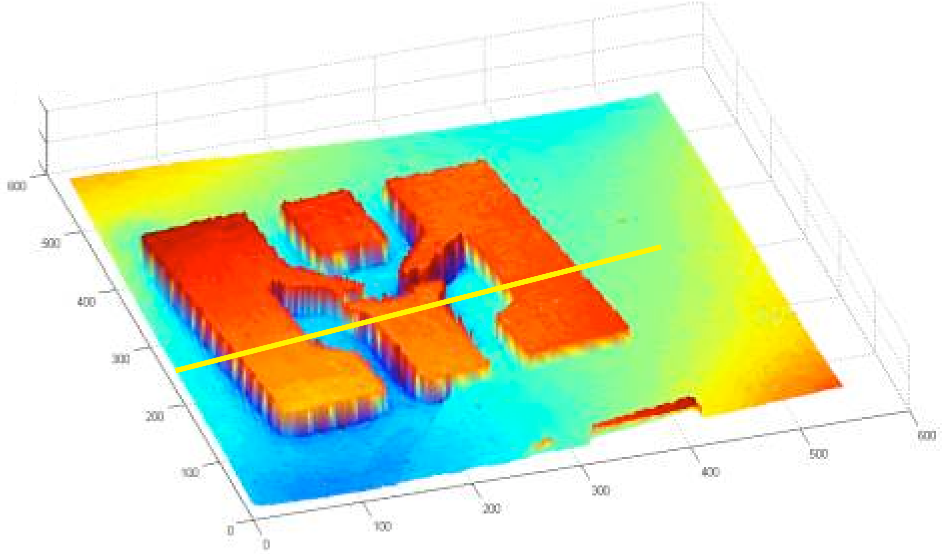
Amplitude

Phase

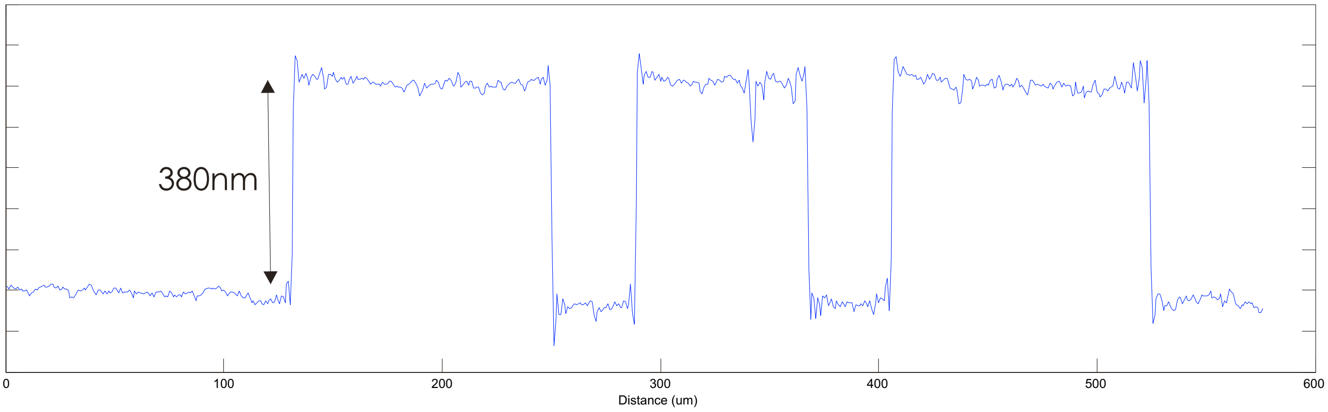
Detailed application example

The National III-V Semiconductor Centre in Sheffield, England regularly produces semiconductor devices in its cleanroom facility. Using the a x10 (0.25NA) objective lens on the Olympus BX41 microscope shown on page 1, the images on the left were obtained with the Phase Focus Virtual Lens®. The images show a typical device, courtesy of Dr. Richard Hogg, consisting of raised features on a planar semiconductor substrate.

From the phase data a topographic map was calculated. The image below shows a 3D projection of the topography of the sample. The profile at the bottom of the page shows clear 50nm high features along the line marked on the phase image. The measured rms z variation across the substrate is <2nm, and we consider this to be a real variation in height rather than the noise floor of the instrument. The lateral dimensions of the device are ~400µm.

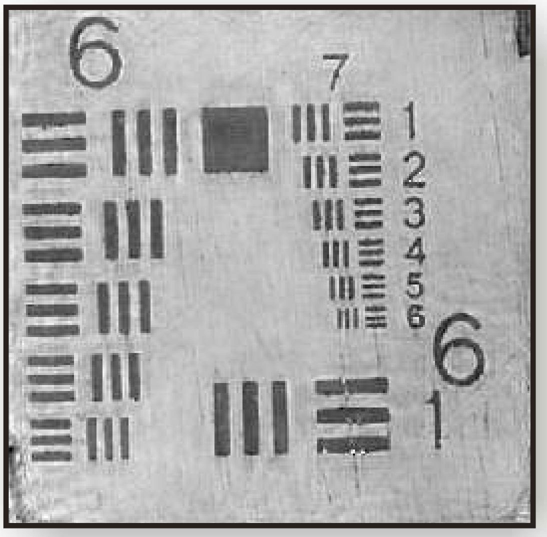


3D representation generated from phase data



Calculated height profile along line marked in yellow above

System Performance

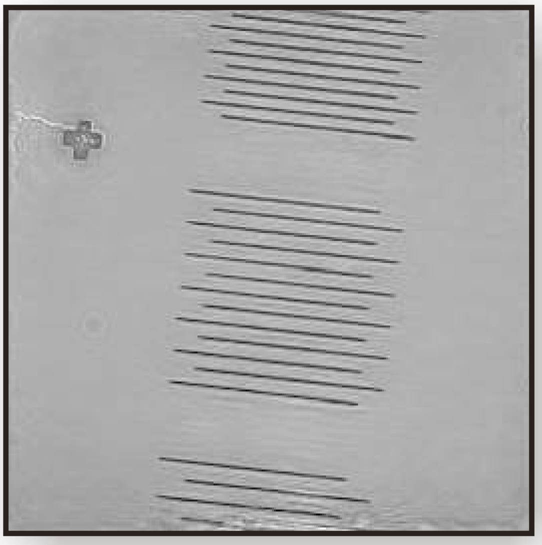


Spatial resolution

The image on the left shows the recorded phase from a USAF 1951 calibration target consisting of evaporated gold lines and numbers on a glass substrate. The smallest features in the image (section 7, row 6) have equal widths and spacings of 2.2um each. This resolution is at the diffraction limit of the 0.25NA lens used in the test with a 633nm laser. Note how the image clearly shows surface scratches and dirt not normally visible with the same target in transmission mode.

Height resolution

With an estimated phase resolution of 0.02 radians, corresponding to <1nm height resolution in reflection mode, we have found it a challenge to obtain a test sample with sufficiently small features to test the ultimate resolution of the Phase Focus Virtual Lens. The image on the right shows 30nm deep features etched directly into a glass substrate. The 30nm steps are clearly resolved in the image, and residue left from the etching process can be seen in the bottom of the cross-shaped etch pit. We are in the process of measuring repeatability and accuracy using a commercial calibrated step sample.



Phase Focus Limited | Kroto Innovation Centre | Broad Lane | Sheffield | S3 7HQ
Tel. +44 (0)114 213 1890 | www.phasefocus.com

Technical contact

Dr. Martin Humphry
martinhumphry@phasefocus.com
Tel: +44 (0)114 213 1890

phasefocus™