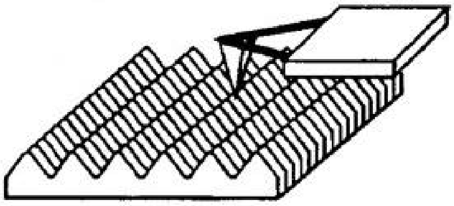
Technische Universität Chemnitz

XI. International Colloquium on Surfaces

XI. ICS



XI. Internationales Oberflächenkolloquium

Proceedings

Part I

February 2nd and 3rd 2004
Chemnitz, Germany

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Highly accurate 2D and 3D surface metrology using confocal white-light sensors with chromatic distance coding

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Abstract

In recent years, white-light confocal microscopes have turned out to be one of the most important optical techniques for 3D rough surface metrology, as this technique's results compare very well to those from stylus instruments.
Compared to imaging confocal microscopes, scanning instruments using confocal single point sensors offer more flexibility in terms of measurement volume, lateral spacing and resolution both in 2D as well as 3D.
Common to all classical versions of confocal single point sensors and confocal microscopes is the need of a z-scan. This is typically done using z-scanning piezos, tuning forks or other tools for scanning the focusing lens.
DIGITAL SURF has developed a new product line of passive confocal single point white-light sensors. The term "passive" means that this technique does not need a z-scan, as the chromatic length-aberration of the sensor optics allows to measure the z-coordinate.
Various sensor heads offer vertical measurement ranges from about 100 microns up to several millimeters, with vertical resolutions of about 10^{-5}.
This paper explains the basic principles of our confocal white-light sensors with chromatic distance coding, discusses specifications and shows some measurement results.

1. Introduction

In recent years, the technique of confocal microscopy, as first described by M. Minski in 1957 [1, 2] has been established as a powerful tool for 3D characterisation of engineering surfaces [3, 4].

In reflection mode confocal distance measurement, light emitted from a point light source is imaged into the object focal plane of a focusing lens (the first focussing). A surface location in focus leads to a maximum flux of the reflected light through a detector pinhole (the second focussing), whereas light from defocused object regions is partly suppressed. The detector signal, as limited by the pinhole size, is reduced strongly when defocusing the surface [5, 6]. This first results in the so called depth discrimination [7], which allows an accurate determination of the surface z coordinate (the confocal distance measurement) and second in a contrast enhancement by suppression of light scattered from defocused surface locations.

Confocal imaging microscopes use these principles for depth discriminated optical sectioning either in confocal laser scanning microscopes with serial xy-scanning techniques (serial within the object field size) or in confocal Nipkow disk microscopes with parallel xy-scanning techniques (parallel within the object field size), as first described by Petran [8]. In both cases, a further z-scan is necessary to acquire all the data for the evaluation of 3D topographic maps [9, 10]. As these types of confocal imaging microscopes need to use high power microscope objectives, the object field size which can be measured with high resolution and accuracy is limited to less than 1 mm^2. The only way to overcome this lateral limitation in confocal imaging microscopes is the stitching technique [11], which is time consuming and results in a huge amount of data.

Using confocal single point distance sensors in scanning systems (like in stylus instruments) offers the flexibility in both the xy measurement field size and the xy spacing. But, using laser light sources, such confocal single point distance sensors again need a z-scan for distance data acquisition. This can be done using tuning forks or piezo-actuators.

In 1984, Molesini [12] has introduced the chromatic length aberration (CLA) into the confocal single point distance measurement. This principle uses white-light sources and allows to design purely passive confocal single point distance sensors without the need of any z-scan for the distance data acquisition. Based on this principle, DIGITAL SURF has developed it's new product line of CLA confocal gauges.

2. Theory of the confocal white-light sensor with chromatic distance coding

A comprehensive description of the theory of confocal distance measurement is given in [7], some relevant formulas are as follows [3, 4].

We first look at monochromatic or axially colour-corrected confocal system (without CLA effects: all wavelengths were focused onto the same z co-ordinate). The depth response $I(z)$ of such a system is proportional to a $SINC^2$ function,

$$I(z) \quad = \quad \left(\frac{\sin(kz(1-\cos\alpha))}{kz(1-\cos\alpha)} \right)^2 I_0 \qquad (1)$$

which is depending on the aperture angle α of the focusing lens, the wavelength of light λ, the wave-number $k = 2\pi/\lambda$ and the co-ordinate of defocusing z. Significant for the depth response $I(z)$ is the Full Width at Half Maximum, which is

$$FWHM \quad = \quad 2\, z_{1/2} \quad \approx \quad \frac{0{,}443\, \lambda}{1-\cos\alpha} \qquad (2)$$

The wavelength together with the numerical aperture determine the full width at half maximum $FWHM$ of the depth response $I(z)$ of the detectors intensity.

In practice, the depth response $I(z)$ is more Gaussian like, where the surface distance is coded by the position of the Gaussian peak. Thus, the measurement task is first to record the depth response $I(z)$ by a z-scan and second to determine the peak position.

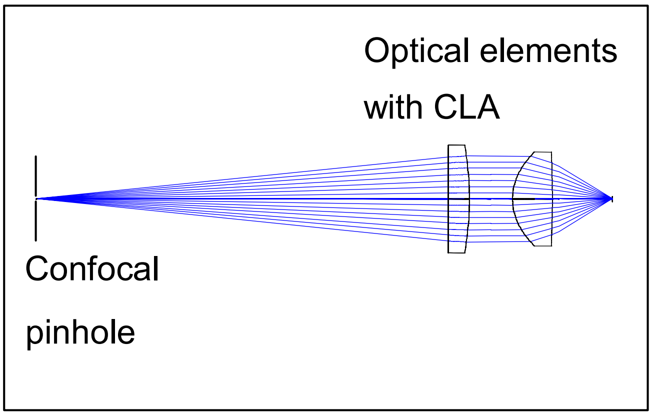

Figure 1: A confocal system with CLA.

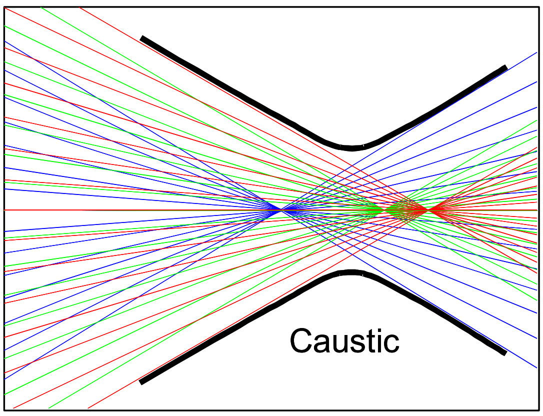

Figure 2: A zoom into CLA focus.

Figure 1 shows a confocal single point distance system with a CLA effect. Due to the CLA, different wavelengths were focused into different z co-ordinates along the optical axis, as shown in figure 2. The longer the wavelength λ, the farer the corresponding z co-ordinate is. Thus, the spectral range of the CLA confocal system results in a continuous wavelength coded range of foci. And this results in a depth response $I(\lambda)$, which in practice is also Gaussian like. Thus, the measurement task is first to record the depth response $I(\lambda)$ by acquiring the corresponding spectrum and second to determine the peak position (figure 3). As the main result, a mechanical z-scan is no more required.

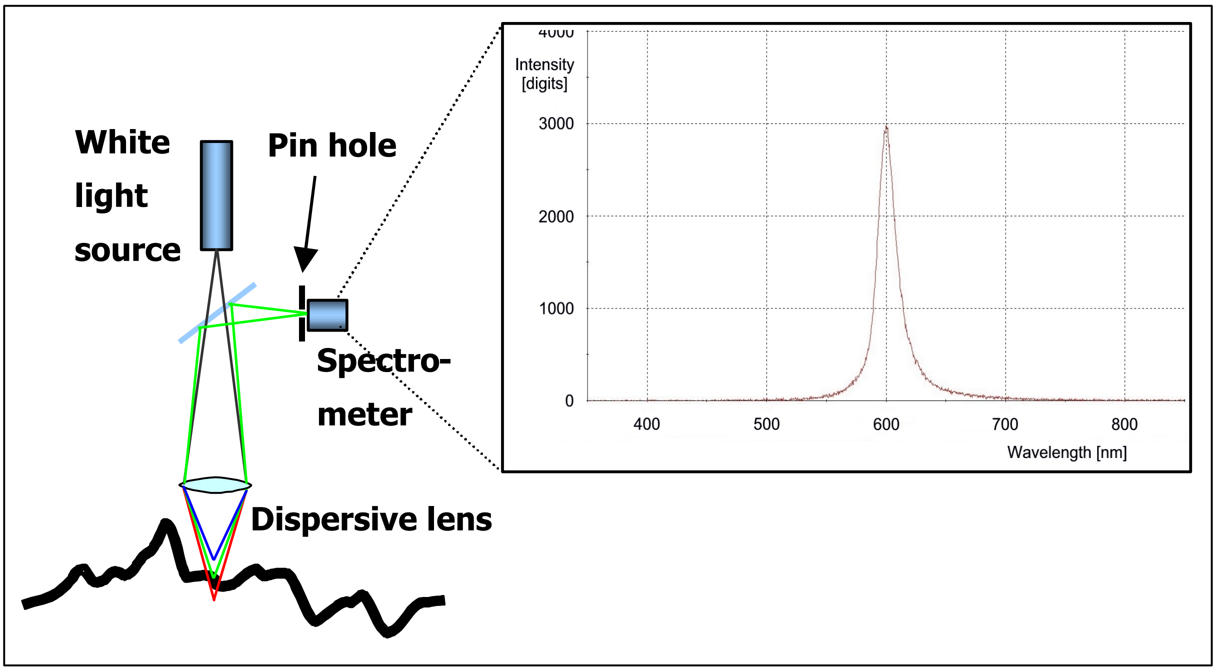

Figure 3: The principle of the CLA confocal gauge.

In well designed CLA gauges, the CLA elements produce diffraction limited foci from the light emitted from the confocal pinhole. All spherical aberration is eliminated. In addition, the CLA elements produce a maximum for the chromatic length aberration. Due to the CLA focus shift, the overall envelope of all wavelengths results in a worse total spot size („Caustic“, figure 2), but this is not the measurements spot size. The measurement focus spot size for all of the wavelengths is still diffraction limited. Very large CLA focus ranges can be produced using diffractive optics [13, 14].

The half angle of the numerical aperture NA determines the maximum surface slope

$$\alpha_{\max}^{spec} = 0.5 \sin^{-1} NA \qquad (3)$$

for specular reflection at a microscopic smooth surface element of the surface.

Engineering surfaces often have micro-roughness within the gauge spot size, therefore diffuse reflection increases the maximum surface slope which can be measured ($\alpha^{diff} \geq \alpha_{\max}^{spec}$) and $\alpha_{\max}^{spec}$ according to equation 3 indicates a lower limit of the surface slope.

3. The NOBIS family of CLA confocal gauges

Up to now, three different CLA confocal gauge heads are available. Their specifications were listed in table 1. The CLA confocal gauge 300 HE is optimized for step height measurement, whereas the CLA confocal gauge 300 BE is optimized for roughness measurement.

	CLA confocal gauge 300 HE	CLA confocal gauge 300 BE	CLA confocal gauge 3000
Range	300 µm	300 µm	3 mm
Working distance	5 mm	5 mm	38 mm
Maximum sampling frequency	1000 Hz	1000 Hz	1000 Hz
Noise level (Pt) on a mirror	80 nm	80 nm	700 nm
Noise level (σ)	15 nm	15 nm	100 nm
Maximum slope (specular surfaces)	25°	25°	13°
Lateral precision*	8 µm	11 µm	40 µm
Lateral resolution**	1 µm	2 µm	5 µm
Repeatability	20 nm	20 nm	100 nm
Linearity	± 0.2 %	± 0.2 %	± 0.2 %

Table 1: Specifications of the CLA confocal gauge heads.
* Lateral precision: The smallest negative crenel that the spot can enter while still giving the correct depth.
** Lateral resolution: The smallest surface detail the spot can see without giving the correct depth.

DIGITAL SURF develops, manufactures and supplies software, electronics and optical sensors as OEM components mainly for surface metrology partners.

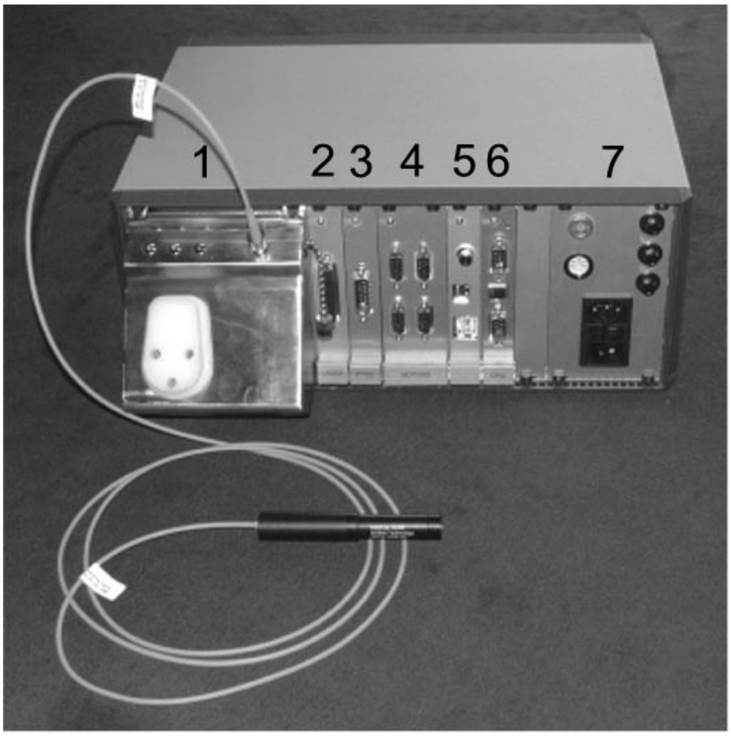

Figure 4: Volcanyon controller

1: CLA confocal gauge controller
2: Laser gauge controller
3: Inductive gauge controller
4: Motor controller
5: Video controller
6: CPU card
7: Power supply module

Based on the technologies of Mountains™ (software) and Volcanyon™ (electronics), modular machines for 2D and 3D surface metrology have been designed for using various kinds of gauges, like inductive gauges from our partners, laser triangulation gauges from external sources or the CLA confocal gauges from our own developed. Figure 4 shows one example of a Volcanyon™ controller together with a CLA confocal gauge 300 HE as the central part of Taylor Hobson's new Talysurf CLI 2000. This type of machine was used for the measurements as presented within the next section.

4. Experimental results using the NOBIS sensors

4.1 VLSI step height standard

Figure 5 shows a line scan across a "VLSI thick step height standard" [15], using the CLA confocal gauge 300 HE. These type of VLSI standard was designed to calibrate surface profilers. Traceable to NIST, these standards consist of a 25 mm x 25 mm x 3 mm quartz block with a precisely etched trench (negative feature), along with diagnostic features to assess stylus dynamics and integrity. The choice of the material for manufacturing the standard - a high quality quartz photomask blank - assures an extremely flat and smooth working surface as well as parallelism of the top and bottom surface within a few seconds of arc.

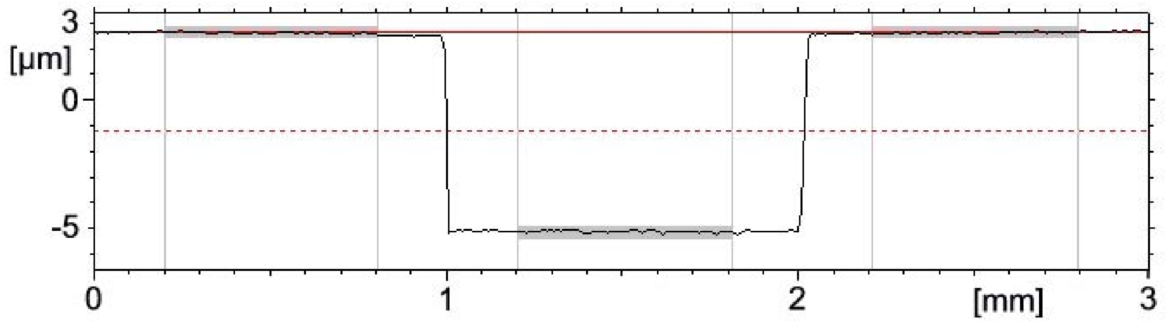

Figure 5: A CLA confocal gauge 300 HE measurement result using a VLSI thick step height standard.

The nominal step height of the VLSI standard used for the measurement in figure 5 was 7.8 µm. The measured maximum step height obtained from the two top and one bottom ranges of the profile as highlighted by the grey bars in figure 5 was 8.87 µm and the measured mean step height was 7.75 µm.

4.2 LINEN type steel sheet

The next measurement example shows a comparison of the CLA confocal gauge 300 BE and a 2.5 mm range inductive gauge, using a LINEN formed steel sheet. Figure 6 shows the topography of CLA confocal gauge 300 BE measurement. The measured area was 5 mm × 5 mm at a spacing of 20 µm × 20 µm. The scan speed was 3 mm/s and the measured height range was 70 µm. Figure 7 shows the topography of corresponding 2.5 mm range inductive gauge measurement. The measured area, the spacing and the measured height range were the same as before. The scan speed was 1 mm/s. Figure 8 shows a profile extracted from the topography from figure 6 (diagonal: 7 mm profile length from the lower left to the upper right corner). The maximum surface slope angle from this profile is 55 degrees.

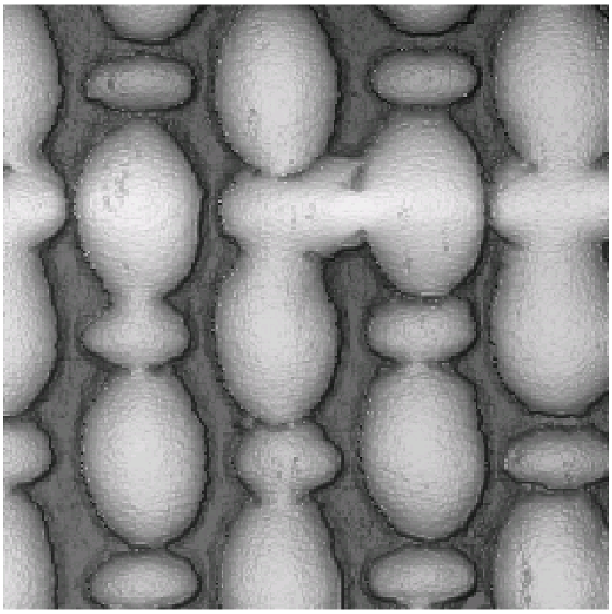

Figure 6: The topography of a CLA confocal gauge 300 BE measurement result.

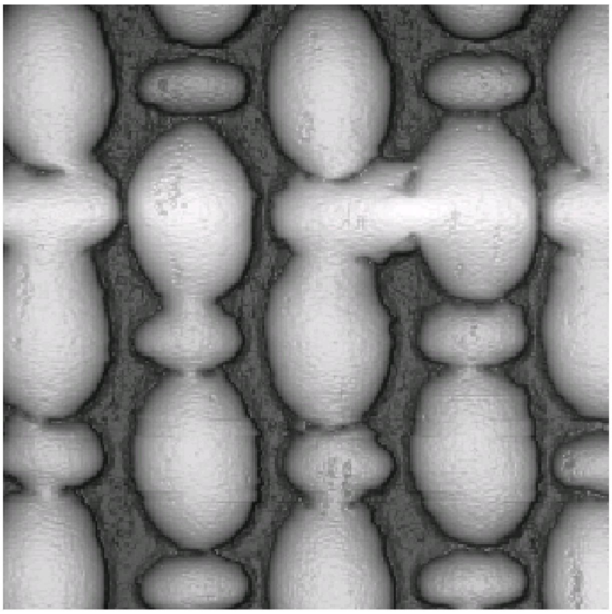

Figure 7: The topography of a 2.5 mm range inductive gauge measurement result.

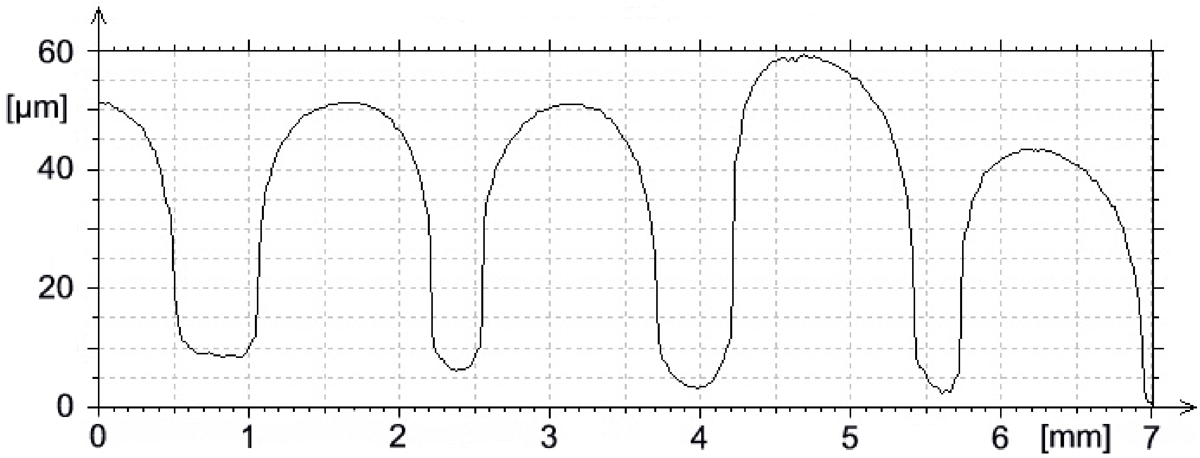

Figure 8: A profile extracted from the topography from figure 6.

4.3 BGA array

The last measurement example shows the characterization of a BGA (Ball Grid Array) from the wafer industry. Figure 9 shows a photograph of the BGA through a microscope, the corresponding BGA size is about 4.2 mm × 3.5 mm. There are bridges between the balls of some pairs. Figure 10 shows the topography of a CLA confocal gauge 300 HE measurement. The measured area was 10 mm × 10 mm at a spacing of 10 µm × 10 µm, the full height range is 200 µm.

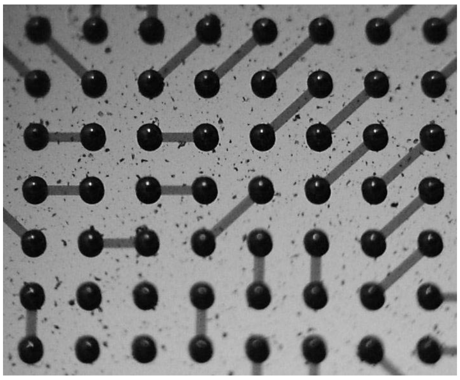

Figure 9: Photograph of the BGA.

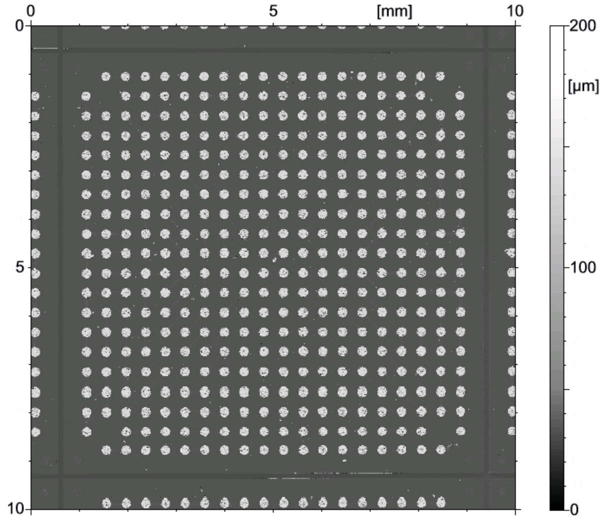

Figure 10: BGA topography, full height range.

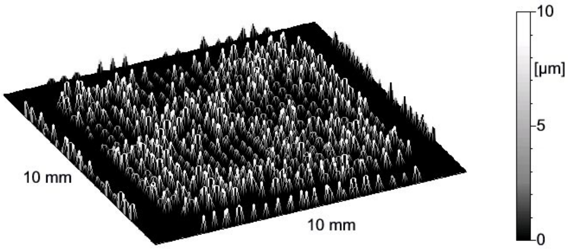

Figure 11: BGA topography, height range thresholded to 10 µm around the top of the balls.

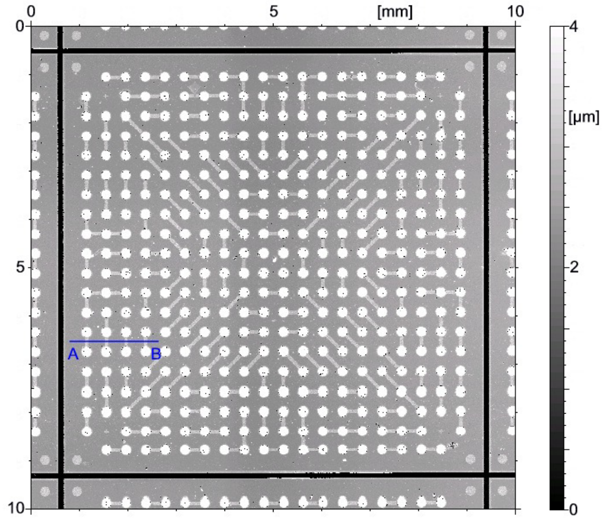

Figure 12: BGA topography, height range thresholded to 4 µm around the substrate.

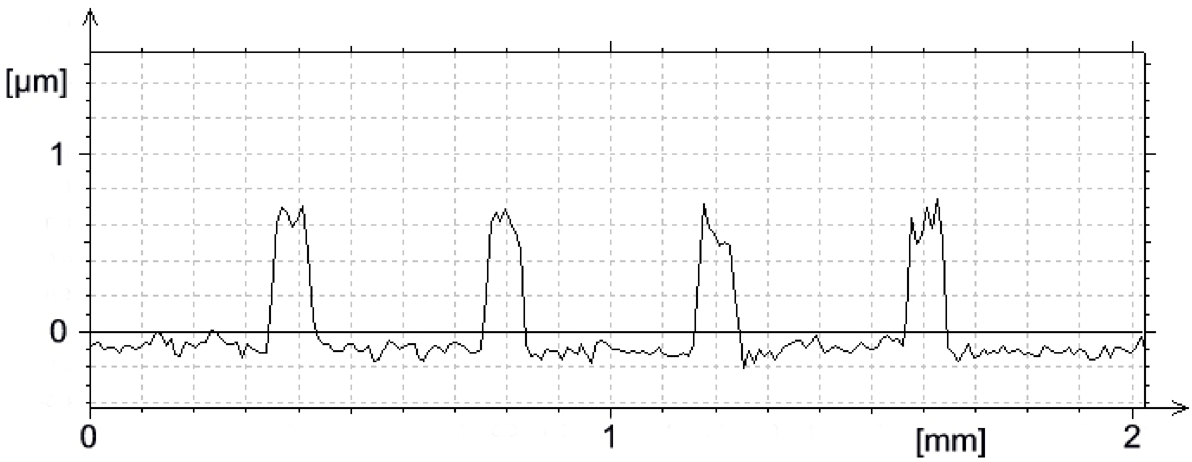

Figure 13: A profile extracted from the topography from figure 12, from the A to B.

Interesting details can be derived from this measurement result by thresholding the height range for further presentations. Figure 11 shows the same measurement result as figure 10, but the height range is now thresholded to 10 µm around the top of the balls in order to show the deviation (co-planarity) of the ball heights. In figure 12, the same was done around the substrate plane with a thresholded range of 4 µm. Now, a lot of the bridges as mentioned above can be seen. Figure 13 shows a profile extracted from the topography from figure 12, from the locations A to B. Thus, figure 13 shows the cross-section of 4 of the bridges (profile length = 2 mm / width of one bridge about 70 µm / height of one bridge about 0.7 µm).

5. Conclusions

The optical non-contact CLA confocal gauges as developed by DIGITAL SURF have shown a high resolution and accuracy in measurements on engineering surfaces. The results from our CLA confocal gauges compare very well to those from inductive gauges, with the additional benefit of being from non-contact measurements. This enables for example the characterization of steep edges and high aspect ratios or measurements on soft materials.

The confocal single point distance measurement principle has the same benefits and power as confocal imaging microscopy, but it overcomes the optical limitation of confocal imaging microscopy in terms of measurement volume and spacing. Measurement instruments using our CLA confocal gauges allow to scale the xyz measurement volume and the corresponding xy spacing in a wide scale.

Furthermore, all CLA confocal gauges have purely passive sensor heads. This avoids edge spike problems, which are well known from optical auto-focus sensors.

6. Acknowledgements

The author likes to thank Isabelle Cauwet from DIGITAL SURF France for the measurement presented in chapter 4.1 and Chris Phillips from Taylor Hobson's Centre of Excellence for the measurements presented in chapter 4.2, which have been carried out during the evaluation of Taylor Hobson's new Talysurf CLI 2000.

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