

A NATIONAL MEASUREMENT GOOD PRACTICE GUIDE

No.108

Guide for the Measurement
of Smooth Surface
Topography using
Coherence Scanning
Interferometry

Measurement Good Practice Guide No. 108

Guide to the Measurement of Smooth Surface Topography using Coherence Scanning Interferometry

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ABSTRACT

This guide describes good practice for the measurement and characterisation of smooth surface topography using coherence scanning interferometry (commonly referred to as vertical scanning white light interferometry). The guide is based on the measurement of the topography of semiconductors, epitaxial wafers and optical thin film coatings. However, the general guidelines described here can be applied to many flat, smooth surface topography measurements. For the purpose of this guide, the definition of a smooth surface is one that has an approximately random distribution of heights with a roughness (S_z) of less than 50 nm.

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GOOD MEASUREMENT PRACTICE

There are six guiding principles to good measurement practice that have been defined by NPL. They are:

The Right Measurements: *Measurements should only be made to satisfy agreed and well-specified requirements.*

The Right Tools: *Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose.*

The Right People: *Measurement staff should be competent, properly qualified and well informed.*

Regular Review: *There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures.*

Demonstrable Consistency: Measurements made in one location should be consistent with those made elsewhere.

The Right Procedures: Well-defined procedures consistent with national or international standards should be in place for all measurements.

Introduction

1

IN THIS CHAPTER

- Scope of this guide
- Introduction to coherence scanning interferometers

Scope of this guide

The purpose of this good practice guide is to assist users in the effective measurement and analysis of smooth surfaces using the technique of coherence scanning interferometry (CSI). The guide will cover the concepts of CSI, the route to repeatable and reliable measurement, an overview of appropriate analysis techniques and a guide to the interpretation of results. Throughout the guide the arbitrary definition of a smooth surface is one that has an approximately random distribution of heights with a roughness (S_z , see chapter 2) of less than 50 nm. Note that a further good practice guide (available in early 2008) will be concerned with the measurement of rough and structured surfaces. That guide will go into much more depth on the theory and practice of interferometry and should be consulted where non-smooth surfaces need to be measured.

Semiconductor and Optical Layer Analysis and Definition using Interference Microscopy (SOLADIM) was a project funded by the MNT Manufacturing Initiative of the UK Department of Trade and Industry (2004 to 2007). The aim of the project was to develop measurement techniques and international specifications for surface texture measurement of epitaxial wafers and thin film coatings. Good practice guide no. 108 was compiled during the SOLADIM project to specifically look at the measurement of epitaxial wafers and thin film coatings, however, the principles can be applied to the measurement and characterisation of many flat and smooth surfaces.

Throughout this guide we will concentrate on the use of coherence scanning interferometers. However, the generic principles of measurement good practice can be applied to many surface texture measuring instruments.

During the formulation of this guide and development of the case study the Taylor Hobson Talysurf Coherence Correlation Interferometer (CCI) was used primarily. However, guidance is given that is entirely applicable to any CSI instrument.

In 2002, the International Organization for Standardization (ISO) Technical Committee 213, dealing with Dimensional and Geometrical Product Specifications and Verifications, formed a working group (WG) 16 to address standardisation of areal (three dimensional) surface texture measurement methods. WG 16 is developing a number of draft standards encompassing definitions of terms and parameters, calibration methods, file formats and characteristics of instruments. Under this working group, a project team is developing standards for optical methods of areal surface texture measurement and one of these methods is CSI.

Where possible the terms, definitions, parameters and measurement practices that are used in the draft standards have been adhered to in this guide. However, as this is a draft standard, it is subject to changes and additions. This guide will be updated to implement any changes and

include any additions when the standard is formally published. The following terms that are listed in the draft standard are also used to refer to CSI:

CPM	coherence probe microscope
CSM	coherence scanning microscope
CR	coherence radar
CCI	coherence correlation interferometry
MCM	Mirau correlation microscope
WLI	white light interferometry
WLSI	white light scanning interferometry
SWLI	scanning white light interferometry
VSI	vertical scanning interferometry
RSP	rough surface profiler
RST	rough surface tester
HSI	height scanning interferometer

Introduction to coherence scanning interferometers

Basics of interferometry

Interferometry is based on the idea that the amplitudes of two waves (for example, light, sound or water) with the same frequency will add to each other. When the two waves are in phase the result will sum to twice the amplitude (figure 1, assuming both have the same amplitude). When the two waves are out of phase by 180° the result will sum to zero amplitude (figure 2, again assuming both have the same amplitude). This adding and cancelling wave property is known as superposition and results in a set of dark and light bands known as interference fringes when viewed on a screen or through a microscope.

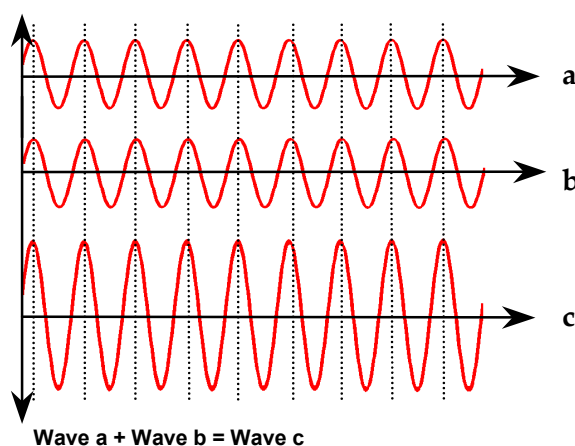


Figure 1. Schematic graph of amplitude against time showing constructive interference

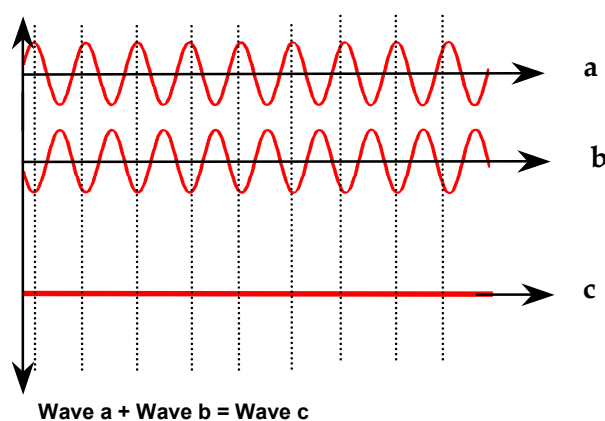


Figure 2. Schematic graph of amplitude against time showing destructive interference

In order to use superposition to construct a CSI using a single light source, a beam splitter can be used to create the two waves to be interfered. Typically in an interferometer, a wave is split into two parts, which travel different paths and the waves are then combined to create interference. When the paths differ by an even number of half-wavelengths, the superposed waves are in phase and constructive interference is observed, increasing the amplitude of the output wave. When they differ by an odd number of half-wavelengths, the combined waves are 180° out of phase and destructive interference is observed, decreasing the amplitude of the output. Anything that changes the phase of one of the beams by only 180° shifts the interference from a maximum to a minimum. A schematic of how the split beams produce constructive interference is shown in figure 3.

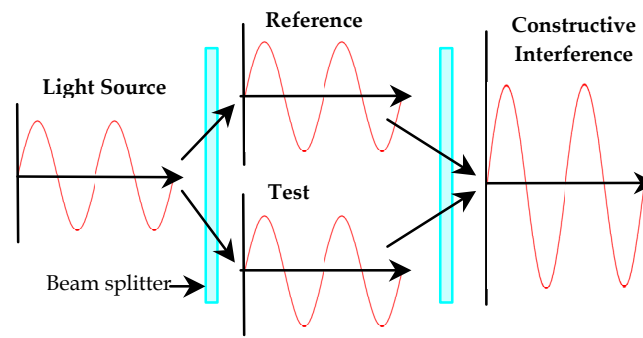
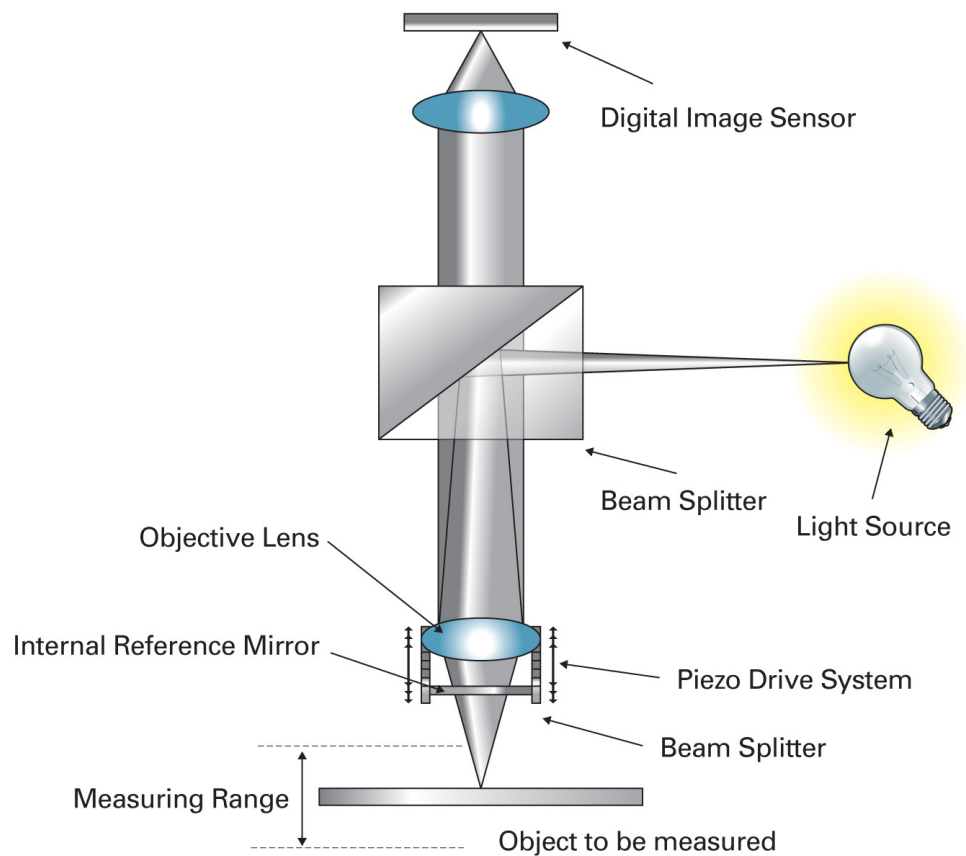


Figure 3. Constructive interference from one light source

Coherence scanning interferometry

A schematic of a CSI is shown in figure 4. The upper beam splitter directs light from the light source towards the objective lens. The lower beam splitter in the objective lens splits the light into two separate beams. One beam is directed towards the sample and one beam is directed towards an internal reference mirror. The two beams recombine and the recombined light is sent to the detector. Due to the low coherence of the white light source, the optical path length to the sample and the reference must be almost identical, for interference to be observed. Note that coherence is the measure of the average correlation between the value of a wave at any pair of times, separated by a given delay. Temporal coherence tells us how monochromatic a source is. In other words, it characterises how well a wave can interfere with itself at a different time (coherence is discussed in detail in the follow up guide discussed at the beginning of this chapter). The detector measures the intensity of the light as the interferometric objective is actuated in the vertical direction (z axis) and finds the interference maximum. Each pixel of the sensor measures the intensity of the light and the fringe envelope obtained can be used to calculate the position of the surface. White light is used rather than monochromatic light because it has a shorter coherence length and, therefore, avoids ambiguity in determining the fringe order. Different instruments use different techniques to control the movement of the objective and to calculate the surface parameters. The accuracy and repeatability of the CSI measurement depend on many parameters including the control and linearity of the vertical actuator, the performance of the camera, the design of the metrology frame, the stability of the sample, the environment, *etc.*

Figure 4. A typical CSI design



As the objective lens is moved a change of intensity due to interference will be observed for each pixel when the distance from the sample to the beam splitter is the same as the distance from the reference mirror to the beamsplitter. If the objective is moved downwards (in figure 4) the highest points on the surface will cause interference first. This information can be used to build up a three dimensional map of the surface. Figure 5 shows how the interference is built up at each pixel in the camera array.

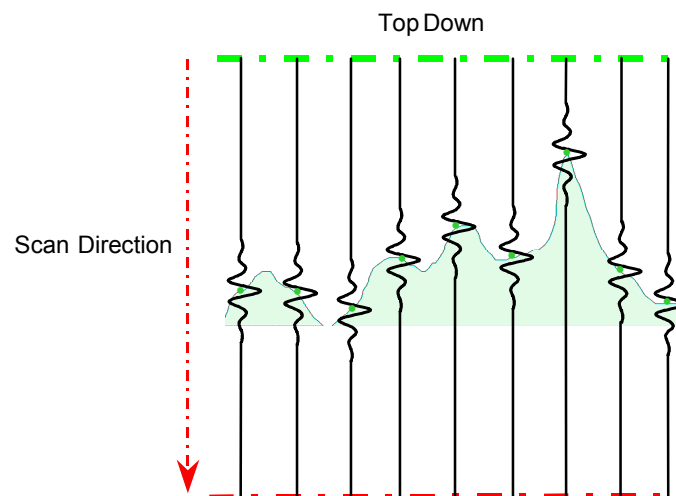


Figure 5. Schematic of how to build up an interferogram on a surface using CSI.
The vertical lines are intensity profiles at the image sensor

There are many commercial coherence scanning interferometers available and this guide does not endorse a specific manufacturer. Figure 6 shows some examples of commercially available coherence scanning interferometers.



Figure 6. Commercially available coherence scanning interferometers. Clockwise from bottom left: Mahr, Phase Shift, Polytec, Taylor Hobson, Veeco, Fogale and Zygo.

Interferometer objective lenses

Different designs of interferometer objective lens can be used for a CSI. Two of the most common are described in this section. In a Mirau interferometer the basic building blocks are a microscope objective lens, a reference surface and one semi-transparent optic (often called a beamsplitter). These are configured as shown in the figure 7. There are two paths from the light source to the detector. One beam reflects off the beamsplitter, travels to the reference mirror and then reflects back, travels through the beamsplitter, to the microscope objective lens and on to the detector. The other beam travels through the beam splitter, to the test surface, reflects back to the semi-transparent mirror and then reflects from the semi-transparent mirror into the microscope objective lens and then the detector.

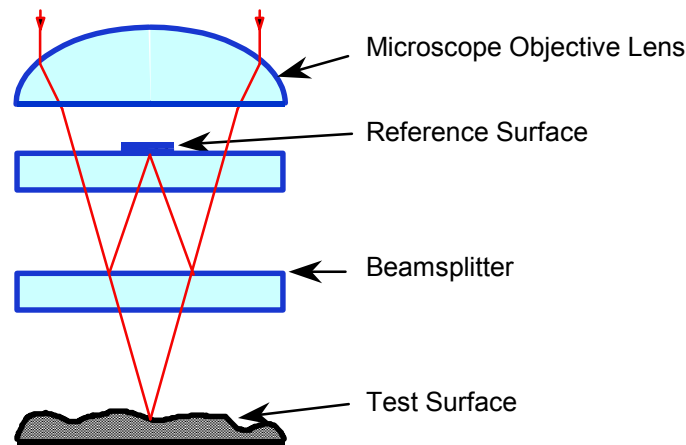


Figure 7. Schematic of a Mirau interferometer

A Michelson interferometer (see figure 8) is configured in a similar way to a Mirau with the exception that the reference surface is in a different position. This configuration is normally used at low magnification when the reference mirror is too large to be placed in the position shown in figure 7.

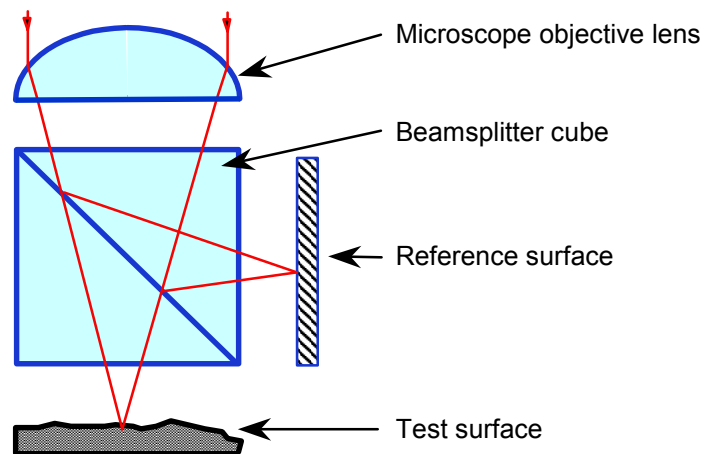


Figure 8. Schematic of a Michelson interferometer

This section has given a very brief introduction to interferometry including coherence scanning interferometry. To fully appreciate the concepts it may be necessary for the reader to have a fuller understanding of these principles than is given here. This may be achieved by reading the follow up generic good practice guide (mentioned at the beginning of this chapter) that will also be available in early 2008.

Terms and definitions

2

IN THIS CHAPTER

- General terms used in this guide
- Areal surface texture parameters
- Filtering techniques

General terms used in this guide

This chapter outlines some of the common terms and principles used in this good practice guide. The chapter aims to assist the user with specialist terminology and promote understanding of basic surface metrology terms and definitions. Many of the general terms and definitions used in surface metrology can be found in an earlier good practice guide, number 37 (see Literature in the appendix) and it is recommended that the reader is familiar with that guide. A further guide is being developed that will cover coherence scanning interferometers in general.

Surface profile measurement

Surface profile measurement is the measurement of a line across the surface that can be represented mathematically as a height function with lateral displacement, $z(x)$. With a stylus instrument profile measurement is carried out by traversing the stylus across a line on the surface. With a CSI, a profile is usually extracted in software after an areal measurement has been taken.

Figure 9 shows the result of a profile measurement extracted from an areal measurement.

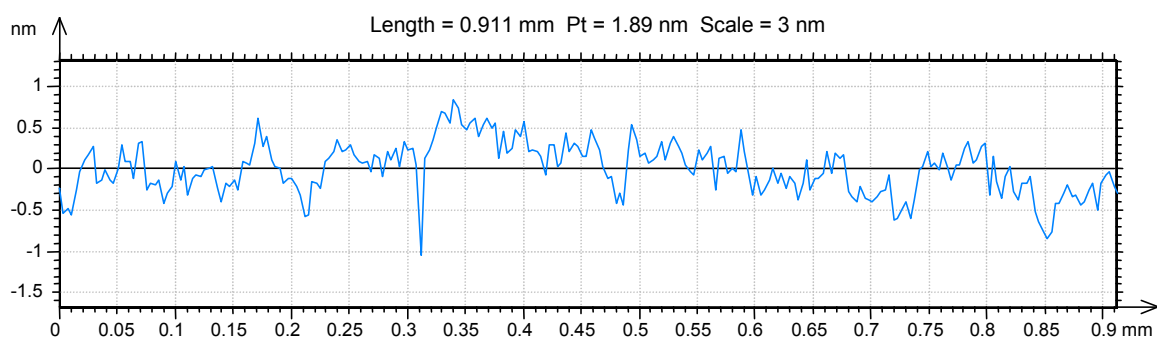


Figure 9. Example of the result of a profile measurement

Areal surface texture measurement

Areal surface texture measurement produces a three dimensional representation of a surface. The height data is represented as a height function in a plane, $z(x, y)$. Figure 10 shows a typical representation of a smooth areal surface texture measurement.

Sampling area

The sampling area refers to the size of the xy plane in which an areal measurement is performed.

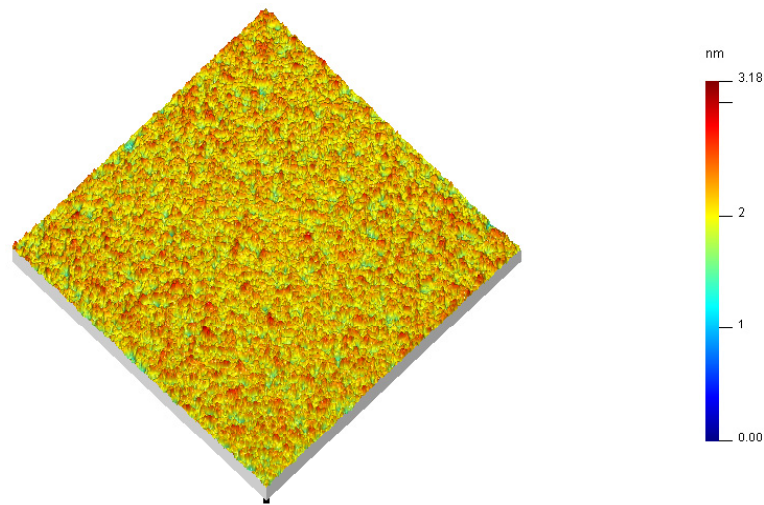


Figure 10. Example of the result of an areal surface texture measurement

Coherence scanning interferometry

As we have seen in chapter 1 this is a surface topography measurement where the localisation of interference fringes during a scan of optical path length provides a way of determining a surface topography map.

Numerical aperture

The numerical aperture (NA) designates the spread of angles over which light illuminates a sample and the spread of angles over which light is accepted by the objective of the optical imaging system, for example, a CSI. With reference to figure 11, the NA is equal to the sine of the acceptance angle, α , multiplied by the refractive index of the surrounding medium. When operating in air, the refractive index is approximately one.

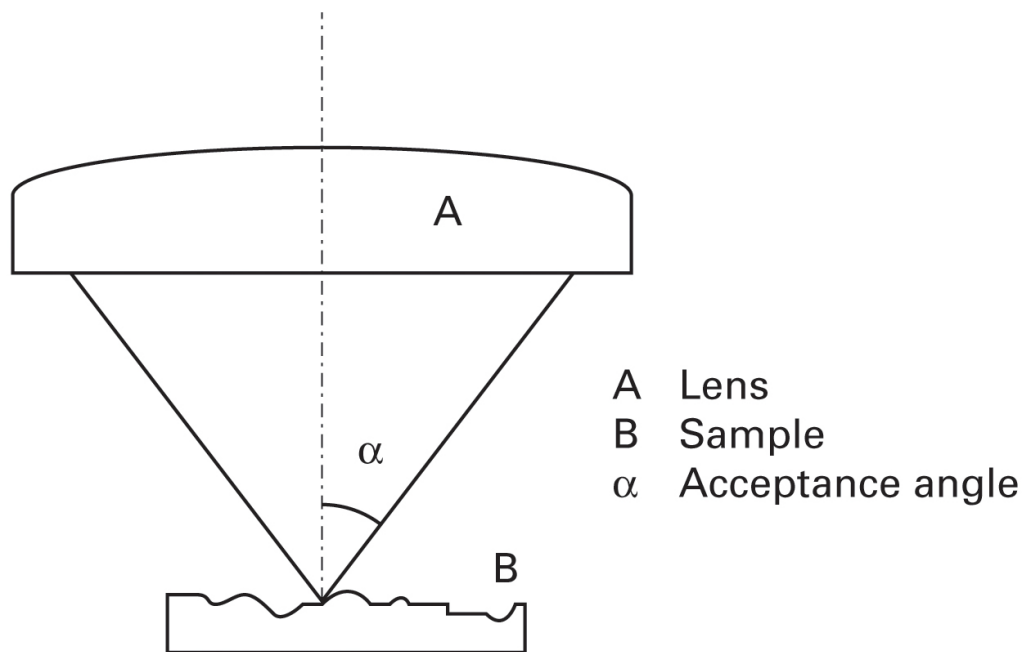


Figure 11. Illustration of the numerical aperture of a CSI objective lens

User defined variables

User defined variables are options in the operating system of the CSI that can be changed or varied by the user thus influencing the measurement result. Examples of such variables include filtering settings and whether to use data filling techniques (see chapter 3).

Smooth surface

In this guide the term smooth surface refers to a surface with an approximately random height distribution and a maximum height (S_z) of less than 50 nm.

Areal surface texture parameters

In this section we will outline some of the areal surface texture parameters that are available for characterisation of surfaces. The parameters that are described here are applicable for use in the characterisation of smooth surfaces. There are additional parameters available, such as those to characterise relative volumes or material characteristics, and also those that would be useful in the depiction of bearing surfaces in preparation. The definition of these additional parameters can be found in the publications suggested in the Appendix and will be included in the ISO specification standards. Note that many of the parameters described here will be available in the software packages that come with commercial CSIs. Therefore, where a parameter may seem mathematically complex, for example the spatial parameters, often the

user only needs a good understanding of the meaning of the parameter and may not need to know its exact derivation.

Areal and profile parameters

There are inherent limitations with 2D surface measurement and characterisation. A fundamental problem is that a 2D profile does not necessarily indicate functional aspects of the surface. For example, consider the most commonly used parameter for 2D surface characterisation, Ra (see NPL good practice guide number 37 for a description of profile parameters). Figure 12 shows the profiles of two surfaces, all of which return the same Ra value when filtered under the same conditions. It can be seen that the two surfaces have very different features and consequently very different functional properties.

With profile measurement and characterisation it is also often difficult to determine the exact nature of a topographic feature. Figure 13 shows a 2D profile and a 3D surface map of the same component covering the same measurement area. With the 2D profile alone a discrete pit is measured on the surface. However, when the 3D surface map is examined, it can be seen that the assumed pit is actually a valley and may have far more bearing on the function of the surface than a discrete pit.

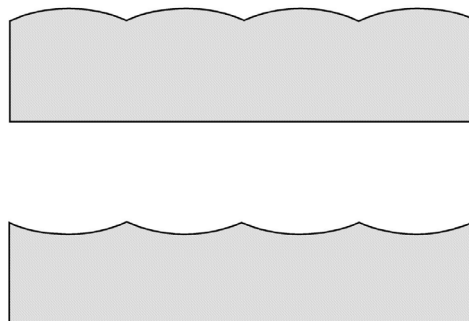


Figure 12. Profiles showing the same Ra with differing height distributions

The limitations of 2D surface measurement and characterisation have brought about the development of 3D surface measurement and characterisation. Three dimensional techniques give a better understanding of the surface in its functional state.

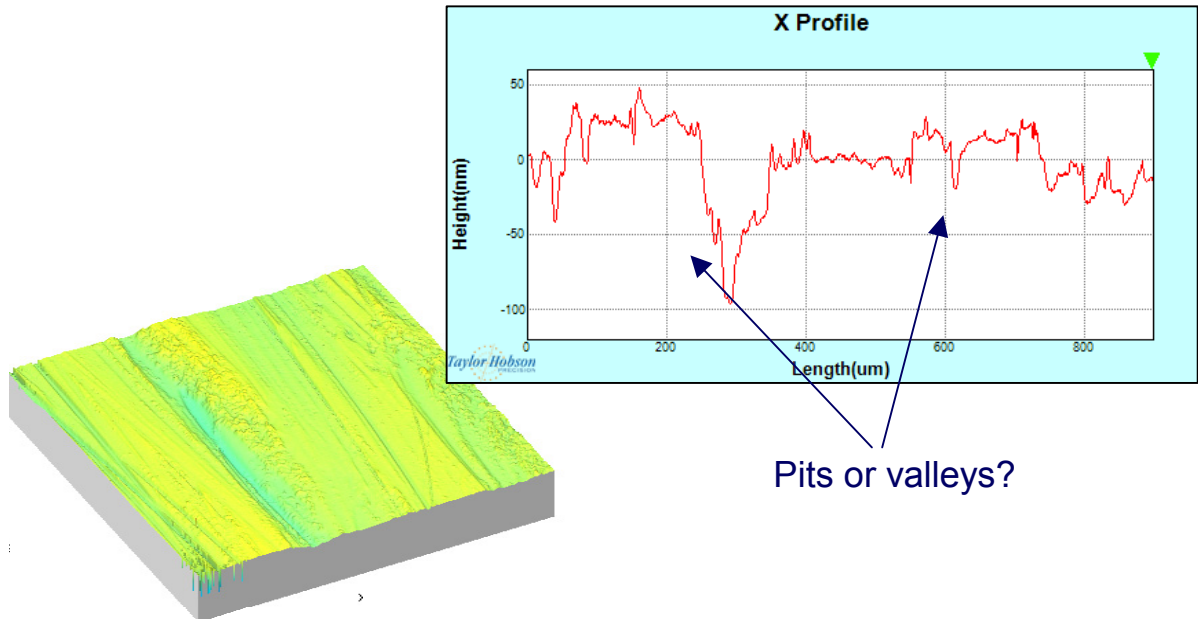


Figure 13. A profile taken from a 3D measurement shows the possible ambiguity of 2D measurement and characterisation

Amplitude parameters

Amplitude parameters give information regarding the areal height deviation of the surface topography. There are seven parameters in the amplitude family that are described in this section.

The root mean square value of the ordinate values within a sampling area, Sq

The Sq parameter is defined as the root mean square value of the surface departures, $z(x, y)$, within the sampling area, thus

$$Sq = \sqrt{\frac{1}{A} \iint_A z^2(x, y) dx dy} \quad (2.1)$$

where A is the sampling area, xy . Note that equation (2.1) is for a continuous $z(x, y)$ function. However, when making surface texture measurements using CSIs (or indeed any surface texture measuring instrument), $z(x, y)$ will be determined over a discrete number of measurement points. In this case equation (2.1) would be written as

$$Sq = \sqrt{\frac{1}{N} \frac{1}{M} \sum_{i=1}^N \sum_{j=1}^M z_{ij}^2} \quad (2.2)$$

where N is the number of points in the x direction and M is the number of points in the y direction. The equations for the other parameters below that involve an integral notation can be converted to a summation notation in a similar manner. The Sq parameter is the most common parameter that is used to characterise optical surfaces as it can be related to the way that light scatters from a surface.

The arithmetic mean of the absolute height, Sa

The Sa parameter is the arithmetic mean of the absolute value of the height within a sampling area, thus

$$Sa = \frac{1}{A} \int_A |z(x, y)| dx dy. \quad (2.3)$$

The Sa parameter is the closest relative to the Ra parameter; however, they are fundamentally different and should not be directly compared. Areal, or S -parameters, use areal filters (see later section) whereas profile, or R -parameters, use profile filters. The Ra parameter is the most common profile parameter for purely historical reasons and the reader should note that Sq is a much more statistically significant parameter than Sa .

Skewness of topography height distribution, Ssk

Skewness is a measurement of the symmetry of the surface deviations about the mean reference plane and is the ratio of the mean cube value of the height values and the cube of Sq within a sampling area, thus

$$Ssk = \frac{1}{Sq^3} \left[\frac{1}{A} \iint_A z^3(x, y) dx dy \right]. \quad (2.4)$$

The Ssk parameter describes the shape of the topography height distribution. For a surface with a random (or Gaussian) height distribution that has symmetrical topography, the skewness is zero. The skewness is derived from the amplitude distribution curve; it is the measure of the profile symmetry about the mean plane. This parameter cannot distinguish if the profile spikes are evenly distributed above or below the mean plane and is strongly influenced by isolated peaks or isolated valleys. This parameter represents the degree of bias, either in the upward or downward direction of an amplitude distribution curve. A symmetrical profile gives an amplitude distribution curve that is symmetrical about the centre line and an unsymmetrical profile results in a skewed curve. The direction of the skew is dependent on whether the bulk of the material is above the mean plane (negative skew) or below the mean plane (positive skew). Use of this parameter can distinguish between two surfaces having the same Sa value.

As an example a porous, sintered or cast iron surface will have a large value of skewness. A characteristic of a good bearing surface is that it should have a negative skew, indicating the presence of comparatively few hills that could wear away quickly and relatively deep valleys to retain oil traces. A surface with a positive skew is likely to have poor oil retention because of the lack of deep valleys in which to retain oil traces. Surfaces with a positive skewness, such as turned surfaces, have high spikes that protrude above the mean plane. The Ssk parameter correlates well with load carrying ability and porosity.

Kurtosis of topography height distribution, Sku

The Sku parameter is a measure of the sharpness of the surface height distribution and is the ratio of the mean of the fourth power of the height values and the fourth power of Sq within the sampling area, thus

$$Sku = \frac{1}{Sq^4} \left[\frac{1}{A} \iint_A z^4(x, y) dx dy \right]. \quad (2.5)$$

The Sku parameter characterises the spread of the height distribution. A surface with a Gaussian height distribution has a kurtosis value of three. Unlike Ssk this parameter can not only detect whether the profile spikes are evenly distributed but also provides a measure of the spikiness of the area. A spiky surface will have a high kurtosis value and a bumpy surface will have a low kurtosis value. This is a useful parameter in predicting component performance with respect to wear and lubrication retention. Note that kurtosis cannot differentiate between a hill and a valley.

The maximum surface peak height, Sp

The Sp parameter is defined as the largest peak height value from the mean plane within the sampling area. This parameter can be unrepresentative of a surface as its numerical value can vary so much from sample to sample. It is possible to average over several sampling areas and this will reduce the variation, but the value is often still numerically too large to be useful in many cases. However, this parameter will succeed in finding unusual conditions such as a sharp spike or burr on the surface or the presence of cracks and scratches that may be indicative of poor material or poor processing.

The maximum pit height of the surface, Sv

The Sv parameter is defined as the largest pit or valley depth from the mean plane within the sampling area. This parameter has the same disadvantages as the maximum surface peak height.

Maximum height of the surface, S_z

The S_z parameter is defined as the sum of the largest peak height value and largest pit or valley depth value within the sampling area.

The S_p , S_v and S_z parameters give absolute values for features on the surface. They can be useful independently, but also can be used in conjunction with other parameters to describe surface topography more comprehensively. For instance, by examining both the S_q value and the S_z value, it may be possible to indicate whether the apparent roughness is due to isolated features or the overall surface roughness.

Spacing parameters

The spacing parameters describe the spatial properties of surfaces. These parameters are designed to assess the peak density and texture strength. These parameters are particularly useful in distinguishing between highly textured and random surface structures. Two parameters are used to characterise spatial properties given below.

The auto-correlation length, Sal

For this parameter it is first necessary to define the auto-correlation function as the correlation between a surface and the same surface translated by (tx, ty) , given by

$$ACF(tx, ty) = \frac{\iint_A z(x, y)z(x - tx, y - ty)dydx}{\iint_A z(x, y)z(x, y)dx dy} . \quad (2.6)$$

The auto-correlation length, Sal , is then defined as the horizontal distance of the $ACF(tx, ty)$ which has the fastest decay to a specified value s , with $0 \leq s < 1$. The Sal parameter is given by

$$Sal = \min \sqrt{tx^2 + ty^2} . \quad (2.7)$$

For all practical applications involving smooth surfaces (as defined in this guide), the value for s can be taken as 0.2, although other values can be used and will be subject to forthcoming areal specification standards. For an anisotropic surface Sal is in the direction perpendicular to the surface lay. A large value of Sal denotes that that surface is dominated by low spatial frequency components, while a small value for Sal denotes the opposite case.

Texture aspect ratio of the surface, Str

The texture aspect ratio, Str , is a parameter used to identify texture strength, *i.e.* uniformity of the texture aspect. The Str parameter can be defined as the ratio of the fastest to slowest decay to correlation length, 0.2, of the surface ACF and is given by

$$Str = \frac{\min \sqrt{tx^2 + ty^2}}{\max \sqrt{tx^2 + ty^2}}. \quad (2.8)$$

In principle, Str has a value between 0 and 1. Larger values, say $Str > 0.5$, indicates uniform texture in all directions *i.e.* for no defined lay. Smaller values, say $Str < 0.3$, indicates an increasingly strong directional structure or lay. It is possible that the slowest decay ACFs for some anisotropic surfaces never reaches 0.2 within the sampling area. In this case, Str is invalid.

Hybrid parameters

The hybrid parameters are parameters based upon both amplitude and spatial information. They define numerically hybrid topography properties such as the slope of the surface, the curvature of outliers, and the interfacial area. Any changes that occur in either amplitude or spacing may have an effect on the hybrid property. The parameters have particular relevance to contact mechanics. The two hybrid parameters are mathematically quite complicated and are not presented here. They would not be expected to be of much use when characterising smooth surfaces.

Filtering techniques

Filtering is a way of extracting different spatial components, such as roughness, waviness and form error, from a measurement. Filtering is used to isolate specific spatial frequency bands relevant to different component information of the surface by decomposing a signal occurring in the spatial frequency or scale domain.

Scale-limited surfaces

Distinct from the 2D profile system, areal surface characterisation does not require three different groups (profile, waviness and roughness) of surface texture parameters as defined in ISO 4287 (1997). For example, in areal parameters only Sq is defined for the root mean square parameter rather than the primary surface Pq , waviness Wq and roughness Rq as in the profile case. The meaning of the Sq parameter depends on the type of scale-limited surface used.

Two filters are defined, the S-filter and the L-filter. The S-filter is defined as a filter that removes unwanted small-scale lateral components of the measured surface such as measurement noise or functionally irrelevant small features. The L-filter is used to remove unwanted large-scale lateral components of the surface, and the F-operator removes the nominal form. The scale at which the filters operate is controlled by the nesting index. The nesting index is an extension of the notion of the original cut-off wavelength (see good practice guide number 37), and is suitable for all types of filters. For example, for a Gaussian filter the nesting index is equivalent to the cut-off wavelength, and for a morphological filter with a spherical structuring element, the nesting index is the radius of the spherical element. These filters are used in combination to create SF and SL surfaces.

An SF surface (equivalent to a primary surface) results from using an S-filter and an F-operator in combination on a surface, and an SL surface (equivalent to a roughness surface) by using an L-filter on an SF surface. Both an SF surface and an SL surface are called scale-limited surfaces. The scale-limited surface depends on the filters or an operator used, with the scales being controlled by the nesting indices of those filters.

Gaussian filtering and others

A Gaussian filter is a good general-purpose filter and it is the current standardised approach for the separation of the roughness and waviness components from a primary surface. Both roughness and waviness surfaces can be acquired from a single filtering procedure with minimal phase distortion. The weighting function of an areal filter is the Gaussian function given by

$$s(x, y) = \begin{cases} \frac{1}{\alpha^2 \lambda_{cx} \lambda_{cy}} \exp \left[-\frac{\pi}{\alpha^2} \left(\frac{x^2}{\lambda_{cx}^2} + \frac{y^2}{\lambda_{cy}^2} \right) \right], & -\lambda_{cx} \leq x \leq \lambda_{cx}, -\lambda_{cy} \leq y \leq \lambda_{cy} \\ 0 & \text{otherwise} \end{cases} \quad (2.9)$$

where x, y are the two-dimensional distance from the centre (maximum) of the weighting function, λ_c is the cut-off wavelength, α is a constant, to provide 50% transmission characteristic at the cut-off λ_c , and α is given by

$$\alpha = \sqrt{\frac{\ln 2}{\pi}} \approx 0.4697. \quad (2.10)$$

With the separability and symmetry of the Gaussian function, a two-dimensional Gaussian filtered surface $z(x, y)$ can be performed by convoluting two one-dimensional Gaussian filters through rows and columns of a measured surface $z'(x, y)$.

$$z(x, y) = z'(x, y) - \left(\sum \sum z'(x - n_1, y - n_2) \cdot s(n_1) s(n_2) \right). \quad (2.11)$$

Figure 14 shows a raw measured epitaxial wafer surface (a), its short scale SL surface (roughness) (b), middle scale SF surface (waviness) (c) and long scale form surface (form error surface) (d) by using Gaussian filtering with an automatic correct edged process (which has been integrated by some CSI instrument software).

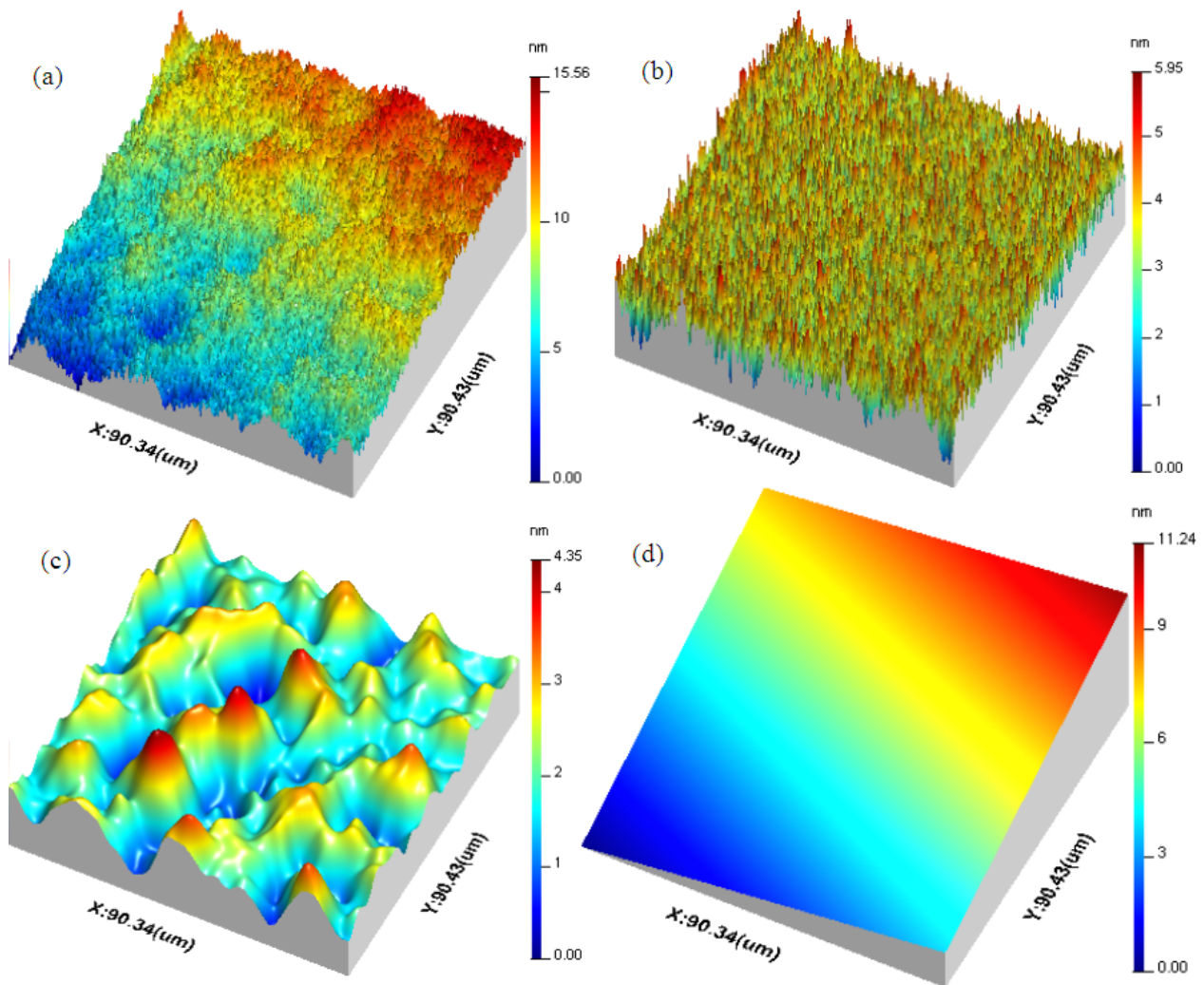


Figure 14. An epitaxial wafer surface topographies in different transmission bands: (a) the raw measured surface; (b) roughness surface (short scale SL-surface) S-filter = $0.36\ \mu\text{m}$ (sampling space), L-filter = $8\ \mu\text{m}$); (c) wavy surface (middle scale SF-surface) S-filter = $8\ \mu\text{m}$, F-operator; and (d) form error surface (long scale form surface), F-operator.

The international standard for the areal Gaussian filter (ISO 16610-61) is being developed by Technical Committee 213 of ISO (the areal Gaussian filter has been widely used by almost all instrument manufacturers). It has been easily extrapolated from the linear profile Gaussian filter standard (ISO 11562) into the areal filter by instrument manufacturers for at least a decade and allows users to separate waviness and roughness in surface measurement.

For multi-processing surfaces (surface topography is a combination of initial rough machining with later ultra precision processing), the roughness data has differing degrees of precision that contains some very different observations or outliers. In this case, a robust Gaussian filter (based on the maximum likelihood estimation) can be used to suppress the influence of the outliers. Nowadays, the robust Gaussian filter can also be found in most CSI instrument software.

It should be noted that the Gaussian filter is not applicable for all functional aspects of a surface, for example, in contact phenomena, where the upper envelope of the surface is more relevant. A standardised framework for filters has been established, which gives a mathematical foundation for filtration, together with a toolbox of different filters. Information concerning these filters has been published as a series of technical specifications (ISO/TS 16610 series), to allow metrologists to assess the utility of the recommended filters according to applications. So far only profile filters have been published, including, the following classes of filters:

Linear filters: the mean line filters (M-system) belong to this class and include the Gaussian filter, spline filter, and the spline-wavelet filter.

Morphological filters: the envelope filters (E-system) belong to this class and include closing and opening filters using either a disk or a horizontal line.

Robust filters: filters that are robust with respect to specific profile phenomena such as spikes, scratches and steps. These filters include the robust Gaussian filter and the robust spline filter.

Segmentation filters: filters that partition a profile into portions according to specific rules. The “motif” approach belongs to this class and has now been put on a firm mathematical basis.

Filtering is a complex subject that will probably warrant a good practice guide of its own following the introduction of the ISO 16610 series of specification standards. The user should consider filtering options on a case-by-case basis but the simple rule of thumb is that if you want to compare two surface measurements, it is important that both sets use the same filtering methods and nesting indexes. Future standards will address default nesting indexes but at the time of writing there is still much debate in the standards committees as to their values.

Measurement preparation and instrument setup

3

IN THIS CHAPTER

- Measurement sample preparation and instrument setup
- Measurement optimisation settings
- Environmental conditions
- Measurement limitations when using coherence scanning interferometry

Measurement sample preparation and instrument setup

In this chapter, an overview of typically available user defined variables is given, and a method for selection of appropriate measurement settings and protocols is offered. The terms used in this chapter are generic and may differ in their description depending upon the instrument being used.

Handling of calibration artefacts

Calibration artefacts should be stored and cleaned in accordance with the manufacturer's guidelines. Cleaning methods are generally dependent upon the material of the artefacts. If there is any doubt as to the proper handling methods, advice should be sought from the manufacturer or supplier. Cleaning materials should be non-abrasive and non-corrosive to the surface. Typically a fluid such as solvent used with a non-abrasive, non-shedding cloth can be used, or a clean air supply to remove any loose contaminants (note that care must be taken as to which solvent to use with a given sample – seek the advice of the manufacturer of the sample or the material supplier).

Calibration artefacts should be stored alongside the instrument in a stable environment with respect to temperature and humidity. Handling of the artefacts should be kept to a minimum, and protective gloves or handling devices should be used to prevent thermal transfer and contamination.

Instrument calibration

Calibration of the CSI is an important factor in producing reliable and repeatable measurements. It is important to calibrate the instrument whenever a major adjustment has been made to the instrument or to the environment in which it is housed. It is recommended that a calibration schedule be written into the overall measurement protocol for the instrument. The frequency of calibration is dependent upon a number of factors such as environment of use, instrument stability and any regulatory requirements particular to the application.

Types of calibration

A comprehensive but not exhaustive list of available types of calibration artefacts for various CSI instruments is given in this section. It is important to note that at the time of writing there are only draft specification standards for calibrating areal surface texture measuring instruments. Indeed, there is no clear traceability route for any areal measurements. Therefore, it is only possible to check that the instrument compares to the calibration value given by the instrument manufacturer and that measurements are repeatable. Where possible surface profile measurements can be calibrated using artefacts described in ISO 5436-1

(2002) as these measurements can be traceable to national or international standards. NPL good practice guide number 37 describes surface profile calibration in detail for a stylus instrument and many of the calibration techniques can be applied to profiles extracted from areal measurement data.

Lateral or spatial calibration

Lateral or spatial calibration of a CSI determines the characteristics of the x and y measurement capability and allows for a correction to be applied. Lateral or spatial calibration is generally achieved by measuring a calibrated pattern on an artefact, for example a grid or series of concentric circles. This calibration serves to accurately set the instrument's basic magnification, which is a function of the optical sensor (camera) and associated optical elements. The result of the measurement of a grid type calibration artefact is shown for example in figure 15.

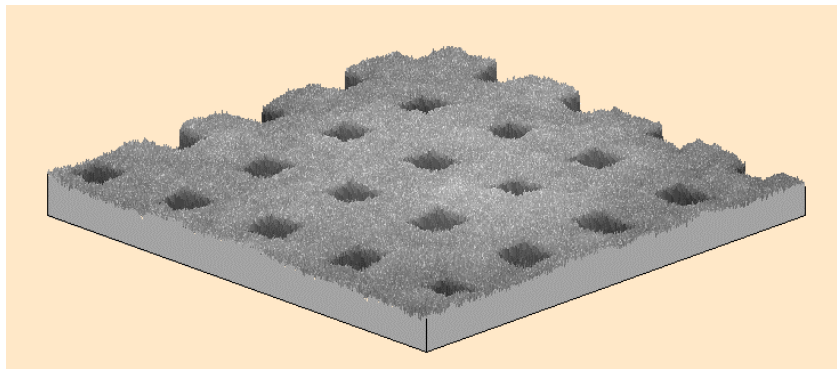


Figure 15. Result of the measurement of a grid type calibration artefact

Vertical calibration

Vertical calibration allows for the correction of any unwanted motion effects in the vertical (z) measuring axis. This may include gain errors, periodic scanner effects (such as from gears or motors) as well as overall nonlinearities. Vertical calibration is generally achieved through the use of a step height of calibrated dimension. Ideally the step height used should be as close to the height that you are routinely measuring as is available such that the calibration is localised to the operating area for any particular sample. Note that some commercial CSIs incorporate a separate displacement measuring interferometer to measure the motion of the z axis actuator. These systems should not require step calibration, although a step should ideally be used for verification purposes. Step height calibration for profile measuring instruments according to ISO specification standards is described in NPL good practice guide number 37. This calibration can be applied to the vertical calibration of areal instruments although it is better to make an areal measurement of the step as opposed to a single line scan. If an areal step height measurement is carried out, least squares planes need to be fitted

to the data where least squares lines would have been fitted for profile data. Figure 16 shows the areal measurement results of a step height artefact.

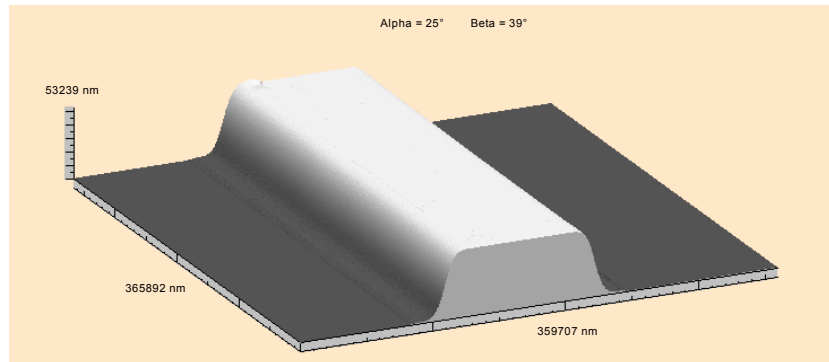


Figure 16. A measurement of a step height artefact

Form correction

Form correction serves to correct errors associated with the reference optics or in the objective lens assembly. Form correction is generally achieved through single or multiple measurements taken of a reference flat surface. By maximising the area of the artefact over which measurements are taken for performing calibration, the effects of noise and residual contamination can be minimised and the quality of the calibration can be enhanced.

The effect of the magnification of the objective lens

The magnification of the objective lens selected for any measurement has an effect on the measurement result. Changing the magnification alters the lateral resolution and slope handling in the following ways:

- Lateral resolution or spacing - for any particular instrument the lateral resolution will generally increase with increase in magnification.
- Slope handling – the higher the numerical aperture of the lens the higher the surface slope handling capabilities.

Instruments are available with varying number and sizes of pixel arrays; this combined with the magnification can affect the lateral resolution and overall field of view. This should be carefully considered when selecting the correct lateral resolution for any particular application.

Typical pixel arrays can range between 320×240 pixels and 2048×2048 pixels. It should be noted that some mathematical analysis techniques (for example filtering methods) work optimally with square pixel arrays.

For any particular instrument a change in the field of view can be achieved either by a change of objective lens, or by utilising an optical or a digital zoom.

The effect of optical zoom

Optical zoom is a process where a measurement area is altered whilst utilising the same pixel array. There are two approaches to achieving a change in optical zoom without a change of objective lens. Firstly the physical introduction of a field of view multiplier optic and secondly the use of a zoom lens. A zoom lens gives the benefit of versatility in the system, giving a larger range of available measurement areas. Using extra optics to adjust the field of view will generally not improve the slope handling capabilities of the instrument, but will change the effective pixel size. Increasing the effective pixel size is especially useful when examining narrow features, where oversampling may reduce the noise present in calculations such as linewidths or tilts. This function should be treated as a change of lens and the instrument will need to be re-calibrated. This is an especially important consideration when using a zoom lens.

Use of digital zoom

Digital zoom is a process where the measurement area is altered whilst keeping the pixel resolution constant. A digital zoom simply uses a localised area of the pixel array (on some instruments the full array of data is maintained whilst on others this data is lost). This function has the benefits of being able to focus on an area of interest and also reducing processing time. This function can be used without the need for re-calibration of the instrument.

Mode of measurement

Most commercial instruments offer a number of modes of measurement within the instrument's capability. The choice of modes can affect the resolution of measurement through "pixel binning" and other averaging or filtering techniques. Within the scope of this document, where smooth surfaces are concerned, it is desirable to maximise the spatial resolution of the measurement and, therefore, the mode of measurement should be selected accordingly. Other modes of measurement allow the user to choose whether phase only, coherence only, or both are used to create the map of the surface. The choice of measurement mode can be fairly complicated and the user should consult the instrument manual or contact the manufacturer where there is doubt.

Fringe set up (levelling the sample)

Fringe set up of the sample can affect the measurement outcome; the accuracy of levelling can be determined by the fringe pattern visible during set up. The fringe set up will depend

upon the nature of the surface. For flat, featureless surfaces it is ideal to have the sample as level as possible, thereby with the fringe pattern optimised (one to two fringes visible, known as “nulled fringes”). In the case of curved surfaces it is important to ensure that the centre of the fringe pattern is centred over the main area of interest if possible. The number of fringes visible will have an effect on the measurement result and should be investigated for any particular sample to give an appropriate levelling target. To ensure good measurement practice, if a series of similar samples are under investigation, it is important to be consistent in measurement set up to ensure repeatable results.

To aid in levelling the user may use an automatic tip/tilt levelling stage (available on some instruments or as an option).

Focus

For high accuracy CSI, it is necessary that every pixel of the sample passes through the focus position during the scan, and that in fact the scan starts before fringes are visible on a given pixel and does not end until all fringes have passed out of the field of view. The scan length required to achieve this is dependent on the bandwidth of the light used and the numerical aperture of the objective. When combining phase with coherence information, focus can be especially important, and some instruments use autofocus to achieve the most consistent results.

Light source and its effect

The intensity of most light sources used in CSI can be varied. It is important to set the light intensity at an optimum level; this will vary from system to system and from sample to sample. It should be noted that a change in light intensity can alter measurement results and this should be taken into account when formulating measurement protocols. It should also be noted that consistent setting of light intensity will improve repeatability of measurement. If the light source intensity is too high saturation of the detector can lead to missing data and similarly, low sample reflectance can cause problems with measurement signal and, therefore, measurement data may not be complete. Typically best results are obtained when the intensity during a scan approaches, but does not exceed, the saturation limit – this will give the highest signal to noise ratio.

Consideration should be given to type of light source and the wavelength of the light used. Ideally the light source should be optimised for the material under investigation. Different commercial instruments have different sources with different bandwidths. The user should consult the instrument manual or the manufacturer when establishing which source or bandwidth is most suitable for which material.

Number of averaged measurements

Using a number of repeated measurements and calculating an average can minimise the effects of system noise and environmental changes. By increasing the number of averaged measurements, an improvement in repeatability may be achieved. Choosing the number of repeat measurements is a compromise between noise reduction and time of measurement. Experience gained during the SOLADIM project suggested that the optimum number of averaged measurements is four, although different surfaces may require a different number of measurements and there may be time constraints.

The number of averaged measurements becomes increasingly important as one approaches the noise floor of the instrument. Changing the number of averaged measurements can cause significant changes in calculated results. If the instrument noise is random, the noise floor will reduce as the square of the number of measurements.

Measurement optimisation settings

All CSI instruments have settings to optimise a measurement. These will depend on the measurement technique used and the system used. Some of the more common settings are briefly discussed below.

Signal to noise threshold

This setting is generally used to remove any obviously incorrect data. The incorrect data can be from a variety of sources such as dirty optics or stray light. This option is often adjusted for unusually rough samples and would probably not be required when measuring a smooth surface.

Data filling

Data filling is often used when there is missing data. The nature of the surface and the implications of the data fill process should be studied and understood before this setting is selected.

Measurement speed

On some instruments it is possible to change the speed of measurement. This can allow the undersampling of the fringe envelope, sacrificing some repeatability for measurement speed. Speeds can range from around 5 mm s^{-1} to 100 mm s^{-1} . Note that changing the scan speed will also effect the vertical resolution so care must be taken.

Environmental conditions

Positioning the instrument

The instrument hardware should be installed with consideration given to the surroundings in which it will operate and the manufacturer's specifications. The overall accuracy of the measurement results can be influenced by environmental conditions, particularly: draughts, vibration and the rate that the ambient temperature changes.

The following items must be considered when positioning the instrument.

Clean area

All forms of airborne particle can be detrimental to the performance of a CSI but particularly smoke, dust and airborne oil particles. Ideally the instrument should be located in a clean environment and clean room clothing should be worn by all personnel in the room. It may be necessary to house the CSI in a dedicated enclosure.

Draughts

Avoid subjecting the instrument to draughts and airborne vibration where possible. Avoid placing the instrument directly under or next to air conditioning vents or laminar flow hoods. An environmental enclosure can be used to reduce the effect of draughts around the component measurement area.

Temperature gradients

Avoid positioning the instrument in areas that have a high temperature gradient or rapid temperature changes, and avoid positioning near windows or skylights where sunlight may fall on the instrument. Thermal stability will enhance repeatability of measurements over extended periods of time.

Vibration

Both acoustic and ground based vibration is particularly detrimental for the measurement of surface texture. It is recommended that all sources of vibration be removed. Where possible, instruments should be placed on the ground floor of a building to maximise stability. It is also important that cables should be fixed correctly to avoid transmission of vibration. Cables should not be bundled together to form a single, rigid mass as this will form a solid pillar that will transmit vibration. Some instruments are supplied with dedicated anti-vibration mounts.

Measurement limitations when using coherence scanning interferometry

This section briefly describes some of the potential sources of error when using a CSI. The error sources described here are only those that are inherent to CSI and do not include such things as environmental effects or mistakes in set-up and use by the operator. A further source of error will be in the calibration of the instrument (see earlier section). Some of the sources of error discussed in this chapter will not be present when measuring smooth surface topography (for example, the batwing effect) but they are included here for completeness.

Sources of error in coherence scanning interferometry

Ghost steps

Stepped artefacts have been reported when measuring perfectly flat objects. Errors of this kind are commonly referred to as ghost steps. These steps usually correspond to a 2π phase jump or a surface height error of around half the mean wavelength. More generally phase jumps of this magnitude are referred to as 2π errors and can be thought of as a misclassification of fringe order. In these cases the error is due to a field dependent dispersion that is inherent in the geometry of some types of interferometers. Note that ghost steps are only present when combining phase with coherence information.

Field dependent dispersion

A similar dispersive effect to the ghost steps makes CSI sensitive to surface gradient. Tilt dependent dispersion is often the cause of 2π errors in CSI measurements even when the tilt is small compared to the NA of the objective. If errors of this kind are present then 2π errors, for example, can appear at regular intervals on regular sinusoidal profiles (see for example figure 17).

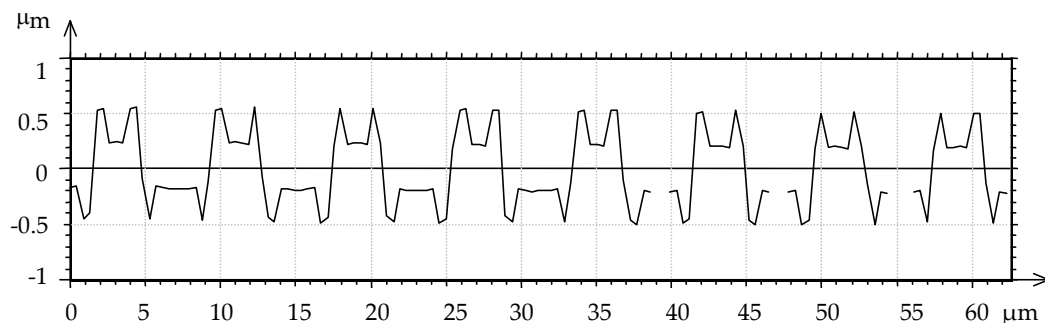


Figure 17. The effect of field dependent dispersion on the measurement of a sinusoidal grating

A combination of field and tilt dependent dispersion is also responsible for errors of similar appearance to the batwing effect. In contrast with regular batwing errors, the presence of these phase jumps depends systematically on position and generally increases in severity toward the edge of the field of view. This effect also depends strongly on the polarity of the discontinuity. It is noted that (depending on the height retrieval algorithm used) in extreme cases the dispersive batwing effect can result in errors that propagate and result in a corresponding error in step height measurement.

The batwing effect

The batwing effect is a well-known example of an error that is observed around a step discontinuity especially for the case of a step height that is less than the coherence length of the light source. The batwing effect is so called because of the shape of the error (see for example figure 18) and it is usually explained as the interference between reflections of waves normally incident on the top and bottom surfaces following diffraction from the edge. CSI does not give the correct surface height at the positions close to the step even if the step height is significantly greater than the coherence length. Note that this effect would not be expected when measuring a smooth surface but must be considered when using a step height artefact to calibrate the instrument.

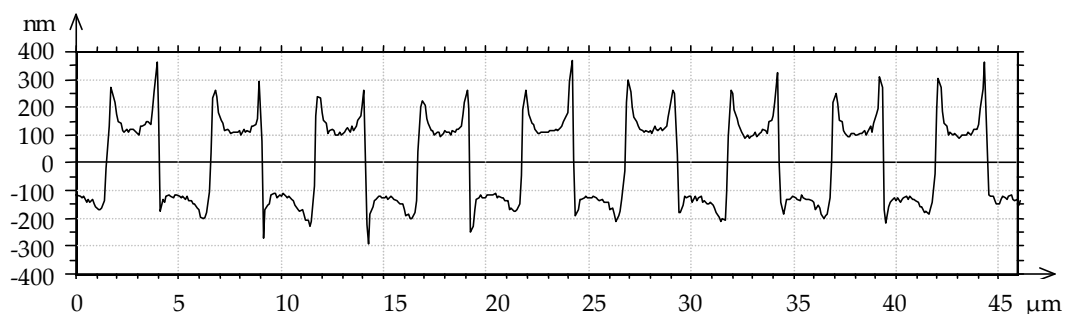


Figure 18. A square wave grating that shows the batwing effect at the step edges

Effect of optical properties of the surface being measured

Dispersive effects of the kind mentioned are clearly a function of the quality of the optical system, however, the optical properties of the surface to be measured are also a potential source of error. Different materials exhibit different phase changes on reflection, and depending on the processing algorithms used, these will affect the surface height measurement. Phase changes are typically less than 45 degrees (corresponding to surface height errors of less than 30 nm) but can combine with dispersive effects to give 2π errors as discussed previously. This type of error is only a problem when two or more materials with different optical properties are present in a sample.

Effect of the surface roughness of the surface being measured

Estimates of surface roughness derived from CSI can differ significantly from other measurement techniques. The surface roughness is generally over estimated by CSI and this can be attributed to multiple scattering. Although it may be argued that the local gradients of rough surfaces exceed the limit dictated by the NA of the objective and, therefore, would be classified as beyond the capability of CSI instrumentation, measured values with high signal to noise ratio are often reported in practice. If, for example, a silicon V-groove (smooth walls, with an internal angle of 70.52 degrees) is measured, a clear peak with its apex at the bottom of the profile is observed. This is due to multiple reflections (scattering) from the sidewalls. Although this example is specific to a highly polished V-groove fabricated in silicon it is believed to be the cause for over estimation of surface roughness since a roughened surface can be considered to be made up of randomly oriented grooves with varying internal angles. Note that the effect of surface roughness is usually only a problem when using coherence-only modes and can be solved by combining phase and coherence modes.

Making measurements and interpreting results

4

IN THIS CHAPTER

- Sample preparation and handling
- Case study SOLADIM

Sample preparation and handling

When using any surface texture measuring instrument samples for measurement must be clean and free from grease, smears, fingerprints, liquids and dust. Handling procedures must ensure that the sample is not contaminated with any contaminants, and handling should be kept to a minimum prior to measurement. A period of sample acclimatisation may also be needed. Any cleaning protocol should note that any fluids used in cleaning may contain contaminants which can leave a residue on the surface; this will affect the measurement detrimentally. Any contaminants may become part of the measured data if present on the surface, or result in missing data.

It is important that care be taken when transporting sample surfaces for measurement. In particular the use of polythene sample bags is not recommended since the internal surfaces are often coated with a release agent, which can be transferred to the sample surface. Use of either lint free paper bags or “Fluoroware” containers overcomes this problem.

Fixturing

It is difficult to give comprehensive guidance on fixturing methods because solutions will depend on the geometry and mass of individual samples. Problems may be encountered by use of any method of fixturing other than the component’s own weight. When using non-permanent adhesives such as adhesive tape or gels for fixturing, scope for movement during measurement is introduced through factors such as creep. When introducing external forces to aid fixturing, the possibility of sample distortion may be encountered and, therefore, the measurement data altered. In addition, use of a vacuum method of fixturing may introduce vibration. Fixturing is essential when stitching together multiple measurements to prevent random movement as the translation stage is scanned. Loosely fixtured parts may also be a source of vibration.

Orientation

The orientation of any given sample may affect the resulting measurement data. Care should be taken that similar samples are measured in the same orientation to ensure repeatability. The lay of the surface texture and the light reflectance may have an effect on the measurement result (also some cameras have different frequency responses in different directions).

Metal coating of a sample

The effects of dissimilar materials (see chapter 3) can be avoided by coating the sample with a single material film, for example gold or chromium. When using this method one must ensure that an even coating is deposited over the entire sample.

Sample replication

Sometimes it is difficult to access a sample for measurement. For example, the sample may be too large to mount on the CSI, you may want to measure inside a cylinder or the sample may have a complex geometry that is not easily accessible by the CSI. For such samples a replication of the surface can be made using a suitable replication compound. These are usually based on polymer material and are widely available commercially. Note that as many of the replication samples are relatively soft polymers, care must be taken to avoid introducing unwanted form into the replica. Some studies have shown that replication compounds can reproduce the surface texture of a sample to within tens of nanometres.

Location and number of measurements

Most components will fall under the guidelines of a particular specification standard where measurement location and quantity are concerned, if there is no comprehensive guide to provide this information for a given sample, it is imperative to establish the required protocol to ensure statistical relevance in the data collected.

The procedures in this guide are aimed at a routine inspection environment; greater flexibility may be used when taking measurements for process improvement or research situations. The important factor would always be consistency in protocol to ensure repeatability.

Case study SOLADIM

The following section is a case study that is based on work carried out as part of the SOLADIM project. A number of experiments were carried out to determine the effect of user defined variables on the measurement result when measuring semiconductor wafers.

Semiconductor substrates and epitaxial wafers (a generally used term in the industry) are usually very smooth samples (Sa 0.1 nm to 1 nm) with very low values of bow and warp (of the order of micrometres across a sample). Semiconductor substrates are thin (normally 0.1 mm to 1 mm total thickness), can be any size from part wafers up to circular 300 mm diameter wafers, and are often mechanically quite fragile. However, most semiconductor substrates are good samples for CSI measurements because they are highly reflective in the visible region of the spectrum. Those materials that are transparent in the visible region of the spectrum have high refractive indexes and thus give more than adequate signal.

Samples must be smooth enough to permit photolithographic definition of features in the region of tens of nanometres.

Semiconductor materials are single crystals and can display features that are strongly orientated – thus it is important to make a record of the lateral orientation of the sample and

keep this consistent during a series of measurements. The lateral orientation of the wafer is normally indicated by a ‘flat’ (usually two flats of differing lengths) or a ‘notch’ ground into the periphery of the wafer.

- a) Because samples are thin they are often of low mass. This can create problems due to environmental factors (particularly air flow) that cause the wafer to physically move or vibrate on the stage – thus producing noisy or unobtainable measurements.
- b) The location and quantity requirements for measurement are stated in the SEMI specification standards.

Background and options

A study was conducted to determine the effects of user defined measurement variables on measurement result. The study was formulated employing design of experiments to create a factorial study to determine the significant effects of some of the possible user defined variables. The study was carried out using the Taylor Hobson Talysurf Coherence Correlation Interferometer (CCI) and, therefore, the options investigated are specific to that instrument. This case study does, however, show how statistical techniques can be effectively and efficiently employed to determine good practice for any given surface. In the case of this study good practice was deduced through comparison of measurement results collected from an AFM that is an established technique in the measurement and characterisation of semiconductor materials.

The following user defined variables were investigated.

Variable	Low Condition (-1)	High Condition (+1)
Intensity	40%	50%
Fringe Set Up	4+ fringes	1 to 2 fringes
Multiple measures	Off	4
Special options	Off	Reduced threshold (70%)
Post Process	Off	On
Peak Only	Off	On

Table 1. Variables investigated as part of the SOLADIM case study

The high and low conditions were set at levels deemed to be feasible in routine use of the CCI. The recommendation from the manufacturer for light intensity is about 50%; other

interferometers recommend that the light level be set just below light saturation. Very little adjustment of the light intensity is needed to shift from 40% to 50%; therefore, the light intensity levels at 40% and 50% have been investigated to determine if there is a marked difference in measurement result.

Fringe set up refers to the degree of levelling of the sample, the more levelled the sample, the fewer the fringes used to measure the surface, the low condition was set to be four or more fringes, the typical number of fringes used in this case study during the course of the experiment was four to six. The high condition was to ensure good levelling of the surface so that only one to two fringes were present on the surface during measurement. The effect of this difference on the measurement outcome was investigated.

Multiple measures refer to the software option of averaging a number of multiple measurements (in multiples of two). The low condition was set to a single measurement; the high condition was set to four measurements, to determine the impact of multiple measurements on measurement outcome.

Special options refer to the software's threshold for signal to noise. The low condition threshold was set as 100%, and the thresholding tool was effectively turned off. The high condition was set as 70% threshold, to determine if the minimum incremental change in the threshold tool would produce a variation in measurement outcome.

Post process is an option in the measurement window of the CCI control software. Selecting the post process option changes the way in which the software handles the data, where post process is selected, the data is all exported for analysis and no data mining is undertaken until the analysis process, ensuring higher resolution. The effect of this option is thought to affect the results of various samples differently. Therefore, it was deemed reasonable to investigate the impact of this on measurements of samples typical to those under investigation during the SOLADIM project.

Peak only is another option within the measurement window of the CCI control software, the peak only option ensures that only the highest peak of intensity of the fringes is recorded and processed. The impact of this option was investigated.

All measurements in this study were completed on gallium arsenide substrates.

Significant effects

Figure 19 and figure 20 shows the change in measurement outcome with change in measurement variable. By using statistical analysis techniques the variables that produced significant effects on the measurement outcome were determined, and from this model a suitable measurement protocol was derived. This ensured repeatable measurement of samples operator to operator and project partner to project partner. In addition to this, depending upon

the nature of the sample and the measurement, it may be advisable to complete a gauge R&R study.

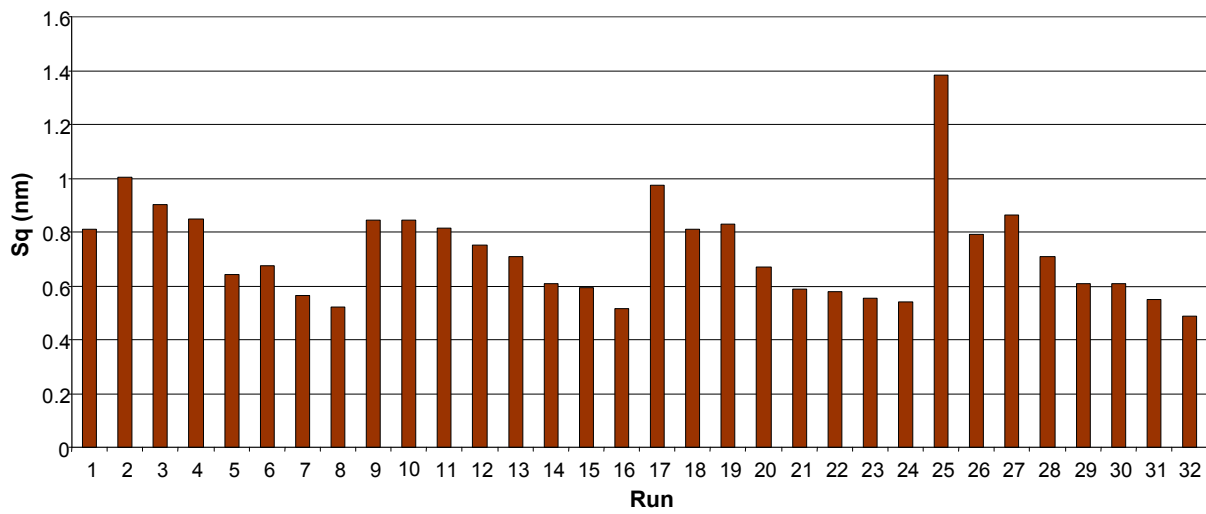


Figure 19. Variation in S_q with change in measurement variables

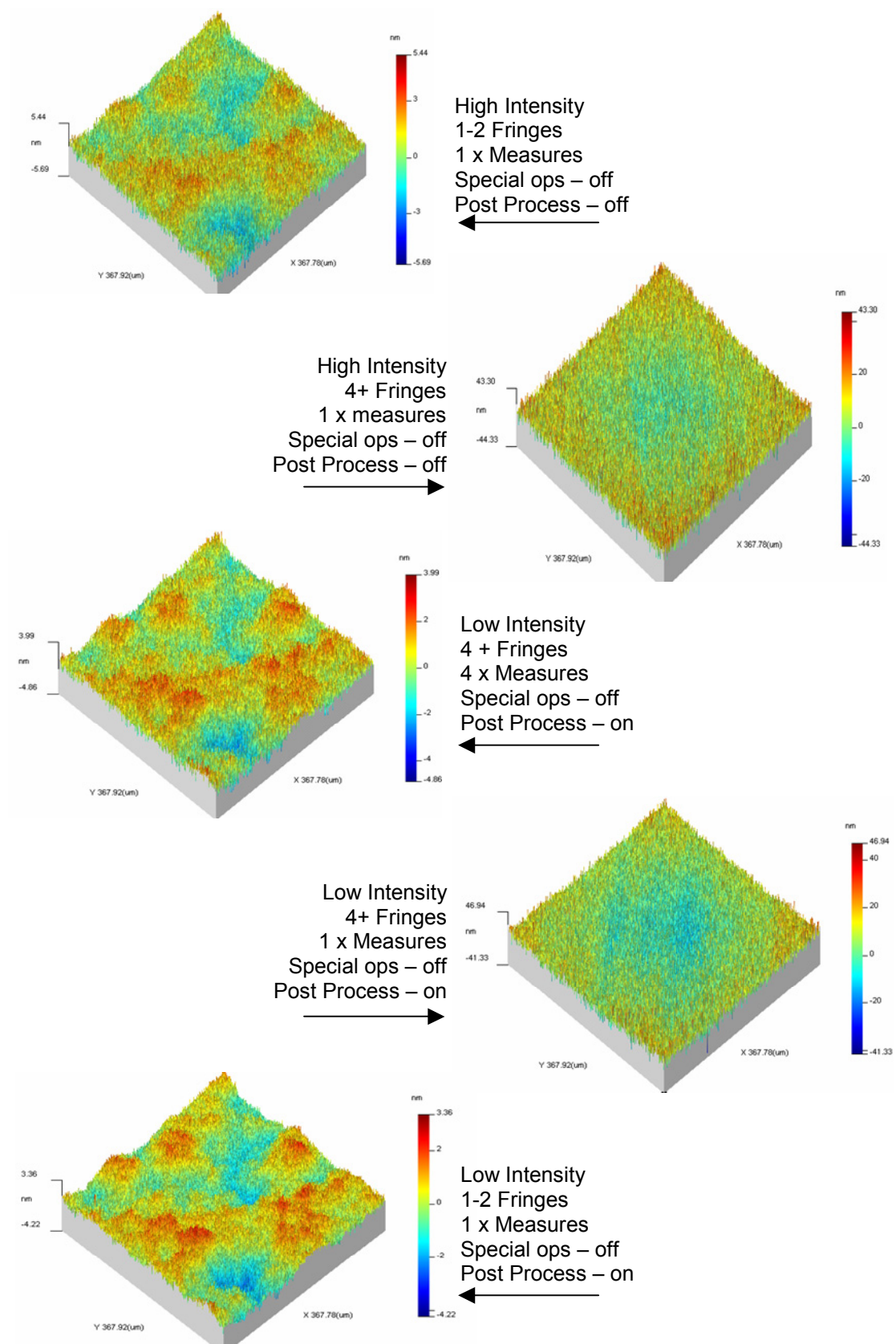


Figure 20. Change in surface topography with variation in measurement variable

Good practice

Following analysis of measurements using statistical evaluation of significant effects, the following were selected as best practice guidelines to be used during measurement of samples:

Intensity

The intensity should be set as close to 40% as possible, the study showed that this was the optimum intensity level for measurements of the samples studied.

Fringe set up/levelling

The study showed that for certain 3D surface texture parameters, better results were gained when care was taken to level the sample so that one to two fringes were visible prior to measurement. The added benefit of this is the reduction in measurement time.

Multiple measures

Employing multiple measures and averaging over four measurements was shown to have a positive effect on measurement outcome. Employing larger numbers of multiple measures improves the outcome further, however, the benefit of doing this is outweighed by the large increase in measurement time.

Special options

Employing the special options function and reducing the signal to noise ratio, did not have a significant effect in this study. It is deemed that the optimum for measuring the samples in question would be to have maximum threshold with special options off.

Post process

The optimum setting was shown to have the post process function turned on.

Peak only

The peak only option should always be turned off when measuring samples; this was shown to have the biggest effect on measurement outcome.

Measurement processing

Before altering the raw measurement data in any way, it is always good practice to save a copy of the data, and also visually check for potential anomalies such as optical spikes or an unacceptable percentage of missing data. The first process to apply to data is form removal where applicable (tilt, cylindricity, sphericity, bow and warp). This will remove simple geometrical form in the measurement data so that the functional surface can be examined.

With the use of mathematical filters it is possible to manipulate the data in order to remove/separate out waviness and roughness. Care should be taken when applying such filters as there is the possibility of losing all data relating to function through over processing the data. As a rule the best practice would be to use no filtering following the simple form removal for smooth surfaces.

Where filters are deemed necessary extreme caution should be used.

Appendices

5

Links to other useful sources of information

National and international organisations

National Physical Laboratory

The National Physical Laboratory (NPL) is the UK's National Measurement Institute and is a world-leading centre of excellence in developing and applying accurate measurement standards, science and technology. For more than a century NPL has developed and maintained the nation's primary measurement standards. These standards underpin an infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

NPL ensures that cutting edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL undertakes research and shares its expertise with government, business and society to help enhance economic performance and the quality of life.

NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all. NPL is a world-leading centre in the development and application of highly accurate measurement techniques. As the UK's national standards laboratory, NPL underpins the National Measurement System (NMS), ensuring consistency and traceability of measurements throughout the UK. NPL offers a unique range of measurement services, contract research, consultancy and training services. Other areas of expertise include the design and characterisation of engineering materials, and mathematical software, especially its application to measurement and instrumentation.

For more information on the wide range of metrology services, facilities and research work carried out at NPL either visit the NPL web site at www.npl.co.uk or contact the NPL Helpline:

Tel: 020 8943 6880, Fax: 020 8943 6458, E-mail: enquiry@npl.co.uk

National Institute of Standards and Technology (NIST)

NIST is the equivalent of NPL in the United States of America. The NIST web site is www.nist.gov and often contains documents relevant to this guide in .pdf format.

EURAMET - European Association of National Metrology Institutes

The European Association of National Metrology Institutes (EURAMET) is the Regional Metrology Organisation (RMO) of Europe. On 1st July 2007 EURAMET e.V. became the successor to EUROMET – the previous RMO which had coordinated European metrology needs for over 20 years. EURAMET coordinates the cooperation of National Metrology Institutes (NMIs) of Europe in fields like research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and of the Calibration and Measurement Capabilities (CMC) of its members.

EURAMET currently has 32 members (including NPL), 5 associate members and operates 12 Technical Committees, one for each physical metrology subject field, plus committees dealing with interdisciplinary metrology and quality matters. More details and information about the many cooperative projects run by EURAMET and its members can be found on the EURAMET web site: www.euromet.org.

Networks

Dimensional Metrology Awareness Club (DMAC) and the Engineering Measurement Awareness Network (EMAN)

The EMAN network is a means of encouraging knowledge exchange between industry, academia and NPL. In collaboration with other networks, both within NPL and elsewhere in the UK, it aims to address the measurement issues in industry and manufacturing.

The network comprises four Special Interest Groups:

- Dimensional - covering coordinate and machine tool metrology, form and surfaces (known as DMAC)
- Force, Torque & Hardness
- Pressmet - covering pressure and vacuum measurement
- Weighing & Density

The activities of the network are steered by members. Although most meetings are related to one of the above special interest group titles, events have been held covering topics ranging

from data acquisition, exporting to the US, and materials testing. The purpose of the network is:

- to facilitate information flow to enable solutions for engineering measurement problems
- to encourage collaborations between NPL, equipment manufacturers and suppliers, and people making engineering measurements
- for members to influence the direction of the National Measurement System Engineering Measurement Programme at NPL.

EMAN is an industry-focused club. The club is managed by NPL on behalf of the DIUS and has the following objectives:

- to provide a focused platform for interaction across all the technical areas covered by the Engineering Measurement Programme;
- to enable members to learn about the latest developments in their own as well as related areas of dimensional metrology;
- to provide a mechanism to encourage and facilitate interaction and exchange of ideas with other member organisations and
- to give members the opportunity to provide input to, and influence the development of future NMS programmes.

For further information visit the EMAN web site at www.npl.co.uk/eman

Software Support for Metrology Programme (SSfM)

SSfM is a metrology-focused programme comprising projects designed to meet the requirements of National Measurement System programmes. The overall aim of the SSfM Programme is to tackle a wide range of generic issues, some of which are problems in metrology that require the application of established software engineering practices, whilst others require advances in mathematics, software engineering or theoretical physics. The programme, thus, includes work in metrology, mathematics, software and theoretical physics, with strong links between the various disciplines.

The SSfM Club is aimed at users and suppliers of metrology software, giving them a say in the direction of the Programme. It is the focal point for the distribution of general information arising from the Programme.

Further details can be found at www.npl.co.uk/ssfm

Traceability

Traceability in measurement is the concept of establishing a valid calibration of a measuring instrument or measurement standard, by a step-by-step comparison with better standards up to an accepted or specified standard. In general, the concept of traceability implies eventual reference to an appropriate national or international standard.

The National Physical Laboratory is the United Kingdom's national measurement institute. It operates at the heart of the National Measurement System (NMS) which is the infrastructure designed to ensure accuracy and consistency in every physical measurement made in the UK. Chains of traceability link UK companies' measurements directly to national standards held at NPL.

For the majority of industrial applications, companies can establish a link to national measurement standards through the calibration and testing services offered by United Kingdom Accreditation Service (UKAS) accredited laboratories, which are in turn traceable to NPL. However, for challenging or novel measurements to the highest standards of accuracy, which are not catered for by UKAS accredited laboratories, NPL can often provide a traceable measurement solution directly to industry.

UKAS is the sole national body recognised by government for the accreditation of testing and calibration laboratories, certification and inspection bodies. A not-for-profit company, limited by guarantee, UKAS operates under a Memorandum of Understanding with the government through the Department of Innovation, Universities and Skills.

UKAS accreditation demonstrates the integrity and competence of organisations providing calibration, testing, inspection and certification services.

Further information on UKAS can be found at www.ukas.com

Training courses

Good measurement supports the technical infrastructure, which leads to new and competitive products with efficient processes. However, knowing how to use a measurement tool is not the same as knowing how to use measurement as a tool. Measurement is a science to be applied with skill, not a manual.

Understanding the principles of measurement can lead to better decisions on product purchasing, reduced need for expensive technical support and reduced operational mistakes with expensive consequences. A better understanding of measurement will reduce the risks to your business.

NPL is able to provide a variety of practical application-based bespoke training courses from optical and laser technology to statistical modelling. The majority of our courses are organised to meet the specific requirements of the customer. To enquire about NPL developing you a bespoke course please contact the NPL Helpline.

NPL also has a training framework for Dimensional Metrology. The NPL-Training for Dimensional Metrology is divided into four levels, covering measurement users to measurement strategy definers, always through a practical hands-on approach:

Level 1 – Measurement User:

Uses measurement knowledge and expertise

Level 2 – Measurement Applier:

Applies measurement knowledge and expertise

Level 3 – Measurement Developer:

Develops and extends measurement knowledge and expertise

Level 4 – Measurement Definer:

Defines new and leading edge application of measurement knowledge

For further information visit the NPL training at www.npl.co.uk/training or contact the NPL Helpline:

Tel: 020 8943 6880, Fax: 020 8614 0446, E-mail enquiry@npl.co.uk

International standards

International Organization for Standardization (ISO)

The International Organization for Standardization (ISO) is a worldwide federation on national standards bodies from some 140 countries.

The mission of ISO is to promote the development of standardisation and related activities in the world with a view to facilitating the international exchange of goods and services, and to develop cooperation in the sphere of intellectual, scientific, technological and economic activity.

ISO's work results in international agreements that are published as International Standards.

Further information of ISO can be found at www.iso.ch

ISO surface texture standards

The following ISO specification standards relate to the measurement of profile using stylus instruments and are included in this guide for completeness. At the time of publication of this guide the standards for areal surface texture measurements and CSIs are being drafted by ISO TC 213 (see chapter 1 – Scope of this guide).

ISO 3274 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Nominal characteristics of contact (stylus) instruments

ISO 4287 (1997) Geometrical product specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters

ISO 4288 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture

ISO 5436 (2000) Geometrical product specifications (GPS) – Surface texture: Profile method – Measurement standards – Part 1 Material measures

ISO 11562 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Metrological characteristics of phase correct filters

ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method; Surface having stratified functional properties – Part 1: Filtering and general measurement conditions

ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method; Surface having stratified functional properties – Part 2: Height characterization using the linear material ratio curve

ISO 13565 (2000) Geometrical product specifications (GPS) – Surface texture: Profile method; surfaces having stratified functional properties – Part 3: Height characterization using the material probability curve

ISO 12085 (1996) ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Motif parameters

General interest

PD 6461 (1995) Vocabulary of metrology – Part 1. Basic and general terms (international)

PD 6461 (1995) Vocabulary of metrology – Part 2. Vocabulary of legal metrology – fundamental terms

PD 6461 (1995) Vocabulary of metrology – Part 3. Guide to the expression of uncertainty in measurement

Semiconductor Equipment and Materials International (SEMI)

SEMI is a volunteer-driven organisation for the exchange of information amongst users and suppliers in the semiconductor industry and flat panel display industries. Approximately 1300 technologists worldwide participate in the development of specifications and standards for these technologies. The documents are published as the SEMI Book of Standards and are available on the web at www.semi.org

Literature

Surface texture books

Bennett J M, Mattson L 1999 *An introduction to surface roughness and scattering* 2nd Edition (Optical Society of America: Washington D. C.)

Blunt L, Jiang X 2003 *Advanced techniques for assessment surface topography* (Kogan Page Science)

Leach R K 2001 *The measurement of surface texture using stylus instruments*, NPL Good Practice Guide No. 37 (available from www.npl.co.uk)

Mainsah E, Greenwood J A, Chewynd D G 2001 *Metrology and properties of engineering surfaces* (Kluwar Academic Publishers)

Smith G T 2001 *Industrial metrology: surface and roundness* (Springer-Verlag)

Stout K J, Blunt L 2000 *Three dimensional surface topography* (Prenton Press)

Thomas T R 1999 *Rough surface* 2nd edition (Imperial College Press: London)

Whitehouse D J 1994 *Handbook of surface metrology* (Taylor & Francis)

Whitehouse D J 1993 *Handbook of surface and nanometrology* (CRC Press)

General measurement and instrumentation books

Flack D R, Hannaford J 2005 *Fundamental good practice in dimensional metrology* NPL Good Practice Guide No. 80 (available from www.npl.co.uk)

Smith S T, Chetwynd D G 1992 *Foundations of ultraprecision mechanism design* (Gordon & Breach Science Publishers)

Williams D C 1993 *Optical methods in engineering metrology* (Chapman & Hall)

