

REPORT

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**Measurement of the Internal
Geometry of MEMS Structures**

**Wenjuan Sun and
Richard Leach**

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Engineering Measurement
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ABSTRACT

Many modern MEMS devices incorporate multi-layered structures. However, the metrology of such structures is struggling to keep pace with their manufacture. In this project, the internal geometry of MEMS devices has been measured using optical coherence tomography and infra-red confocal microscopy, where both instruments provide non-contact, non-invasive measurements of internal geometry. However, both measurement techniques are relatively new technologies for measuring internal geometry and the understanding of their capabilities is limited. This study has mainly focused on the thickness measurement of layers. The axial resolution of the two instruments has been investigated, as this is a vital parameter when measuring thickness. The performance of the beam axis of both instruments has been calibrated by measuring a 50 μm thickness artefact that had been calibrated using a traceable stylus instrument. The standard uncertainties associated with the measurements of the thickness artefact are 0.391 μm for optical coherence tomography and 1.085 μm for infra-red confocal microscopy. The capabilities of the two instruments have been extensively studied by measuring a pressure sensor with multi-layered structures. The thicknesses of the layers range from 20 μm to 300 μm with a total thickness of around 800 μm . These measurements demonstrated that both instruments have the ability to measure the thickness of layers and to image internal geometrical structures. This study has revealed that infra-red confocal microscopy has a larger range of depth scan and optical coherence tomography has higher axial resolution. The characteristics of these two instruments are summarised and the potential to improve the performance of the instruments is discussed.

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1 Background

Several techniques exist in the micro-electro-mechanical systems (MEMS) and semiconductor industries for measuring wafer thickness. For MEMS devices there is a requirement to measure internal dimensions in multi-layered structures [1]. In addition there are applications where the wafer cannot be accessed from both sides so that conventional measurement systems, such as white light interferometry, confocal microscopy and stylus instruments, are not able to measure the thickness of each individual layer. Current techniques in the semiconductor industry involve layer separation prior to examination. Both scanning electron microscopes (SEMs) and atomic force microscopes (AFMs) are not capable of carrying out such measurement without destructive pre-processing. Such time consuming and destructive processes are not suitable in a production environment. Measurement of a large quantity of MEMS samples requires a non-invasive, cost-effective and flexible measurement technique.

Techniques available to measure MEMS devices are reviewed elsewhere [2]. Optical coherence tomography (OCT) and infra-red confocal microscopy (IRC) are two candidates for measuring the internal geometry of MEMS devices. Both techniques are non-contact and capable of measuring the thickness of layers in silicon. In this project, Michelson Diagnostics Ltd provided the OCT system and Olympus Life Science Europa GmbH provided the IRC. The light sources of both systems can penetrate silicon and silicon dioxide without physical contact. Due to this advantage, the structure of the samples can be maintained during measurement. However, both instruments are relatively new to the area of internal geometry measurement, hence a comprehensive study of the capabilities of the instruments is required.

The main objective of this work is to use both the OCT and IRC systems to produce traceable thickness measurements of several different MEMS devices (provided by GE Sensing and QinetiQ), thereby demonstrating the suitability of the techniques for use within the MEMS industry. There are a few fundamental questions that should be addressed:

- What is the thinnest layer that the instruments can measure?
- What is the largest range in depth that the systems can measure?
- Are the measurements acceptable to control MEMS processing?

The details of the OCT and IRC systems are introduced in section 2. Section 3 presents the data processing used with the OCT and IRC systems, including data extraction and optimisation. The beam axis of both systems has been calibrated by measuring a 50 μm artefact and this process is detailed in section 4. The resolution of the two systems is discussed in section 5. The capability of the OCT and IRC systems is further studied in section 6, where an example of measuring a MEMS device with multi-layered structures is demonstrated. The ability of each instrument to detect wafer defects is further explored by imaging a range of devices with known defects and the results are also discussed in

this section. The relative merits of the OCT and IRC systems are discussed in section 7 and future work is addressed.

2 Introduction to the two thickness measurement systems

2.1 Optical coherence tomography

OCT is a non-invasive, non-contact imaging technique that provides volumetric information of a sample. It is widely used to examine biological pathologies. The EX1301 model (see Figure 1) provided by Michelson Diagnostic Ltd is a swept source OCT, a subset of frequency domain OCT (FD-OCT) [3] based on a free-space Michelson interferometer. The centre wavelength is 1310 nm with a 75 nm bandwidth. The system uses a “rattle plate” (Fabry-Pérot etalon) to generate four virtual sources at the input to the interferometer (refer to Figure 2). The system simultaneously scans these virtual sources and focuses each at slightly different depths. A mosaic image is then combined from the resulting multiple Fourier domain OCT interferograms.



Figure 1 The EX1301 OCT instrument (courtesy to Michelson Diagnostics Ltd).

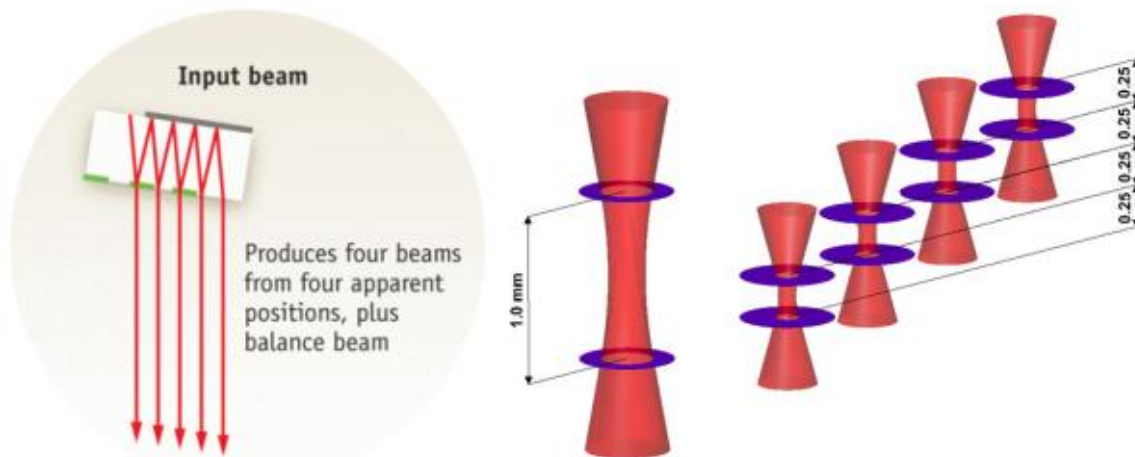


Figure 2 Four-beam OCT system (courtesy to Michelson Diagnostics Ltd). Left - generation of four beams. Centre - a single beam structure. Right - a four-beam arrangement.

The diagram of a single beam is shown in Figure 2 (centre), where the beam is focused over a range of 1 mm along its beam axis. The four beams focus at adjacent depths with a 0.25 mm displacement of each beam. The advantage of the four-beam structure is that each individual beam focuses on a narrower width compared to the one-beam structure with 1 mm displacement. This provides higher lateral resolution than conventional OCT using only one beam. The resolution will be further discussed in section 4.

One advantage of OCT systems over conventional surface measuring instruments is that they acquire volumetric data. This is different to conventional surface measuring instruments, where the measurement is effectively 2.5D. The fundamental element of volumetric data is the voxel, which is a grid in 3D space. The other advantage of OCT systems is that their fast scan speed allows the data acquisition to be completed within a short time - usually less than ten minutes. During a measurement, the laser beam scans through the sample along beam axis (*A*-scan) and sweeps across the sample (*B*-scan). While the OCT sweeps across a sample, a motorised stage drives the sample moving along the direction perpendicular to the *B*-scan plane to acquire volumetric data (*C*-scan). The *A*-scan, *B*-scan and *C*-scan correspond to a scan along *Z*-axis, a scan along *XZ* plane and a scan in *XYZ* volume in conventional coordinate system. The details of the scans are given in Table 1.

OCT scan direction	Correspond to coordinate system
<i>A</i> -scan	A series of data along <i>Z</i> -axis
<i>B</i> -scan	A set of data scanned along the <i>XZ</i> plane
<i>C</i> -scan	A set of data collected within the <i>XYZ</i> volume

Table 1. Terminology for the OCT system compared to a conventional surface measuring instrument.

2.2 Infra-red confocal microscopy

The OLS3000-IR IRC (see Figure 3) is an infra-red confocal laser microscope with the centre wavelength 1310 nm. It has high transmission in silicon and silicon oxide. The schematic is shown in Figure 4. The laser beam is projected through an objective lens and only focused light can be delivered back to light detector via the pinhole. In the measurement, the laser beam focuses at a small spot using the objective lens and scans over the samples along the *XY* plane. The motorised drive moves the nosepiece up and down to achieve the best focus. The height of the nosepiece associated with corresponding intensity value is recorded during the measurements.



Figure 3 The OLS3000 IRC (courtesy to Olympus Life Science Europa GmbH).

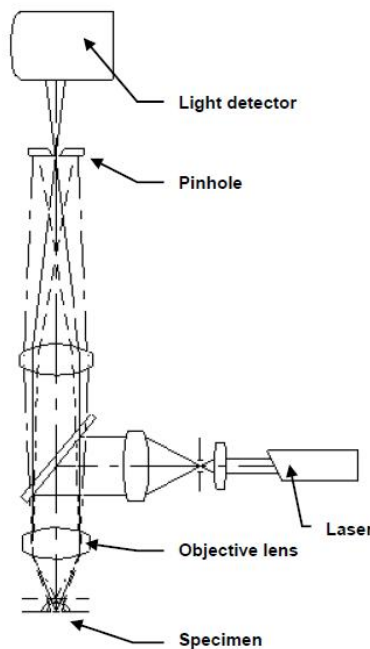


Figure 4 Schematic of the IRC (courtesy to Olympus Life Science Europa GmbH).

The IRC has two modes: “3D” and “XZ”. In “3D” mode, the system produces scans over the XY plane with an increment in Z . The system acquires 3D images by choosing the best focal point along the beam axis to form the best focal image. Usually, the light reflected back from the top surface has the strongest intensity. Therefore, “3D” mode provides topography information of the top surface. Also, the light reflected back from intermediate layers interferes with light reflected back from the top surface. Thus an interference pattern can be achieved that reflects the internal structure of the sample. In “XZ” mode, the system scans the sample in depth along X -axis with an increment in Z -axis. An intensity profile is thus achieved associated with the movement of the nosepiece. The step size can be manually controlled. The minimum step size is 10 nm with a maximum range of one thousand steps allowed in the current software version.

Although the IRC performs depth scans in both modes, the processes are slightly different. The “XZ” mode is similar to a conventional microscope, where the system stacks multiple image planes taken by scanning a component throughout the range of height required. However, in “3D” mode, IRC systems use the calculated focus operation (CFO) function, which allows the best focal fit to be estimated based on a limited number of scans. This process significantly reduces the number of steps to be measured, thus increases the speed of measurement.

In this project, the “3D” mode was primarily used to view the overall internal structure of samples. The “XZ” mode has particularly been used to measure the thickness of layers or to inspect defects of samples in detail. Currently the IRC does not have built-in functions to implement volumetric measurements.

3 Data processing

The volumetric data acquired by OCT systems allows users to have a comprehensive view of the internal sample structure. However, there are challenges that remain in dealing with volumetric data. The first challenge is the size of data set. For example, the size of a complete data set of an 803×1000 A-scan measurements is 6.12 GB. Data processing of such a data set can take a relatively long time. Therefore, reducing the size of the data set to a manageable size and processing the data in an efficient way are important, and a fast computer with a high-quality graphics card is necessary.

Compared with data acquired by surface measuring instruments, where the result shows only one interface, volumetric data acquired by OCTs provides a stack of scans. It requires functions to view internal structures and to calculate volumes or surface areas. Currently, there are a few open source software packages available via the Internet to render volumetric data. They are ImageJ [4], Voxv [5], Drishti [6] and ImageVis3D [7]. It is applicable to use these software packages to visualise data acquired by OCTs. However, the sample structure may be distorted without applying a correction for the refractive index of the sample. With a known sample, it is feasible to apply refractive index correction, but it is difficult to apply a refractive index correction to a sample if the boundary between media is ambiguous, particularly for samples with unknown structures. There is a general lack of research regarding the refractive index issue.

Considering the reasons above, the OCT data analyses in this report will focus on *B*-scan images of the OCT, corresponding to “XZ” measurement results of the IRC. The *C*-scan results from the OCT, together with the “3D” measurement results from the IRC system, will only be used to measure overall sample internal structure. Detailed analyses, for example, the thickness of an individual layer will only be considered for cross section data in this report. In the following sections, the data processing of the OCT and IRC will be illustrated when measuring a $50\ \mu\text{m}$ thickness artefact (see Figure 5). More information about this artefact can be found in [8].

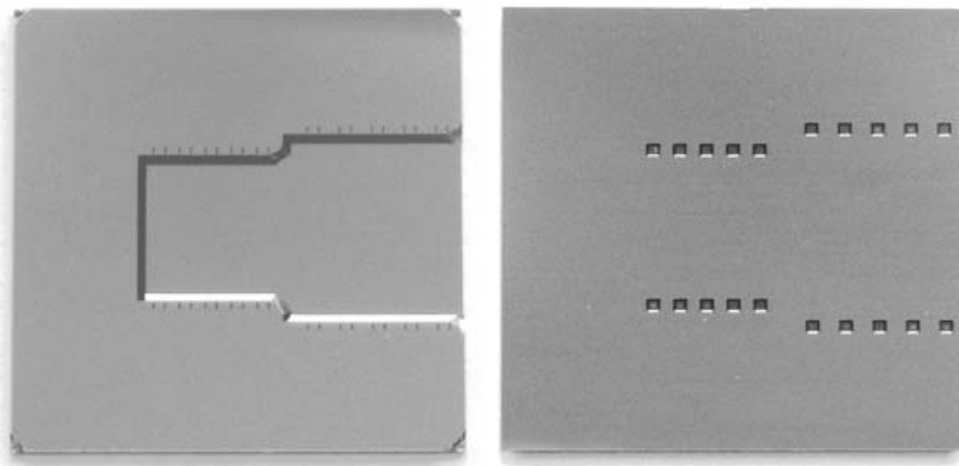


Figure 5 A silicon $50\ \mu\text{m}$ thickness artefact. Left – Frontside of the artefact. Right – Backside of the artefact. (courtesy to SiMETRICS GmbH)

3.1 Data processing of the OCT system

OCT has been widely used in imaging subsurface tissue structures since it was introduced in the early 1990s. Its application in industry has only started in recent years. OCT is more often used to image a sample rather than measuring the dimension of a sample and there is lack of understanding of system capabilities for thickness measurements. Currently, no scale of the beam axis of the EX1301 OCT system is available for measuring silicon material. The beam axis unit of the OCT results will be kept as pixels in this section. There are a total of 1024 sampling points per channel per *A*-scan. With the default Mosaic (values that determine the offset in pixels between channels) setting, the four channels can be stitched together with a total number of 410 pixels.

The complete data collected from the OCT system is stored in a file with the extension “.oct”. The file includes all information acquired from the four channels. The data are also available as a set of “.png” images, which is effectively a series of combined *B*-scan images from the four channels. The pre-set Mosaic values have been used to stitch images from four channels together. With all necessary information included, the .png image has been used in the following data analyses.

Figure 6 is a raw *B*-scan image of the measurement of the 50 μm artefact. The detail of the process is as follows:

- The first step is to remove noise and header information. The OCT system has DC and autocorrelation noise [9]. Also, *B*-scan images include headnotes and footnotes. The information is removed prior to analysis. In the measurement of MEMS devices, a threshold of fifty-five intensity units was found to be acceptable as a cut-off level of the data acquired from *B*-scan images. Figure 7 shows the updated image of Figure 6 with noise and header information removed.

The threshold mentioned above is an empirical value and it may not be applicable to the measurement of other samples with different materials, for example tissues. The threshold may also affect data towards the bottom of the measurements, where the intensity of data could be much lower than data from the top of the sample.

In Figure 6, apart from the top and the bottom surface of the 50 μm artefact, there is a third interface below. It is in fact not any part of the artefact, but an artificial component, which may be due to the Fourier transform [10]. It can be removed during the data process.

- The second step is to acquire depth information from the intensity image, which is essentially an optimisation problem. A Gaussian fitting algorithm has been used based on the assumption that the intensity along the surface interface is a Gaussian profile. Figure 8 shows a fitting result of an intensity profile. By

applying a Gaussian fit to the whole image, the profile in Figure 7 can be converted to that in Figure 9. This is a significant improvement compared to a direct conversion - as shown in Figure 10 where surface point is determined by the position of the point with highest intensity. With this process, the original intensity image has been converted into height profile, and the data size can be one hundred times smaller than original .oct data.

- The final stage of data processing is data alignment. This process is particularly important in measurements involving planar structures. High reflection of light from the top surface of MEMS devices can significantly increase the noise level of the measurement and results in poor image quality. Tilting the sample can usually reduce this effect. However, measurement results from a tilted sample cannot be directly used in a thickness analysis. Figure 11 shows two interfaces of the 50 μm artefact after alignment.

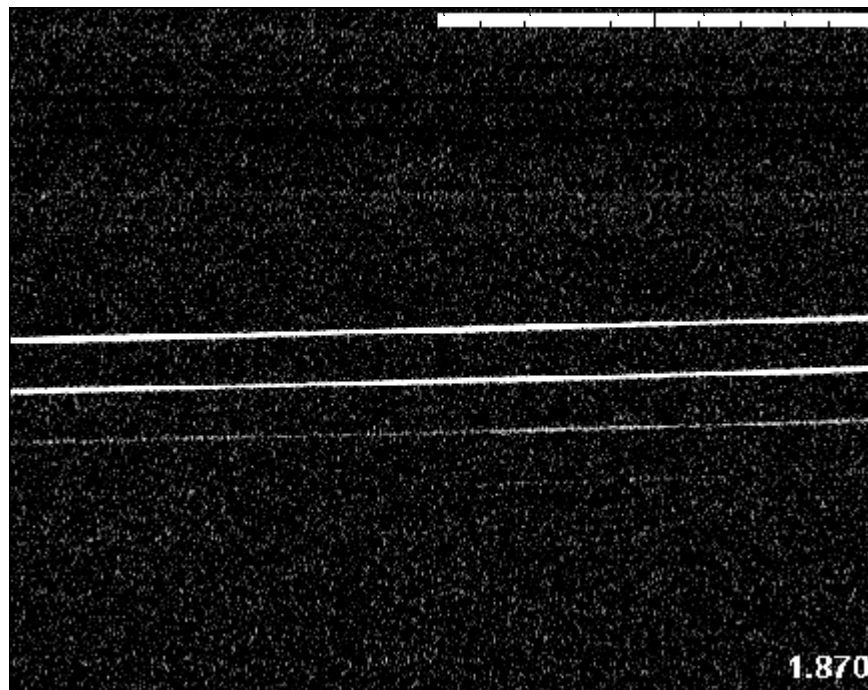


Figure 6 Original *B*-scan image taken by the OCT system

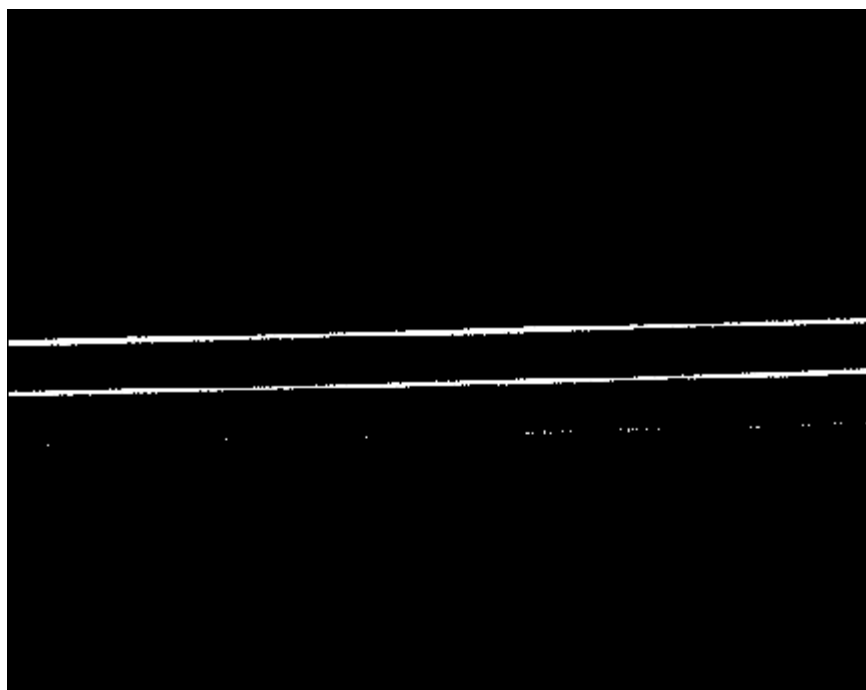


Figure 7 An OCT *B*-scan image with image information removed and noise reduced.

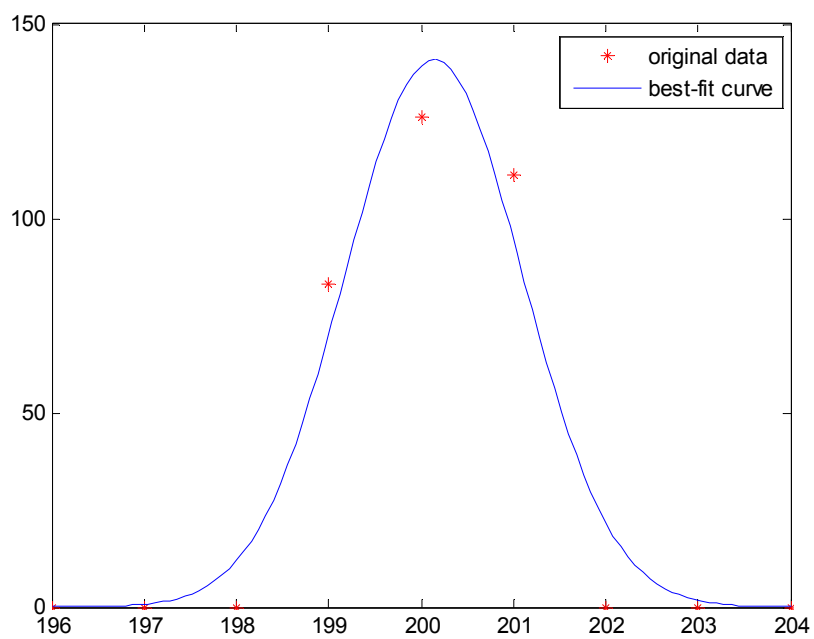


Figure 8 Gaussian fit to an intensity profile.

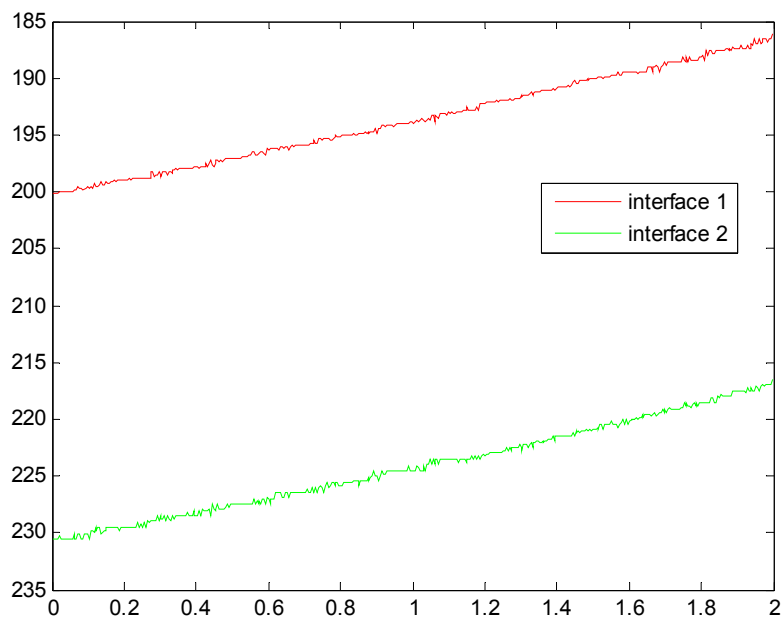


Figure 9 Interfaces optimisation using the Gaussian fitting algorithm.

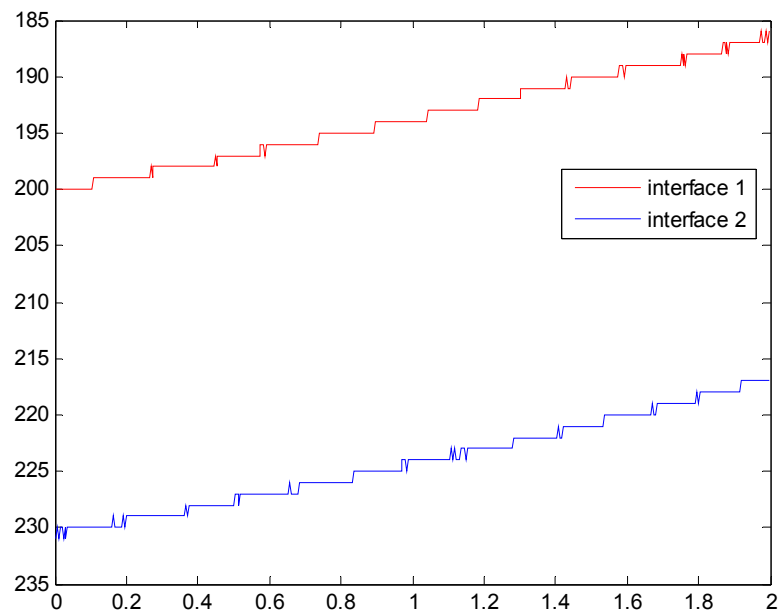


Figure 10 Interface optimisation using the highest intensity points.

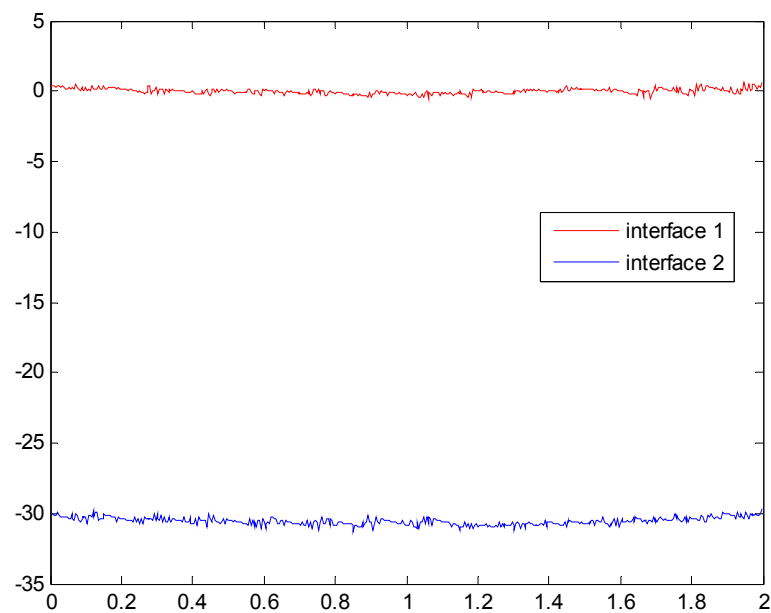


Figure 11 Estimated interfaces with alignment

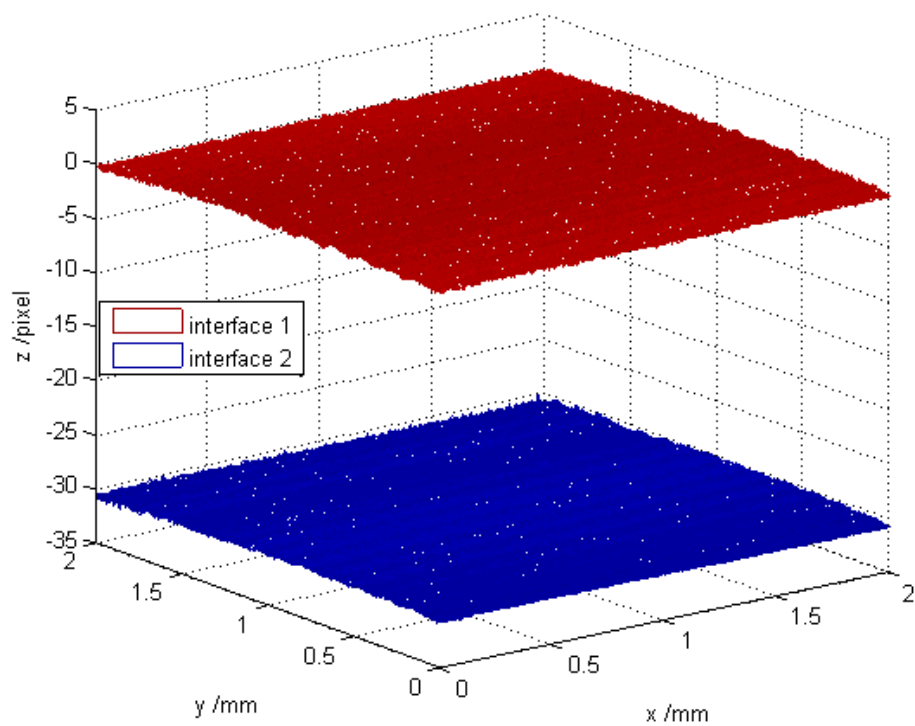


Figure 12 3D data processing of the measurement of the 50 μm artefact

The averaged thickness after alignment is 30.545 pixels with a standard uncertainty of 0.245 pixels. The data processing procedure described above can be applied in processing volumetric data (see Figure 12). However, the processing of volumetric data can be complicated and time consuming when investigating samples with complex structure. As visualisation of volumetric data is not the main objective of the work here, the process of 3D data will not be discussed further.

3.2 Data processing of the IRC system

Thickness measurement is available in the “XZ” mode of the IRC system. The data processing is similar to the data processing of the OCT .png images, which both involve a conversion from intensity to a depth profile. Figure 13 (Left) shows the measurement results of the 50 μm artefact using the IRC system. The range of the field of view is 250 μm with the 50 $\times$ objective. The reason to choose the 50 $\times$ objective will be explained in section 4. There are 841 steps with a step size of 0.05 μm . A large number of sampling points along beam axis allows the user to achieve a large amount of detail of the intensity profile. Therefore, the peak of the intensity profile can be directly located rather than by estimation. Figure 13 (Right) presents the averaged intensity profile of the scan. The first peak and the third peak indicate the top and bottom interfaces respectively. The second peak is an artificial component that may be caused by the misalignment of the internal optical components. With refractive index 3.505, the thickness of the 50 μm artefact measured by the IRC 50 $\times$ objective is 47.668 μm , with a standard uncertainty of thickness 1.064 μm .

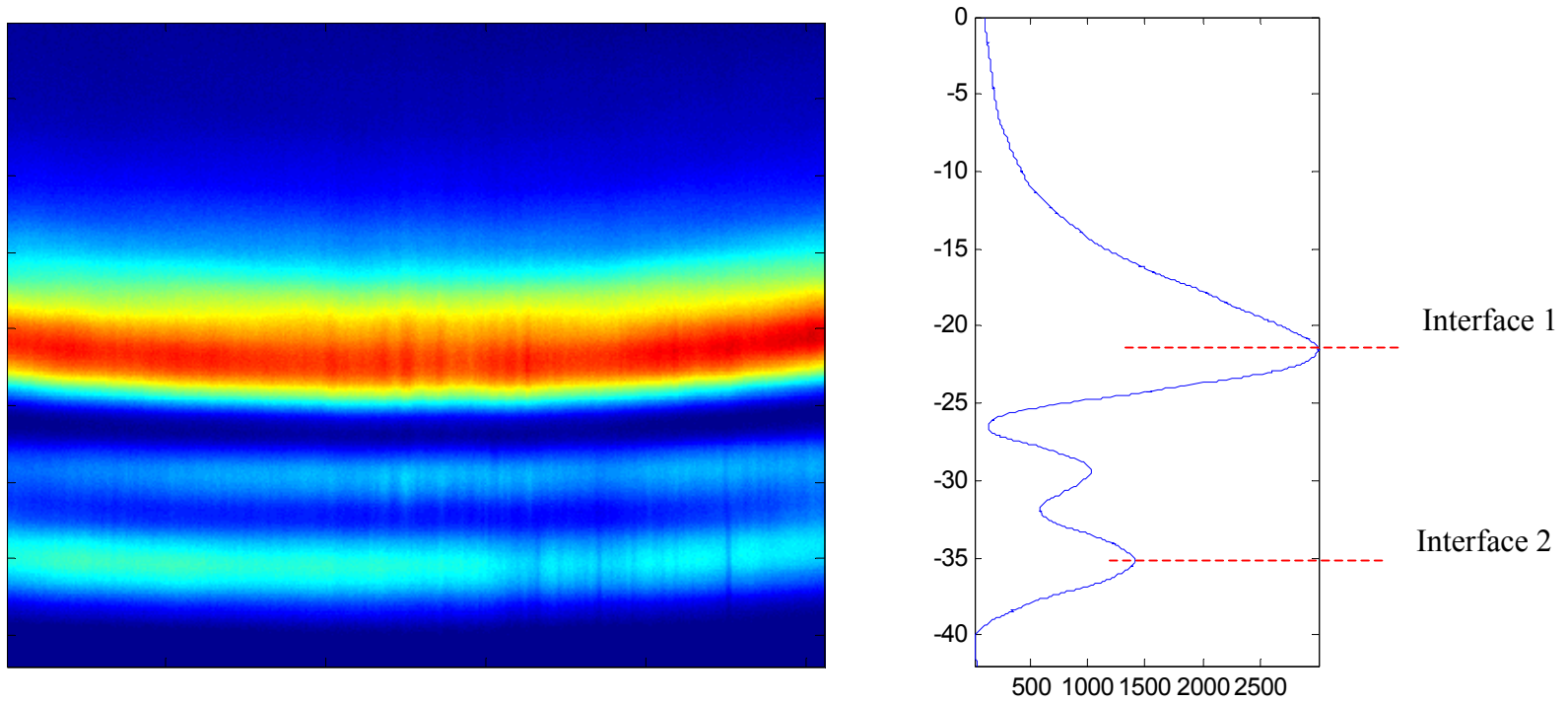


Figure 13 Measurement of the 50 μm artefact using the IRC 50 $\times$ objective. Left - Intensity image of depth scan. Right - Averaged intensity profile of the artefact.

4 Calibration of the beam axis of the OCT and IRC systems

Calibration of the OCT and IRC is essential prior to measurements. The International vocabulary of metrology (VIM) [11] defines calibration as:

Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

This report focuses on the calibration of the beam axis, as this is important in the measurement of layer thickness.

A 50 μm artefact (see Figure 5) has been used in the calibration of the OCT and IRC systems. The thickness of the artefact has been calibrated by a traceable stylus measurement instrument (Taylor Hobson PGI 1000). In the VIM, traceability is defined as:

The property of a measurement result whereby the result can be related to references, through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

The measurement of the thickness of the 50 μm artefact using the stylus instrument is 48.633 μm with a standard uncertainty of 0.091 μm . By comparing the data from the OCT with the traceable measurement results of the artefact, the scale of the OCT system is 1.592 μm per pixel in silicon and the standard uncertainty associated with the calibrated OCT in measuring the 50 μm artefact is 0.391 μm . The scale of the OCT system in air is then 5.580 μm per pixel.

The scale of the IRC system in measuring the thickness of silicon layers has also been calibrated by comparing the measurement results of the 50 μm artefact with the measurement acquired by the stylus instrument. Assuming a linear system, a calibration factor of 1.020 is calculated for the 50 $\times$ objective in measuring thickness of silicon layers. The measurement result of the artefact using the IRC 50 $\times$ objective is presented in Figure 13. The standard uncertainty associated with the calibrated IRC in measuring the 50 μm artefact is, therefore, 1.085 μm .

5 Resolution of the OCT and IRC systems

In optical imaging systems, resolution is defined as the smallest difference between displayed indications that can be meaningfully distinguished [11]. The axial resolution is the resolution along the direction of beam propagation and the lateral resolution is the resolution along the direction perpendicular to the direction that the beam travels. In thickness measurement, the axial resolution is vital. For example, in the measurement of the 50 μm artefact, as the material is homogeneous and the structure is uniform, the axial resolution is more important than the lateral resolution. However, the lateral resolution is also important when measuring samples with multi-layered structures, for example to measure the pressure sensor in section 6. Therefore, both the lateral and axial resolutions have to be considered.

5.1 Optical resolution of the OCT system

- Lateral resolution

The lateral resolution $r_{lateral}$ of the OCT systems is determined by the centre wavelength (λ_0) of the light source and the numerical aperture (NA) of the objective, see equation (1).

$$r_{lateral} \approx \frac{1.22}{\sqrt{2}} \frac{\lambda}{2NA} \approx 0.4 \frac{\lambda_0}{NA}. \quad (1)$$

With $\lambda_0 = 1310$ nm and $NA = 0.059$, the lateral resolution of the EX1301 OCT system is 7.97 μm .

- Axial resolution

The axial (depth) resolution (r_{axial}) of the OCT systems is given by [12], see equation (2). It is related to the centre wavelength λ_0 and source bandwidth $\Delta\lambda$ by

$$r_{axial} = \frac{\ln 2}{\pi} \frac{\lambda_0^2}{\Delta\lambda} \approx 0.44 \frac{\lambda_0^2}{\Delta\lambda}. \quad (2)$$

Equation (2) is based on the assumption that the measurement is in a vacuum. The influence of sample refractive index is discussed in [13], and given by equation (3). For the EX1301 OCT system, with $\lambda_0 = 1310$ nm and full width half maximum $\Delta\lambda = 75$ nm, the corresponding value of r_{axial} is 9.99 μm in vacuum. The average

refractive index, n_{ave} , of single crystal silicon is 3.505 [14, 15]. Consequently, the theoretical axial resolution of the OCT system in silicon is 2.85 μm .

$$r_{axial} = \frac{\ln 2}{\pi} \frac{\lambda_0^2}{\Delta\lambda} \approx 0.44 \frac{\lambda_0^2}{\Delta\lambda} \frac{1}{n_{ave}}. \quad (3)$$

5.2 Optical resolution of the IRC system

The resolution of confocal microscopes is directly related to the full width at half maximum dimensions of its point spread function [16]. Both the lateral and the axial extent of the point spread function is approximately thirty percent higher than that of a conventional microscope.

- Lateral resolution

The lateral resolution of the IRC is the same as that of the OCT system as they are both governed by the diffraction limit [12, 17]. The lateral resolution can be calculated based on equation (4). The light source of the IRC is a semiconductor laser with central wavelength $\lambda_0 = 1310 \text{ nm}$.

$$r_{lateral} \approx 0.4 \frac{\lambda_0}{NA}. \quad (4)$$

- Axial resolution

The axial resolution of confocal microscopes can be calculated by equation (5).

$$r_{axial} \approx \frac{1.4\lambda_0 n_{ave}}{NA^2}. \quad (5)$$

There are seven objectives with different NA available for the IRC system. The details of these lenses can be found in Table 2, where a lens with higher NA has better lateral and axial resolutions. The best theoretical lateral resolution is 0.55 μm and best theoretical axial resolution is 1 μm for single crystal silicon. However, there is a trade off between the working distance and the measurement range in depth. The working distance, especially for objectives with high NA , can limit the measurement range in depth. In order to cover the thickness of a whole wafer with a thickness of approximately 800 μm , the 50 $\times$ lens was chosen due to its moderate axial resolution and working distance (WD). The theoretical optical lateral resolution of the 50 $\times$ objective is 0.99 μm and the axial resolution is 22.88 μm in silicon.

Comparing equations (5) and (3), the axial resolution of the OCT is proportion to $1/n_{ave}$ and the axial resolution of the IRC is proportion to n_{ave} . Consequently, the

IRC 50× objective has a higher axial resolution in air and the OCT has a better axial resolution in silicon.

Experimentally, the optical resolution of the OCT and IRC systems can be determined by measuring the full width at half maximum of their point spread functions. This can be achieved by illuminating a small particle. The detailed work of defining the point spread function of the OCT systems can be found in [13]. The measurement of point spread function of confocal microscopes can be found in [18].

Objectives	<i>NA</i>	<i>WD</i> /mm	<i>FOV</i> / μm	<i>LR</i> / μm	<i>AR</i> / μm
5×	0.10	20	2560×2560	5.24	642.82
10×	0.25	18.5	1280×1280	2.10	102.85
20×	0.40	8.1	640×640	1.31	40.18
50×	0.53	7.0-6.8	256×256	0.99	22.88
90×	0.69-0.71	1.2-1.1	142×142	0.76-0.74	12.75-13.50
L100×	0.80	3.4	128×128	0.66	1.00
100×	0.95	0.3	128×128	0.55	7.12

Table 2 Specification of the IRC systems [19]. *NA*: Numerical aperture. *FOV*: Field of view. *WD*: Working distance. Field of view: range of digital image of the “3D” mode. *LR*: Lateral resolution. *AR*: Axial resolution. Axial resolution is calculated for silicon material.

The direct measurement of the point spread function of these instruments in silicon is currently unavailable as it requires a measurement of a particle in silicon with a diameter less than 15 % of the incident point spread function full width at half maximum [13]. Yoo has investigated the point spread function of confocal microscopy and has found that the size of particle affects the point spread function [20]. Furthermore, the spherical and chromatic aberrations may affect the measurement of the point spread function when measuring a particle in depth. This is particularly important for confocal microscopes as the *NA* of objective is considerably larger than the lens used in OCT systems. The polarization of light also affects the point spread function [21]. Due to these reasons, there are challenges that remain in measuring the point spread function of light in silicon.

The overall resolution of an optical system is not only governed by optical components, but may also be affected by other factors, such as image resolution. For the IRC system, 50× objective, the image resolution along *X*-axis is 0.05 μm and the step of the motorised *Z*-drive can be as small as 0.035 μm in silicon. These values are much smaller than the optical lateral resolution of 0.99 μm and optical axial resolution of 22.88 μm . Therefore, the optical resolution is dominant in this system. For the EX1301 OCT system, the image resolution along *X*-axis is set at 4.4 μm in the current software version and the scale along *Z*-axis is 1.592 μm , correspondingly less than the optical lateral resolution of 7.97 μm and the optical axial resolution of 2.85 μm . From experience, high image resolution leads to better image contrast so that a better understanding of sample structure can be achieved.

6 Measurements of MEMS devices

6.1 Measurements of a pressure sensor

In this section, a MEMS device with a multi-layered structure is chosen to demonstrate measurements using the OCT and IRC systems. The sample provided by GE Sensing is a Trench Etched Resonant Pressure Sensor (TERPS). The application of TERPS is introduced elsewhere [2]. The schematic (cross section) of the sample is shown in Figure 14. The sample is fusion-bonded silicon. The colour scheme in Figure 14 is to distinguish different layers and sections for the following analyses. Figure 15 shows the 3D measurement of samples using the IRC system and Figure 16 is the 3D volumetric presentation of TERPS using the OCT system.

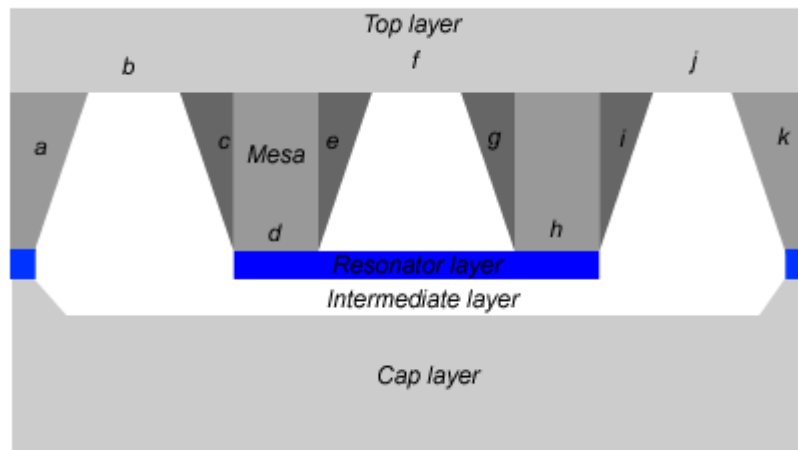


Figure 14. Schematic (cross section) of the TERPS, letters *a~k* are used to indicate different sections of the sample.

The experimental setup for measurements of the TERPS is not significantly different to that used for the measurement of the 50 μm artefact. The IRC system allows the user to increase the laser intensity and brightness when measuring thick samples. This compensates for the attenuation of light when penetrating multi-layered structures.

The interpretation of the measurement result of the TERPS is more complicated than that of the 50 μm artefact. For example, in Figure 14 region *f*, there are five layers with six interfaces. The challenge arises in the visualisation of the cross section data, as the results are shown based on an assumption that the material of sample is homogeneous. This leads to a faulty impression of the sample structures, especially along the beam axis. Also, defining the exact location of the boundary between layers can affect the estimation of layer thickness. The issue of application of refractive index in volumetric data has been discussed elsewhere [22]. As it is not an important factor in this project, it will not

be further discussed and the data analyses of samples are focused on 2D cross section data.

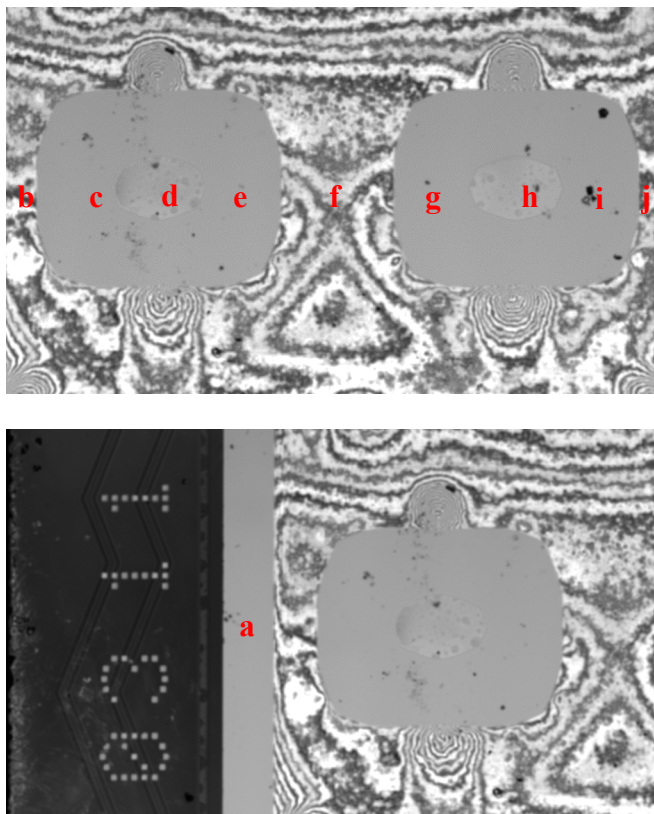


Figure 15. Images of the TERPS using the IRC 5× objective.

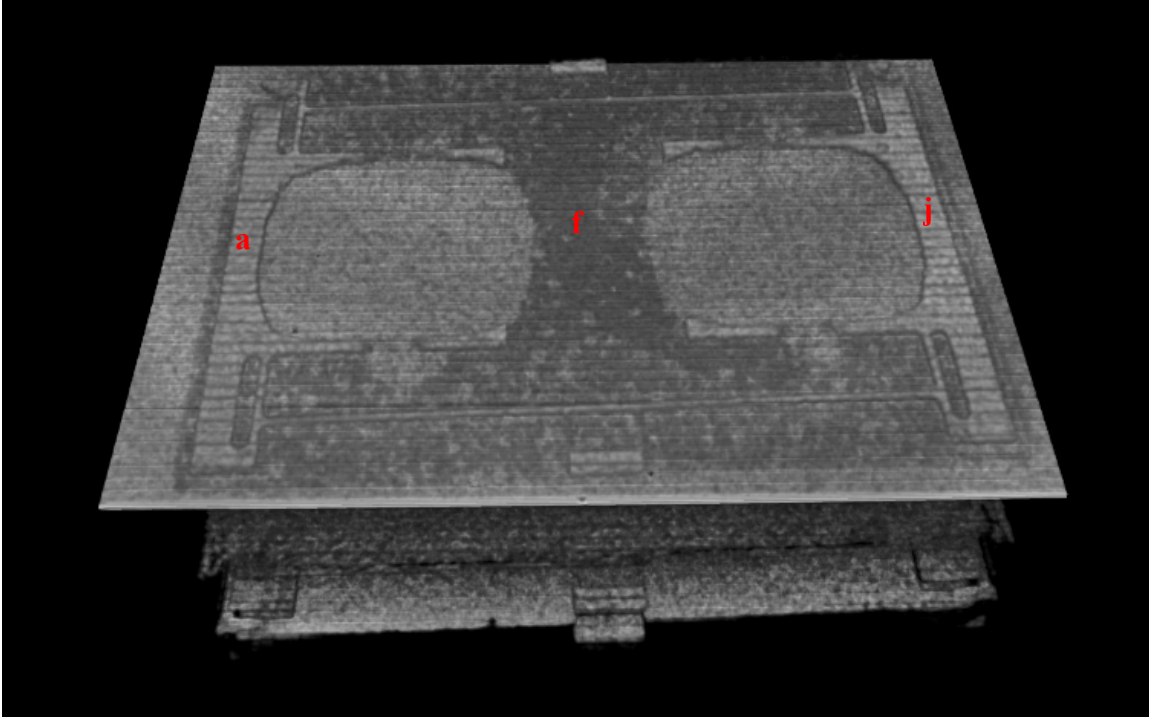


Figure 16 3D volumetric image of the TERPS taken by the OCT.

Layers	Designed value
Top	150 μm
Mesa	300 μm
Resonator	60 μm
Intermediate	20 μm
Cap	307 μm

Table 3 Designed value of the TERPS.

The sample has been divided into eleven regions along X -axis of the cross section in Figure 14 for easy of description. The structures of regions $\{g, h, i, j, k\}$ are similar to those of regions $\{e, d, c, b, a\}$, therefore the measurement results of these regions will not be discussed in detail. Also, both the OCT and IRC systems are not capable of measuring internal structure below interfaces with high aspect ratio, for example, the structure below the sidewall of the mesa layers. Thus, interest is only focused on regions $\{b, d, f\}$, where a maximum of three, five and five layers, respectively, may be able to be detected in corresponding regions. The designed thickness of each layer is presented in Table 3.

For the IRC system, the 50 $\times$ objective has been chosen in the measurements of the TERPS to allow a sufficient depth of view and moderate resolution. The field of view of the 50 $\times$ objective is 256 μm along X -axis in “XZ” mode.

Figure 17 to Figure 19 present the measurement results of the TERPS using the IRC system. The left hand side of each figure is the cross section of the sample and the right

hand side is the averaged profile for a particular region. The interest is particularly focused on regions $\{b, d, f\}$. Measurements of regions of $\{a, c, e\}$ only show the top surface as the system cannot image through a sample under a surface with high aspect ratio.

The measurement across regions a and b is shown in Figure 17. There are three layers (silicon, air and silicon) in region b . The measurement results are shown in Table 4 where two layers with three interfaces have been detected (silicon and air). Five peaks in total can be identified in the intensity profile. However, the two peaks adjacent to the last peak do not relate to any internal structure, but to possible artificial components caused by the optical system. These artificial components usually appear next to the real image and the intensity is much lower than that of the real image. The artificial components can also be found in Figure 18 and Figure 19.

Figure 18 and Figure 19 present the measurement results of regions $\{d, e, f\}$. Three layers in total can be detected by the IRC in both regions d and f . The thickness of each layer is calculated in Table 5 and Table 6.

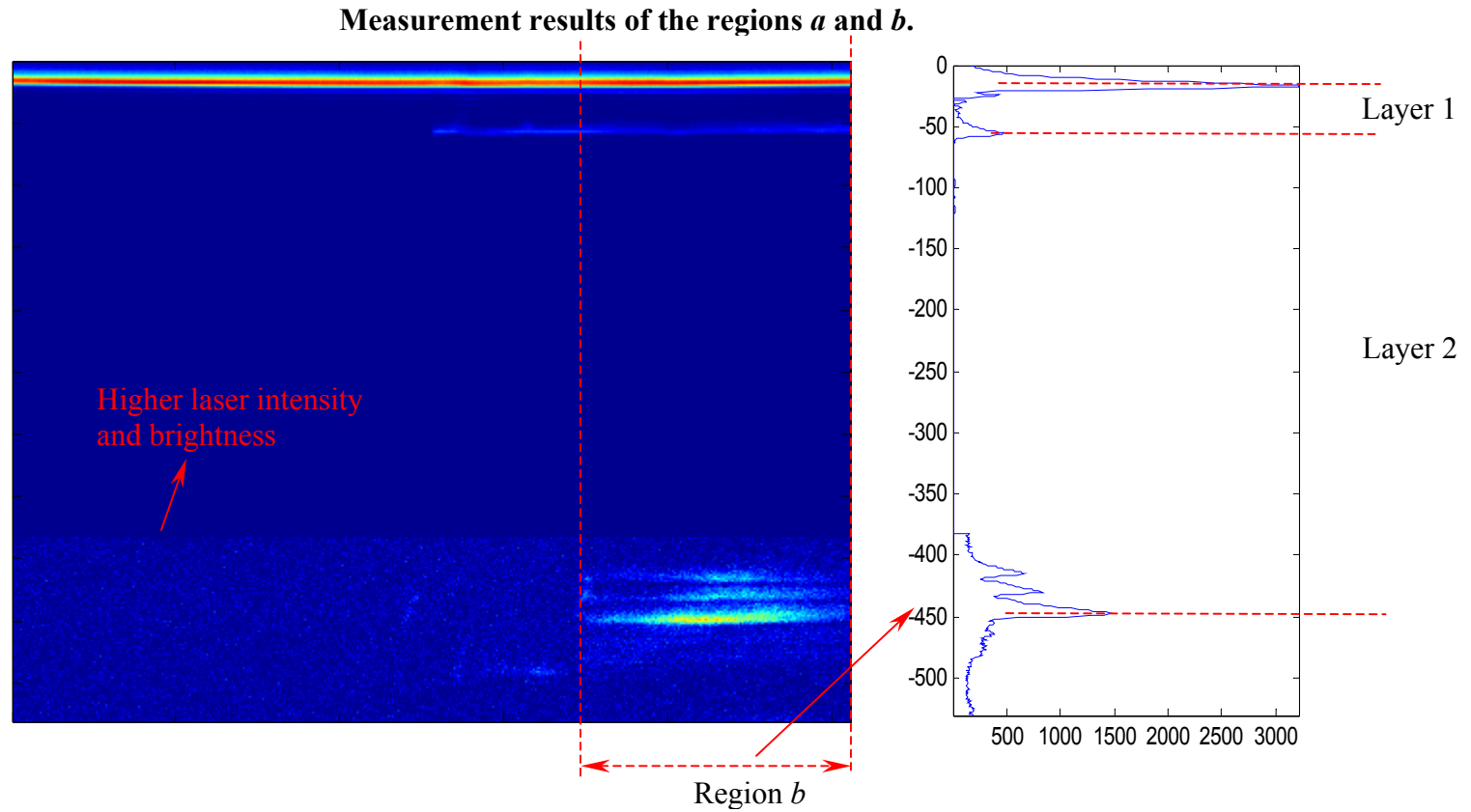


Figure 17 Investigation of the TERPS regions *a* and *b* using the IRC system. Left - Cross section of the regions *a* and *b*. Right - Depth profile, averaged depth profile along *X*-axis of the region *b*.

Zoom magnification	1	Layer	<i>n</i>	Measured / μm	Designed / μm
Image size /pixel	1024 x 885	1	3.505	139.4	150
Measurement range in air / μm	256 x 531	2	1	391.2	380
Sampling interval in air / μm	0.25 x 0.6				

Table 4. Information of measurements and results of the regions *a* and *b*.

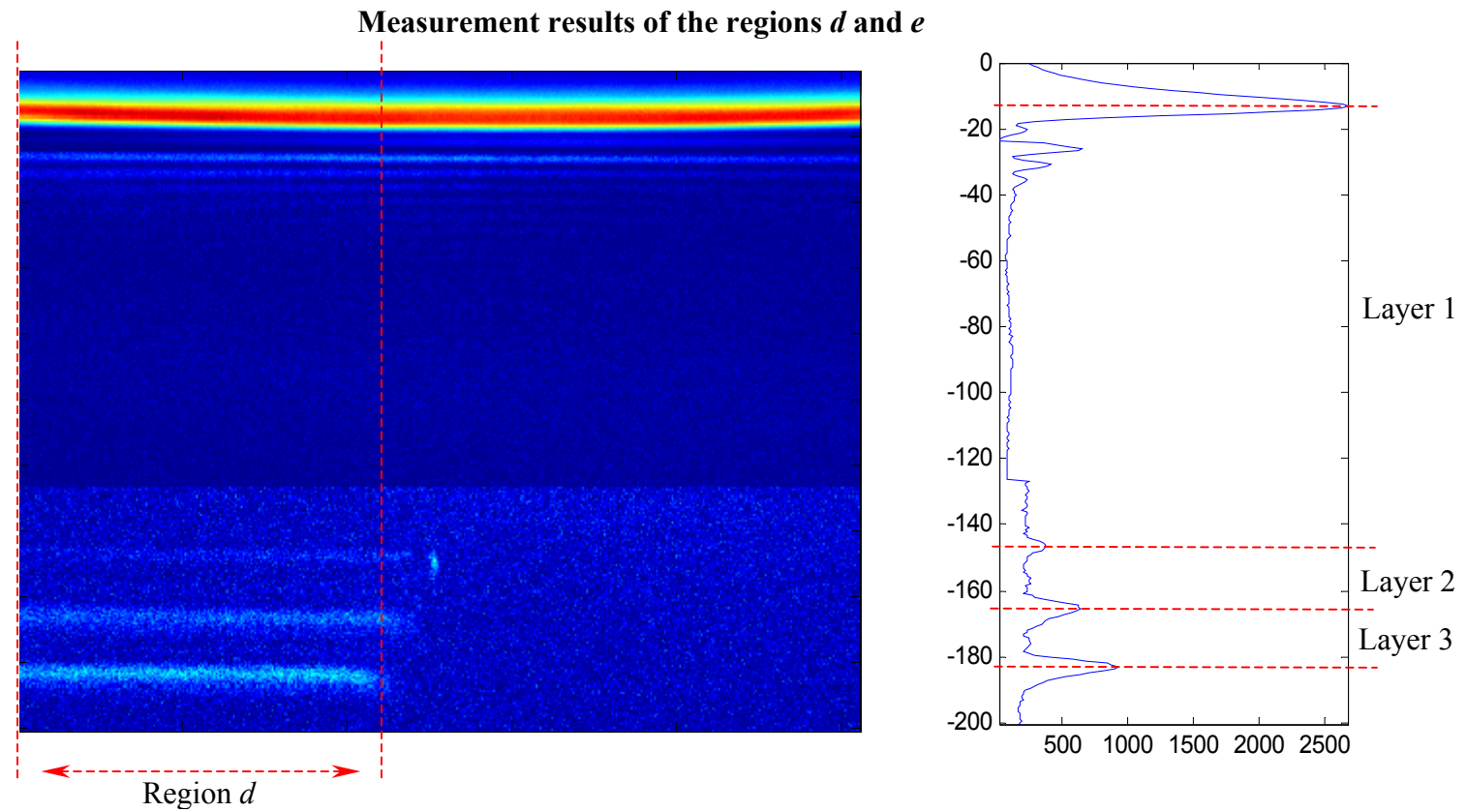


Figure 18 Investigation of the TERPS regions d and e using the IRC system. Left - Cross section of the regions d and e . Right - Depth profile, averaged depth profile along X-axis of the region d .

Zoom magnification	1	Layer	n	Measured / μm	Designed / μm
Image size /pixel	1024 x 335	1	3.505	478.4	450
Measurement range in air / μm	256 x 201	2	3.505	66.5	60
Sampling interval in air / μm	0.25 x 0.6	3	1	17.4	20

Table 5 Information of measurements and results of the regions d and e .

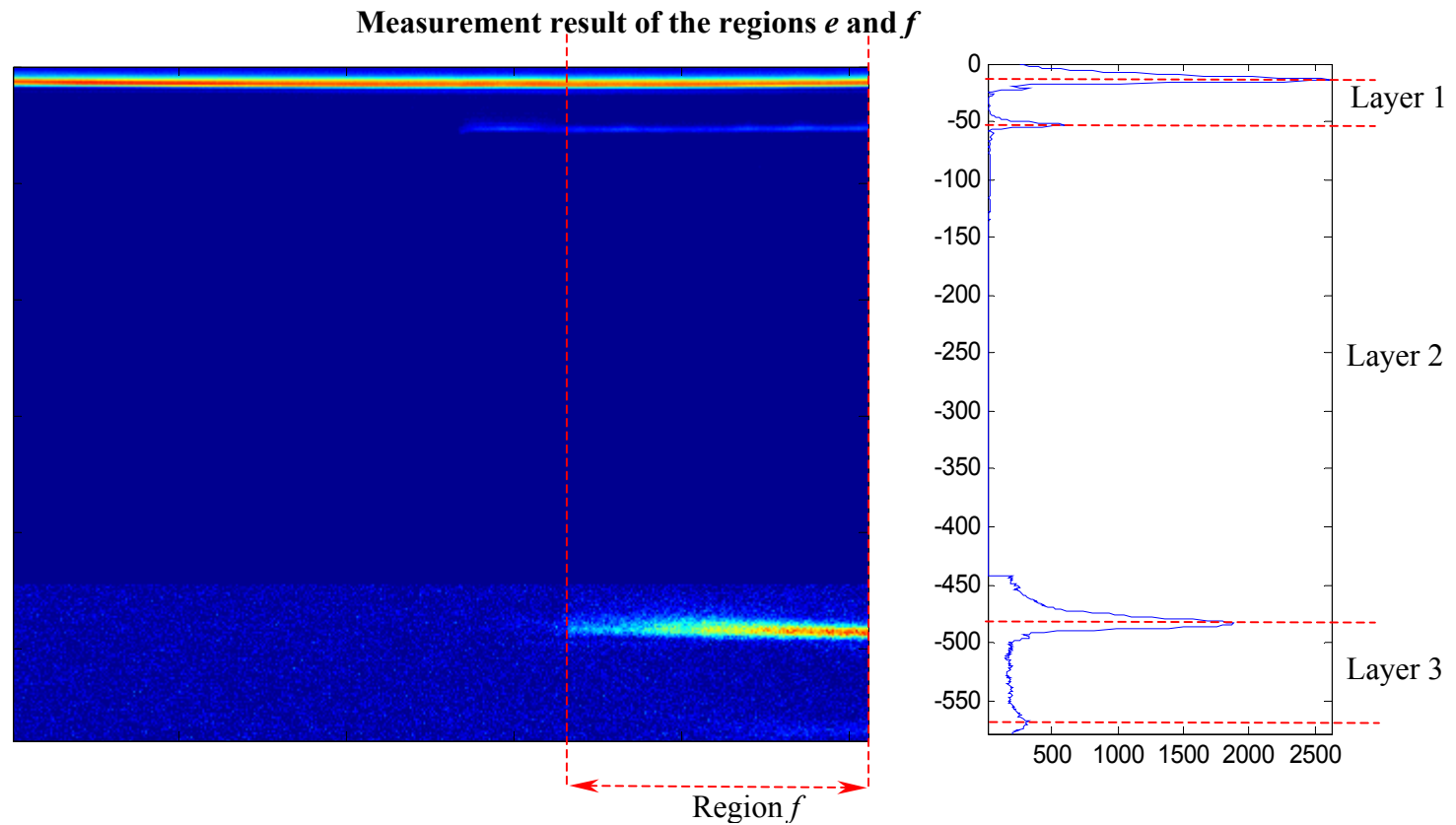


Figure 19 Investigation of the TERPS regions e and f using the IRC system. Left - Cross section of the regions e and f . Right - Depth profile, averaged depth profile along X-axis of the region f .

Zoom magnification	1	Layer	n	Measured / μm	Design / μm
Image size /pixel	1024 x 965	1	3.505	139.4	150
Measurement range in air / μm	256 x 201	2	1	430.2	300
Sampling interval in air / μm	0.25 x 0.6	3	3.505	304.6	60

Table 6 Information of measurements and results of the regions e and f .

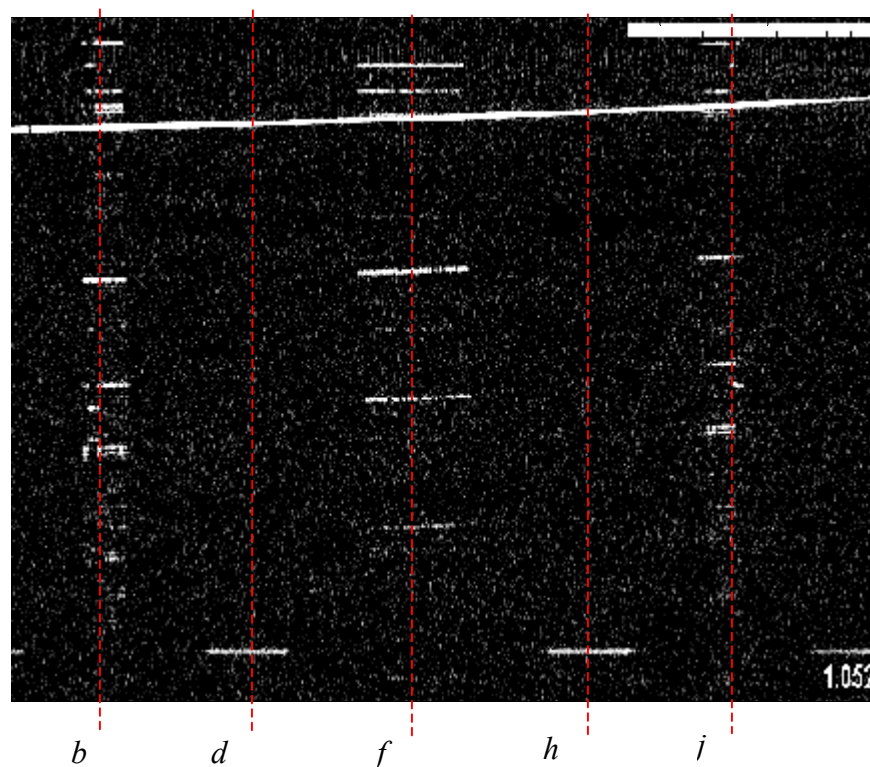


Figure 20 A measurement of the TERPS using the OCT system. The regions $\{b, d, f, h, j\}$ have been highlighted.

The TERPS sample has also been measured using the OCT system. Figure 20 is a *B*-scan image of the sample. The image is a combination of 803 *A*-scans covering a range of 3.5 mm along *X*-axis, where the information of regions $\{a, b, c, d, e, f, g, h, i, j, k\}$ are all included. It is noted that the sample is tilted with respect to the measurement system coordinates. A tilt correction has been applied to level the surface prior to analysis. The detailed interpolation of region $\{b, d, f\}$ is given in Figure 21 and the results are shown in Table 7. The details of the data processing can be referred to section 3.

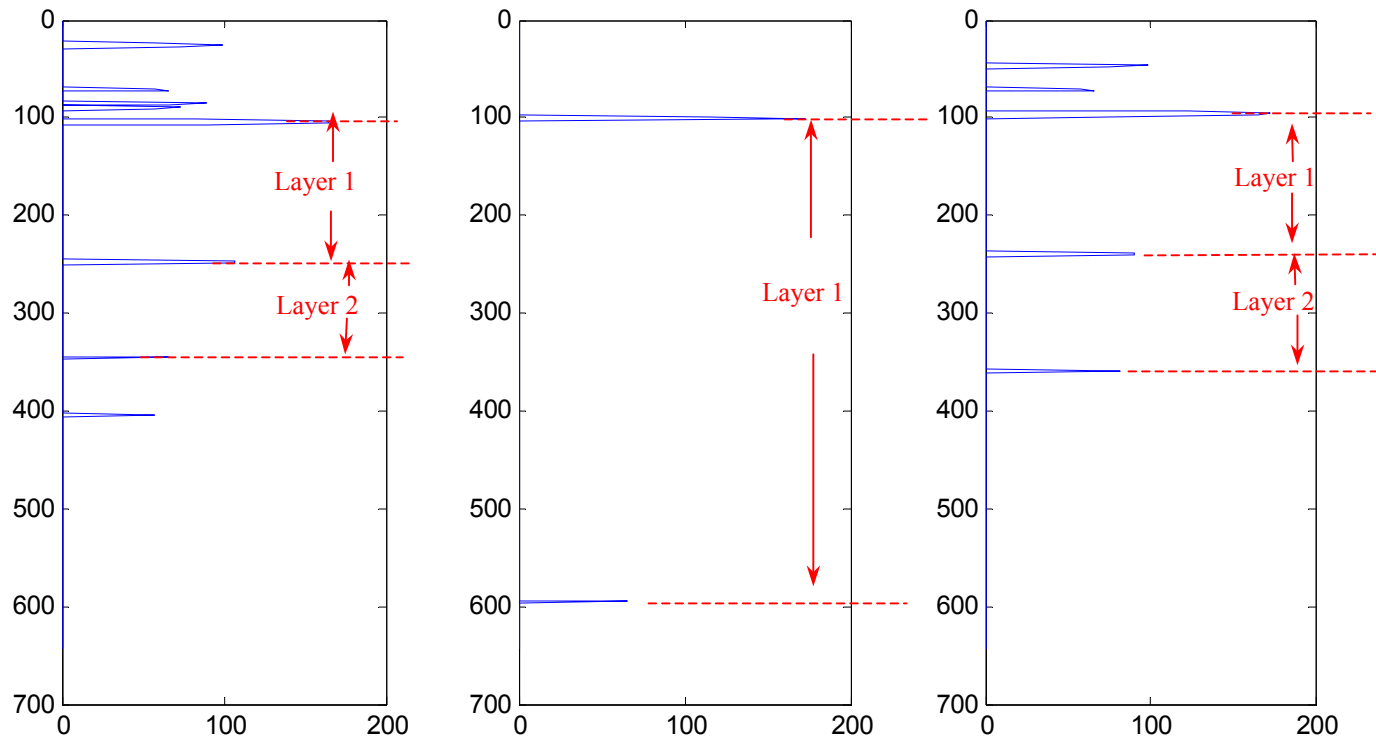


Figure 21 Detail of the OCT results. Left - A profile in the region *b*. Centre - A profile in the region *d*. Right - A profile in the region *f*.

Thickness / μm		Region <i>b</i>		Region <i>d</i>			Region <i>f</i>		
Layer	<i>n</i>	Designed	Measured	<i>n</i>	Designed	Measured	<i>n</i>	Designed	Measured
1	3.505	150	143.4	3.505	450	493.5	3.505	150	143.6
2	1	380	343.2	3.505	60	NA	1	300	418.5

Table 7 Measurement results of the TERPS using the OCT system.

Region	Layer	Designed		OCT Results	IRC Results
		Thickness / μm	Refractive Index	Thickness/ μm	Thickness / μm
<i>b</i>	1	150	3.505	143.4	139.4
	2	380	1	343.2	391.2
<i>d</i>	1	450	3.505	493.5	478.4
	2	60	3.505	NA	66.5
	3	20	1	NA	17.4
<i>f</i>	1	150	3.505	143.6	139.4
	2	300	1	418.5	430.2
	3	60	3.505	NA	304.6
<i>h</i>	1	450	3.505	504.6	479.9
	2	60	3.505	NA	65.9
	3	20	1	NA	18.0
<i>j</i>	1	150	3.505	142.7	134.9
	2	380	1	351.6	391.0

Table 8 Comparison between the IRC results and the OCT results in measuring the TERPS sample.

The results from both the OCT and the IRC system have been compared with the designed value, as shown in Table 8. The comparison is based on an assumption that the systems can detect all interfaces within their capacity.

The results of the layer 1 in all regions measured by both systems are reasonably close to the designed values and both instruments show consistency with themselves in repeat measurements. However, both systems underestimate the thickness of layer 1 in region *b* and overestimate layer 1 thickness in region *d*. One reason that may lead to this can be that the system is nonlinear in measuring silicon material. Currently, there is no evidence to prove this possibility.

It has also been noticed that there is a large error between the designed and measured results of the region *f*, layer 2. In the design, region *f* has five layers in total, with the thickness of 150 μm (silicon), 300 μm (vacuum), 60 μm (silicon), 20 μm (vacuum) and 300 μm (silicon) respectively. There is no error regarding the first layer as both systems show good consistency in measurements. The challenge arises from the second layer. The measurement results of the second layer are 430.2 μm using the IRC and 418.5 μm using the OCT. These values are far from the designed 300 μm . For the IRC system, the third layer measured by the system is 304.6 μm in silicon, which is much more than the thickness of the third layer in design of 60 μm . The mismatch suggests that the assumption made earlier may be incorrect, *i.e.*, the systems may not necessarily detect all layers in the measurements.

For the IRC system, the thickness of the second layer detected is 430.2 μm in vacuum. It can also be interpreted as a sum of the second (300 μm in vacuum), the third (60 μm in silicon), the fourth (20 μm in vacuum) and the fifth (300 μm in silicon) layers, which is equivalent to imaging through a layer of 422.7 μm in vacuum. The difference between designed and

measured data is then around $7.5\text{ }\mu\text{m}$. This interpretation resolves the discrepancy encountered in previous analyses. However, it leads to three more questions:

- Why can the system not detect the interfaces between the Top layer and the Cap layer? Is this caused by the interfaces with high aspect ratio?
- What is the third layer measured in the region f ? If it is not any one of the five layers, is it the substrate of the MEMS device?
- If the system can detect substrate of the MEMS device in region f , why can the system not detect the substrate in region b , let alone the Cap layer?

It is difficult to explain the results estimated by the OCT system. The thickness of $418.5\text{ }\mu\text{m}$ (in vacuum) is far beyond the designed value of $300\text{ }\mu\text{m}$ and is too small to be considered as a combination of a few layers.

In conclusion, both systems can measure the thickness of silicon layers and they are self-consistent in measuring the same layers. With a large field of view, only one measurement was required by the OCT system to measure all regions of the TERPS. The maximum field of view is 7 mm along X -axis and no limit on Y -axis. However, the system can only measure up to two layers of the TERPS, with a design thickness of $450\text{ }\mu\text{m}$. The measurements using the IRC included a series of scans, which is time-consuming. However, the machine has a better depth of view, where a thickness of approximately $800\text{ }\mu\text{m}$ of silicon can be measured.

Both the OCT and IRC systems are not able to measure the internal structures below surfaces with high aspect ratio as the scattered light may not be detected by the optical system. Also, both systems produce artificial components in the measurements. The artificial components shown in the OCT measurement results may be due to the Fourier transform [10] and the one shown in the measurement results of the IRC system may be caused by the internal reflection between layers.

For unknown reasons, both systems have encountered problems when measuring region f and there is ambiguity in defining the layers that they have detected. Further study of this issue requires detailed calibration information of the TERPS sample.

7 Discussion

This report studied the measurement of MEMS internal geometry using non-contact, non-destructive methods. Two systems, based on OCT and IRC have been chosen. The understanding of the two systems has been achieved by studying a wide range of aspects, such as axial resolution, lateral resolution, field of view and depth of scan. The optical resolution of the systems has been studied in more detail. It revealed that the OCT system has a better axial resolution and the IRC has a better lateral resolution. Also it concluded that the IRC system has a larger depth of view in measuring thickness of silicon layers and the OCT system has a wider field of view.

The performance of the beam axis of both instruments has been calibrated by measuring a 50 μm thickness artefact that had been calibrated using a traceable stylus instrument. The standard uncertainties associated with the measurements of the thickness artefact are 0.391 μm for the OCT system and 1.085 μm for the IRC system (50 $\times$ objective). The capability of the two systems has been extensively investigated via measuring a few MEMS devices. It has been concluded that both the OCT and IRC system are capable of measuring internal geometry of MEMS devices, to a certain extent.

The advantage of the OCT system is clear, in that it provides volumetric data of measured samples. Fast scanning speed allows the measurement to be completed within minutes. The system provided by Michelson Diagnostic utilises four beam channels, which provides a better lateral resolution over conventional designs. The optical theoretical axial resolution is less than 2 μm (in silicon) and lateral resolution is less than 7 μm . However, as a new technology introduced in dimensional metrology, there remain some issues:

- The user cannot view overall sample structure prior to measurement. Therefore, it is a challenge to locate the sample if the structure is complicated and embedded inside the sample. The development of associated software is still in its early stage. The current software only implements measurement functions and does not include functions to view and analyse data.
- The autocorrelation and dc noise reduce the sensitivity of the measurement results [9] and the noise can affect the optimisation process mentioned in section 3.
- The limited number of sampling points along the beam axis is a limitation. Only about 400 data points can be used in data processing, though each channel produces effectively 512 data points. The beam axis scale of a pixel of 1.59 μm is very close to optical axial resolution of 2.85 μm . A maximum of 4 points along the intensity profile in experiments can be used to resolve a surface point. This significantly limits the ability of the system in resolving the internal geometry of a sample.

Compared to OCT, microscopy is a more sophisticated technology for use in metrology. The IRC system is similar to a conventional confocal microscope. The advantage of the IRC system is that the “3D” mode allows the user to easily observe the internal geometry prior to measurements. This function can be extremely useful when examining a sample with

complicated internal geometry. Different objectives allow users to have more flexibility in measurements. Volumetric measurements are not available in the current software package. Although, in theory volumetric data can be constructed by stacking a series of scans along y-axis using the “XZ” mode, it can be time-consuming.

The study of MEMS internal geometry is still in its early stage. There are a few issues that are worthy of further study in the future:

- One issue is the visualisation and analysis of volumetric data. A good visualisation should reflect the real sample geometry. Thus the refractive index corresponding to different media should be applied. This involves defining the boundary between media.
- Axial resolution is critical in measuring layer thickness of MEMS devices. Unlike lateral resolution, axial resolution varies with respect to materials. At present, study of the resolution inside silicon is still in its preliminary stage. In theory, experimental results can be achieved by measuring the point spread function in silicon. However, it may be difficult to mount such a small particle and it will be even more difficult to measure it as it may not be visible to the human eye inside silicon.
- In the measurement of the TERPS sample, the overestimate and underestimate of layer thickness may be caused by the nonlinearity of the measurement systems. To rule out this possibility, calibration of beam axis has to be extended to the full capacity of the systems. A MEMS device with calibrated internal geometry will be desirable in investigating this issue.

Measurements of MEMS internal geometry are new to OCT and IRC systems. Both systems show great potential in this field. Although there is still much work to be done to enhance their performance, this does not hamper these technologies from being applied in MEMS thickness measurements and eventually these technologies will improve the manufacture of MEMS devices.

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References

- [1] Reilly S P, Leach R K, Cuenat A, Awan S A and Lowe M 2006 Overview of MEMS sensors and the metrology requirements for their manufacture *NPL Report DEPC-EM 008*
- [2] Robinson A and Leach R K 2008 Overview of tomography techniques to measure wafer thickness in MEMS structures *NPL Report ENG 8*
- [3] Fercher A F, Drexler W, Hitzenberger C K and Lasser T 2003 Optical coherence tomography—principles and applications *Reports on Progress in Physics* **66** 239-303
- [4] ImageJ Website: rsbweb.nih.gov/ij/ Accessed on 02/03/2010
- [5] Voxx The Trustees of Indiana University Website:
www.nephrology.iupui.edu/imaging/voxx/ Accessed on 02/03/2010
- [6] Drishti Website: anusf.anu.edu.au/Vizlab/drishti/ Accessed on 02/03/2010
- [7] ImageVis3D Website: www.sci.utah.edu/cibc/wiki/index.php/CIBC:Project:ImageVis3D Accessed on 02/03/2010
- [8] SiMETRICS GmbH Website: www.simetrics.de/pdf/TS.pdf Accessed on 02/03/2010
- [9] Leitgeb R, Hitzenberger C and Fercher A 2003 Performance of fourier domain vs. time domain optical coherence tomography *Opt. Express* **11** 889-894
- [10] Zhang J, Nelson J S and Chen Z 2005 Removal of a mirror image and enhancement of the signal-to-noise ratio in Fourier-domain optical coherence tomography using an electro-optic phase modulator *Opt. Lett.* **30** 147-149
- [11] VIM 2008 International vocabulary of metrology - basic and general concepts and associated terms (International Organization for Standardization)
- [12] Tomlins P H and Wang R K 2005 Theory, developments and applications of optical coherence tomography *J. Phys. D: Appl. Phys.* **38** 2519-2535
- [13] Tomlins P H, Ferguson R A, Hart C and Woolliams P D 2009 Point-spread function phantoms for optical coherence tomography *NPL Report OP 2*
- [14] Optical properties of silicon Virginia Semiconductor, Inc. Website:
www.virginiasemi.com/pdf/Optical%20Properties%20of%20Silicon71502.pdf Accessed on 02/03/2010
- [15] Aspnes D E 1988 *Properties of silicon* (London: INSPEC)
- [16] Olympus Corporation Website: www.olympusfluoview.com/theory/resolutionintro.html Accessed on 02/03/2010
- [17] Haver T J 2007 The assessment and application of point spread function deconvolution to high pressure fluorescence microscopy imaging (Miami University. MSc Thesis)
- [18] Shaw P and Rawlins D 1991 The point-spread function of a confocal microscope: its measurement and use in deconvolution of 3-D data *J. Microscopy* **163** 151-165
- [19] Olympus industrial microscopes: LMPlan-IR/Mplan-IR for infrared light observation Website: industrial-microscope.olympus-global.com/en/ga/product/uis2/lmplan-ir/ Accessed on
- [20] Yoo H, Song I and Gweon D-G 2006 Measurement and restoration of the point spread function of fluorescence confocal microscopy *J. Microscopy* **221** 172-176
- [21] Jiao S and Ruggeri M 2008 Polarization effect on the depth resolution of optical coherence tomography *J. Biomed. Opt.* **13** 060503
- [22] Rodgman D and Chen M 2006 Refraction in volume graphics *Graphical Models* **68** 432-450