MINIMISING SPHERICAL ABERRATIONS

Temperature-controlled optical profilometry has historically been a difficult procedure due to imaging issues caused by spherical aberrations. In this case study, Linkam Scientific Instruments and Sensofar Metrology demonstrate an experimental set-up in which these problems have been minimised. Using Linkam's precision temperature control chamber with Sensofar's Linnik objective lens allows accurate measurement of 3D topographic profiles of nanoscale materials. As an example, the changes in the topography of silicon wafers as they evolve with temperatures from 20 up to 380 °C are presented.

ROBERT GURNEY AND DAVID PÁEZ

Introduction

Rapid thermal processing (RTP) is an important step in the manufacturing process of silicon wafers. The wafer is rapidly heated to high temperatures for a short period of time, and then slowly cooled in a controlled manner, in order to impart the desired semiconducting properties to the wafer. However, RTP causes thermal stress leading to problems in photolithography that may affect the performance of the device, such as breakage due to thermal shock or dislocation of the molecular lattice. Understanding the behaviour of a wafer under these conditions can help optimise the process, improving semiconductor properties and wafer durability.

A key method of evaluating the effects of temperature change during wafer manufacturing is to measure the surface roughness of the wafer as a function of temperature. To do this, the surface roughness is observed by an interferometric technique in conjunction with using a thermal chamber, allowing the temperature to be raised to values similar to those during the manufacturing process, while inspecting the sample through microscopy.

There are several factors that introduce some complexity in obtaining these interferometric measurements. Firstly, in order to visualise the sample and obtain the data while accurately controlling the temperature in the chamber, it is necessary to make observations through the chamber's optical window. The window is 0.5 mm in thickness, but in some cases, this can be as much as 1 mm, depending on the degree of thermal insulation required. This window, being of a different refractive index to air, introduces optical aberrations and misalignments that, when analysing silicon wafers, should be corrected in order to obtain reliable data.

Furthermore, when the temperature inside the chamber is increased, heat is emitted to the exterior through the observation window, and this is not ideal for optical microscopy. In the air close to that window, the temperature can reach levels up to 60 °C, which can lead to deformation of the objective lens, again introducing aberrations.

This work presents a study of the effect of the RTP process on silicon wafers while accounting for optical aberrations brought about by temperature changes. Two samples were used, corresponding to different chip designs from silicon wafers. Sample A was 2.8 mm x 1 mm in size, whereas sample B was 3.0 mm by 2.35 mm. Silicon wafers have typical surface roughness values at the sub-micron scale, so the ideal optical technology for this application is coherence scanning interferometry (CSI, ISO 25178, part 604). CSI introduces only 1 nm of measurement noise, regardless of the magnification of the lens being used.

Optical configuration

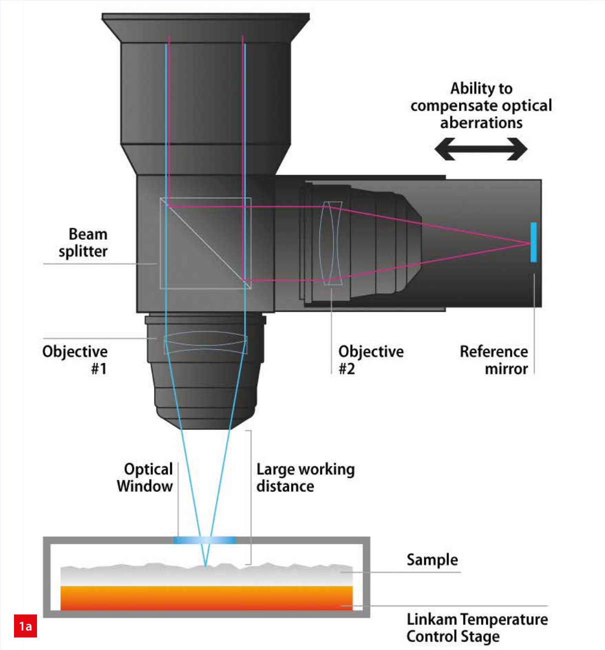
In order to address the experimental issues of interferometry at varying temperatures, a Linnik interferometer is used. Such a two-beam interferometer introduces the use of measurement optics within the reference arm of a classic interferometer. This allows for compensation and correction of the aforementioned effects of the optical window, such as chromatic dispersion and optical aberrations, which enables employing brightfield objectives that have a greater working distance than traditional interferometric objectives.

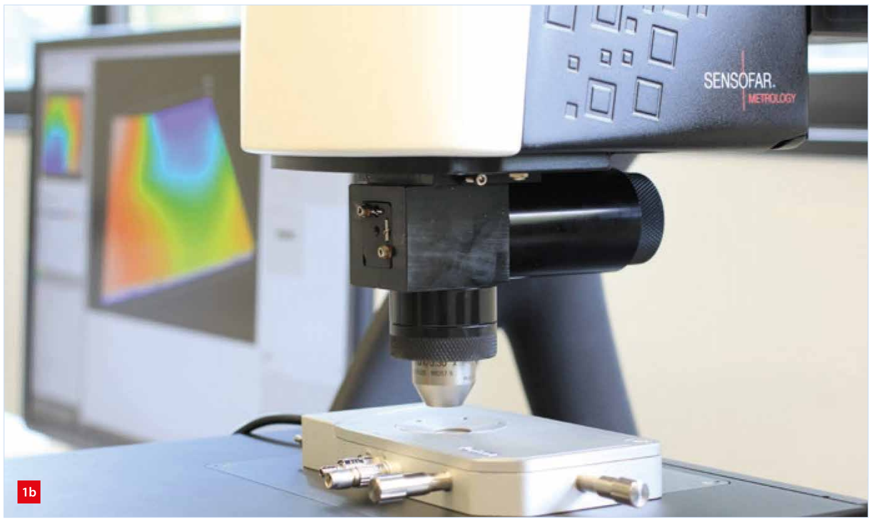
The optical configuration is shown in Figure 1. For the design and construction of the Linnik objective, two Nikon 10x EPI objectives (MUE12100) with 17.5 mm working distance were used. The same configuration is available with 10x SLWD objectives (Nikon, MUE31100), providing a 37 mm working distance. This makes the thermal emissions from the camera almost imperceptible to the lens and will not affect or damage the measurement quality. The Linnik

AUTHORS' NOTE

Robert Gurney is a marketing and applications specialist at Linkam Scientific Instruments, located in Salfords (UK). David Páez is a product specialist at Sensofar Metrology, headquartered in Barcelona (Spain).

paez@sensofar.com
www.sensofar.com
www.linkam.co.uk





The optical configuration featuring the Sensofar optical profiler with the Linnik objective and the Linkam temperature control stage.
(a) Schematic.
(b) Experimental set-up.

objective was mounted on a Sensofar 3D optical profilometer (S neox), which combines four optical technologies in the same sensor head: confocal, CSI, PSI (phase shifting interferometry) and focus variation. These techniques are covered in ISO 25178.

The temperature is controlled using a Linkam LTS420 chamber and the T96 temperature controller, which allows the temperature to be ramped and controlled between −195 and +420 °C to a precision of 0.01 °C, while the sample roughness is observed through the chamber window. The chamber also allows control of the pressure and humidity, but this has not been investigated here.

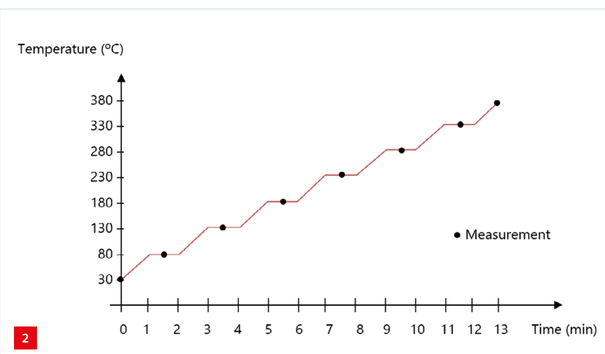
Experiments

The wafer sample was placed in the Linkam chamber under the S neox optical profiler with the Linnik configuration. The acquisition routine consisted of ramping the temperature from 30 to 380 °C in steps of 50 °C, taking eight topographic measurements of the sample at each step (Figure 2). This procedure was repeated for two samples.

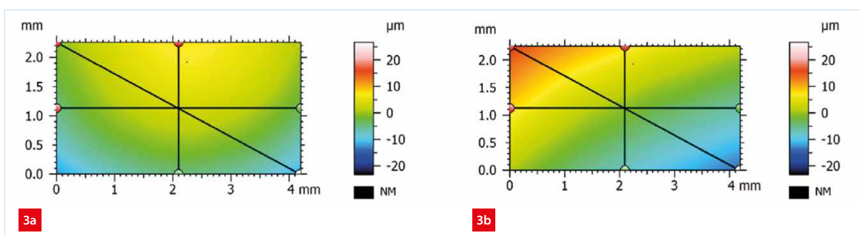
Using Sensofar's SensoMAP software, the results were visualised and analysed by creating a template and applying it to all samples. The template extracts three profiles in each topography (horizontal, diagonal, and vertical) and their representation in the same plot, and furthermore builds a sequence of the topographies to export it as a video and represent it in a 4D plot.

Two topographic images of sample A were imaged using the above methodology and are shown in Figure 3 as 2D height maps. The three solid lines represent the three different profiles (horizontal, vertical and diagonal) extracted for each topography. The profiles in each direction are shown in Figure 4, where we can see the evolution for the different temperatures at which the sample was taken. The images show that when heating the sample, its topography changes.

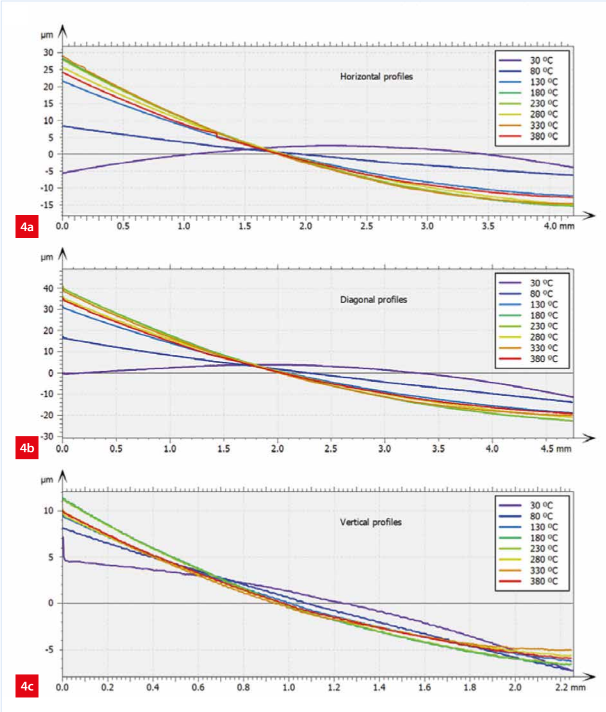
The data can be plotted in 3D topographic images as shown in Figure 5. By stacking the 3D images as a function of temperature, creating a "4D plot", showing the topographical changes at different temperatures using the same height colour scale, it is demonstrated how the samples



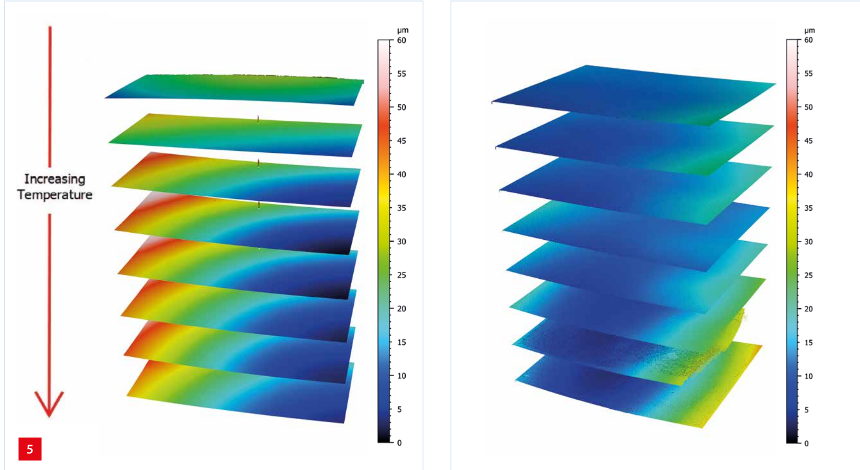
Time-temperature graph showing the temperature steps at which optical measurements were taken.



2D height maps showing the topography of sample A at different temperatures. The black lines indicate the three directions at which profiles were taken for further studies.
(a) 30 °C.
(b) 80 °C.



Profiles extracted in different directions from the measurements of sample A at eight different temperatures.
(a) Horizontal.
(b) Diagonal.
(c) Vertical.



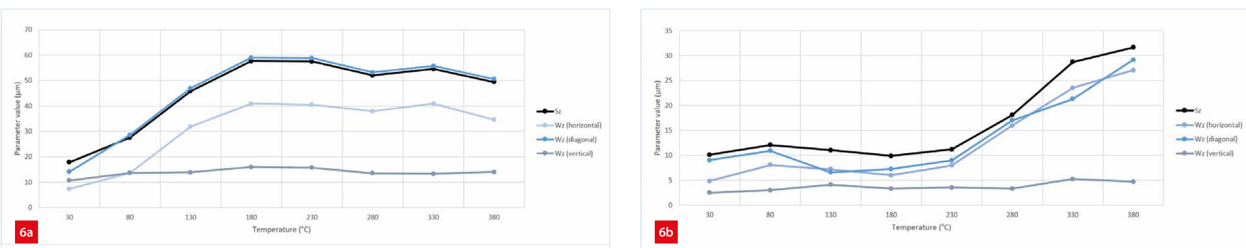
Stacked 4D view of the topographies extracted from samples A (left) and B (right) for visual comparison of the observed bow change when samples go from 30 to 380 °C. The scale on the right of each graph runs from 0 to 60 µm.

bend as temperature changes. It is clear that the higher the temperature, the greater the bending experienced by the samples. To quantify the bow of the samples, two different parameters were used. The first is S_z, which is the surface roughness parameter for the maximum height of a surface according to ISO 25178. The second is W_z, corresponding to the (1D) counterpart of S_z in profile analysis (ISO 4287). Both S_z and W_z were obtained after applying an S-filter to the surface (or profile) with a 0.8 mm cut-off. In this way, only the longer spatial wavelengths remain on the surface, getting rid of roughness and only leaving waviness for bow analysis.

The resulting parameters for samples A and B are depicted in Figure 6. For sample A, an almost-linear relationship between bow and temperature is observed up to 180 °C, after which the bow stabilises from 180 to 380 °C. On the other hand, sample B did not show any noticeable bow change until the temperature rose above 230 °C.

Conclusion

The feasibility of the proposed configuration has been proven by successful roughness and waviness measurements at different temperatures. Two different behaviours of the surface topography were observed, depending on the chip design. Sample A showed an early bending behaviour when heating up the sample, whereas sample B exhibited bending at a later stage. The S neox 3D optical profiler with a Linnik objective has been shown to be a fitting complement for Linkam's LTS420 chamber to perform such experimental measurements. Moreover, different brightfield objectives are compatible with the Linnik configuration, offering working distances up to 37 mm and magnifications up to 100x for applications that require high lateral resolution.



Bow evolution in two samples as a function of temperature. Waviness parameters W_z were extracted from the horizontal, diagonal and vertical profiles in Figure 4. Roughness parameter S_z was computed from the surface roughness. All parameters were obtained after applying an S-filter of 0.8 mm.
(a) Sample A.
(b) Sample B.