White Light Interferometry – a production worthy technique for measuring surface roughness on semiconductor wafers

Roy T. Blunt

IQE (Europe) Ltd., Cypress Drive, St. Mellons, Cardiff, CF3 0EG, UK.
e-mail: rblunt@iqep.com Tel:+44 (0) 2920 839400

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Abstract

Reproducible, quantitative, and rapid surface roughness measurements would be valuable in many aspects of semiconductor and optical technology – e.g. routine assessment of polished substrates and of epitaxial layers. However, such measurements are rarely made – probably because most measurement techniques available have serious disadvantages in a production environment. In this work we have used white light interferometry to measure a range of semiconductor surfaces. This technique offers many advantages in terms of measurement speed, ease of use, reproducibility and freedom from damage or contamination. The fundamentals of the technique are described and results obtained on a wide range of semiconductor surfaces discussed. Results are shown to be comparable to those obtained by AFM and to show excellent long term reproducibility and stability.

INTRODUCTION

The ideal inspection technique for surface roughness measurement (indeed, for measurements of almost any parameter) would be truly contactless, objective, reproducible, and ideally assess the full area of the wafer or, at least, a statistically significant fraction of it. The measurement should also be fast - a lengthy inspection time is undesirable for either production or cleanliness reasons.

Optical microscopy using Nomarski interference contrast is still by far the commonest procedure used for assessing surface roughness in semiconductors. Whilst being extremely sensitive and giving a real image of the surface, it is subjective and, even if partially automated, is slow and tiring for an operator – particularly if a full 150 mm diameter wafer is to be scanned at any reasonable magnification. More automated techniques using light scattering (such as the KLA-Tencor Surfscan) have the advantage of being fast, objective, and scan the full area of the wafer, but are essentially surface particle detectors rather than roughness measuring instruments and do not produce a real image of the surface. These machines produce a 'haze' output (and map of the entire wafer surface) which is related to surface roughness but can be very difficult to interpret – particularly for 'optically active' surfaces where the optical reflectivity can vary. Both X-ray reflection and optical ellipsometry can produce quantitative surface roughness measurements over small areas by fitting a model to the data but neither of these techniques can give an image of the surface. Atomic Force Microscopy (AFM) is probably the best conventional measurement method as it produces both an image of the surface and quantitative roughness measurements. However, except for very large and expensive fully automated units, it needs a relatively skilled operator and is not truly non-destructive as it involves a 'tapping tip' which can damage or contaminate some surfaces. In addition set-up and inspection times are lengthy and the area of inspection is quite limited (typically an AFM scan over a area of 50 x 50 µm takes several minutes to complete).

The issue of measurement area is an important point to be considered in all surface roughness measurements. A typical AFM scan of a 50 x 50 µm area only covers 1.4×10^{-5} % of the total area of a 150 mm diameter wafer. Thus measurements at multiple positions are required for any statistical significance – this increases total inspection time for an AFM to an hour or longer per wafer. Use of a 50 µm scan also means that any features approaching, or larger than, 50 µm in wavelength are ignored in the analysis.

White light interferometry has been used for many years as a reliable non-contact optical profiling system for measuring step heights and surface roughness in many precision engineering applications. It would seem to be an ideal technique - however sensitivity has previously been marginal for semiconductor surface roughness measurements. Recent developments in both instrumentation and in measurement software for this technique have increased the vertical (i.e. height) resolution of these instruments to give a capability of better than 0.01 nm (i.e. 0.1 Angstrom), which makes it a potentially practical tool for assessing good semiconductor surfaces. The main disadvantage compared to AFM measurements is that, being an optical technique, the ultimate lateral resolution is limited to around 0.35µm. However for routine examination of most semiconductor surfaces in common use this is not a severe limitation.

In this work a state-of-the-art White Light Interferometer (Taylor Hobson CCI 3000A) has been used to measure a wide variety of semiconductor substrates (III-Vs, silicon, sapphire, etc) and epitaxial layers under production conditions in a clean room environment. A x50 objective lens allows this machine to measure a sample area of approximately 300 µm x 300 µm (imaged onto a CCD array of 1024 x 1024 pixels) with a working distance of 3.4 mm between lens and wafer, and a measurement time of one to two minutes at this roughness level (around 0.1 to 0.2 nm). Wafer-to-wafer set up time is very short (particularly when dealing with a series of wafers with very similar overall thickness), as is set up time when moving from place to place on a given wafer. Lower magnifications can be used to enable larger areas to be examined but this will increase the minimum achievable lateral resolution. The machine is similar in size and shape to a high quality microscope and has been used in standard cleanroom conditions without an environmental cabinet to protect it from local airflows – however some slight modifications have proved necessary to achieve the required level of performance under these conditions.

Optical interference is a widely known and used technique [1]. The basic technique involves splitting an optical beam from the same source into two separate beams – one of the beams is passed through, or reflected from, the object to be measured whilst the other beam (the reference) follows a known and constant optical path. The same basic principle can be used in a microscope arrangement as shown in Fig 1.

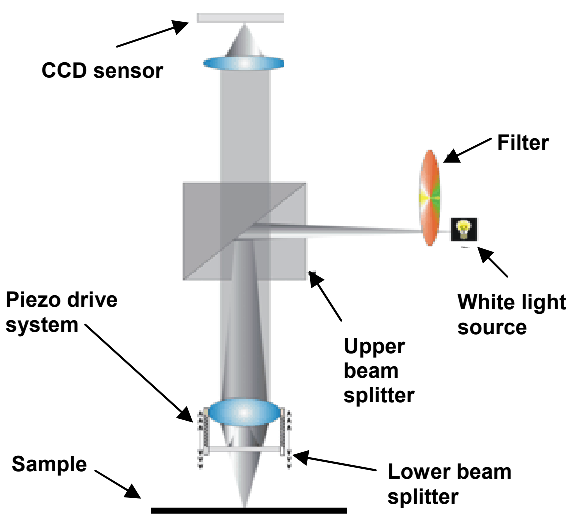


Figure 1 Schematic diagram of an interference microscope

Here a light source provides a beam which is passed through a filter and reflected by the upper beam splitter (acting essentially as a mirror at this stage) down to the objective lens. The lower beam splitter in the objective lens creates and combines the light beams reflected from the sample surface and the reference surface in a Mirau type interferometer arrangement as shown in figure 2. This creates an interference pattern of light and dark fringes (an interferogram) which is magnified by the microscope optics and finally imaged by the CCD camera. This static fringe image would show differences in distance apart of the reference and sample – essentially revealing local 'bow and warp' of the sample. However if the objective lens is moved vertically the path length between sample and beam splitter changes and creates a series of moving interference fringes which will be detected by the camera. The aim is to establish the point at which maximum constructive interference occurs

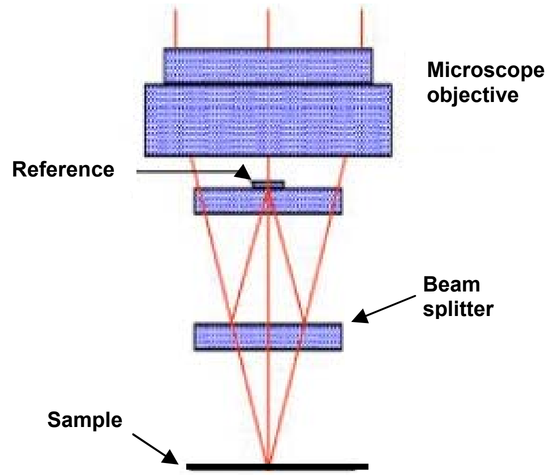
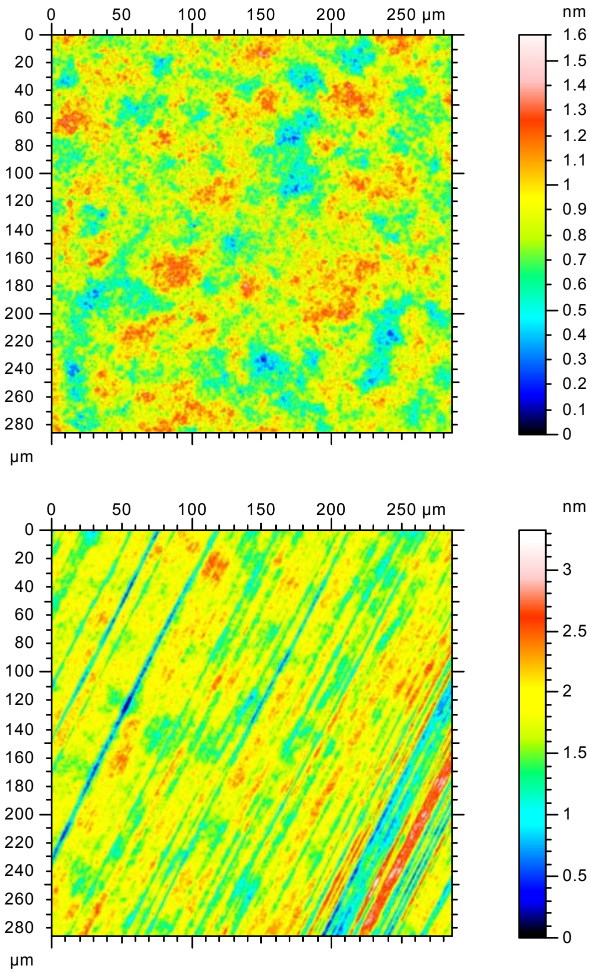


Figure 2 Schematic diagram of a Mirau type interferometer

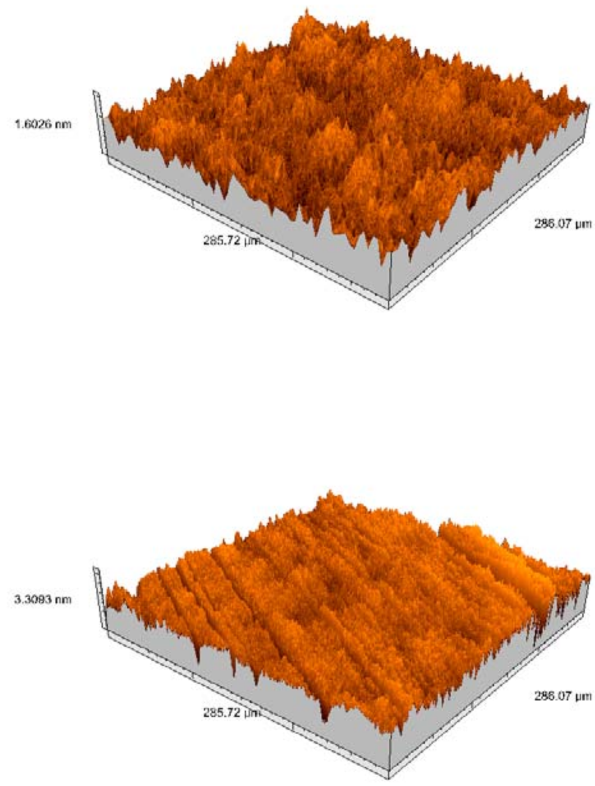
(i.e. at which the image is brightest). Once this is achieved, provided the vertical movement of the lens can be accurately tracked, it is possible to create a 3D map of the sample surface by measuring the position of the lens required to produce the brightest image at each point on the CCD array. This would normally be carried out using a monochromatic light source – however there could be several different positions at which a maximum in the signal would occur. By using multiple wavelengths (and white light is the ultimate case) it is possible to set the system up so that there is only one point at which this maximum occurs. The only limit on the achievable height resolution is set by how well the measurement algorithm can define the maximum brightness (and thus the surface position) as the objective lens is scanned vertically using a piezo-electric drive. Modern systems are very good at achieving this and the system used here (Taylor Hobson CCI 3000A) employs a patented correlation algorithm [2] to find both the coherence peak and phase position of an interference pattern produced by a white light source. Each pixel of the CCD array effectively acts as an individual interferometer and thus builds up a very accurate map of the surface.

RESULTS

Figures 3a & b show examples of 'good' and 'damaged' GaAs substrates measured using the technique and displayed using a 'false colour' image where the height information is represented by colour changes. We have found that this to be



Figures 3a (top) & 3b– Pseudo-colour CCI images of ‘good’ (rms roughness 0.18 nm, average roughness 0.14 nm) and ‘damaged’ (rms roughness 0.35 nm, average roughness 0.28 nm) semiconductor substrates



Figures 4a (top) & 4b – ‘3-dimensional’ presentations of data from figures 3a & 3b

probably the most generally useful representation of the surface for applications where colour presentation is available. However the data can also be processed to give a ‘pseudo 3 – dimensional’ presentation (figures 4 a & b) which give a more physical representation of the surface. In addition it is possible to display the data as a pseudo photographic interpretation (similar, in some ways, to a Nomarski microscope image) or it can be reduced to a simple 2D profile between any two points on the surface. This is less important in substrate/epitaxy surface investigation but would be very useful in inspection of processed devices.

Obviously, for any technique to be used successfully it must be demonstrated that it gives results in agreement with more established techniques. A valid direct comparison of three dimensional surface roughness measurements between different machines and techniques can only be made if the measurement techniques and analyses applied are capable of making similar measurements over similar areas – essentially the different techniques must produce a similar effective bandwidth of data. In the case of line profiling techniques using different stylus profilers this is not particularly difficult to understand – the main considerations tend to be stylus radius together with horizontal and vertical resolution and sensitivity. However the situation with the area profilers is somewhat more complicated as the manner of data gathering is totally different. Thus data treatment (so-called ‘filtering’ - which is applied in all area measurement techniques) must be carried out carefully to enable a valid comparison to be made. This is a complex topic – a good but reasonably brief introduction to this is given in SEMI Guidelines [3], [4].

In view of these difficulties, comparison of results (particularly at this level of roughness) should be treated with some caution. However comparison of optical measurements with AFM measurements (which, despite its limitations as a production technique, probably remains the only truly valid comparison for surface roughness measurements at this level) obtained during this work show a generally good agreement in the working area of interest as shown in Figure 5.

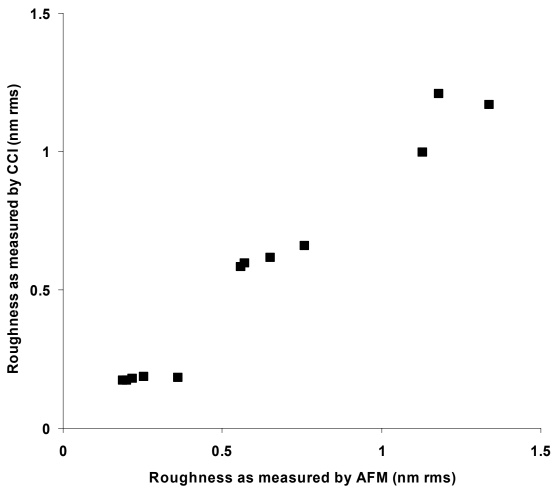


Figure 5 – CCI determined roughness values vs. AFM determined values

Any viable production worthy measurement technique must also be stable over a long term period. The data given in table 1 has been derived from weekly measurements on the same area of a polished sapphire substrate taken over a period of some six months. Sapphire was used because of its mechanical robustness and lack of long term oxidation effects. The stability shown is impressive for any measurement technique operating at these levels.

TABLE 1
Long term stability of rms roughness measurements on sapphire

	nm	% (parameter expressed as % of average value)
Average rms roughness	0.190	100
Maximum “	0.196	103.2
Minimum “	0.183	96.3
Range	0.013	6.9
Standard Deviation	0.004	2.0

Although the results presented within this extended abstract have concentrated on substrate measurements on GaAs and sapphire the technique is equally useful on epitaxial layers and other materials. To date measurements have been made on all the normal epitaxial layers deposited on GaAs and InP substrates. Measurements have also been successfully made on GaN, InAs, GaSb, InSb, SiC, and Si based materials. Provided that there is a significant amount of reflection from the surface (probably in excess of 1%) it should be possible to measure almost any material using the technique. Besides measurements on polished surfaces and good epitaxial layers, excellent results have also been obtained on ‘lapped’ and on ‘as-sawn’ surfaces with surface roughness values upto 600 nm.

CONCLUSIONS

The results presented here show that White Light Interference is a production worthy technique for the measurement of surface roughness in semiconductor wafers. The technique is truly contactless, clean room compatible, rapid, and reproducible. Measurements agree well with comparable AFM measurements from the same areas. Although the area measured is still relatively small (about 300 µm x 300 µm – roughly 5.1 x 10^{-4} % of the area of a 150 mm diameter wafer) the speed of the technique allows multiple measurements over the area to be made quickly and easily to gather statistically significant data in a production environment.

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REFERENCES

[1] P.Hariharan, *Interferometers* in *Handbook of Optics,* McGraw Hill, New York, 1996.

[2] A. Bankhead, UK Patent Application 0206023.4

[3] SEMI Guideline M40-0200, *Guide for measurement of Surface Roughness of Planar Surfaces on Silicon Wafer.* SEMI, San Jose, California, USA, 2000

[4] SEMI Guideline M43-0301, *Guide for Reporting Wafer Nanotopography.* SEMI, San Jose, California, USA, 2001

ACRONYMS

CCI: Coherence Correlation Interferometry
AFM: Atomic Force Microscopy
SEMI: Semiconductor Equipment & Materials International
SOLADIM: Semiconductor and Optical Layer Analysis and Definition using Interference Microscopy
UK DTI: United Kingdom Department of Trade and Industry
rms: root mean square