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Infra-red interference patterns for new capabilities in Laser End Point Detection

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Abstract

Standard laser interferometry is used in dry etch fabrication of semiconductor and MEMs devices to measure etch depth, rate and to detect the process end point. However, many wafer materials, such as silicon are absorbing at probing wavelengths in the visible, severely limiting the amount of information that can be obtained using this technique. At infra red wavelengths around 1500nm and above, silicon is highly transparent. In this paper we describe an instrument that can be used to monitor etch depth throughout a thu' wafer etch. The provision of this information could eliminate the requirement of an 'etch stop' layer and improve the performance of fabricated devices.

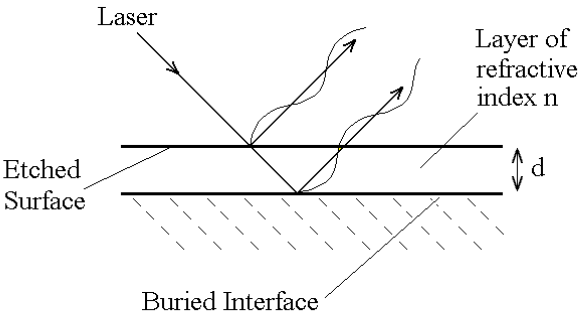
We have added a further new capability by using tuneable lasers to scan through wavelengths in the near infra red to generate an interference pattern. Fitting a theoretical curve to this interference pattern gives in-situ measurement of film thickness. Whereas conventional interferometry would only allow etch depth to be monitored in real time, we can use a pre-etch thickness measurement to terminate the etch on a remaining thickness of film material.

This paper discusses the capabilities of, and the opportunities offered by, this new technique and gives examples of applications in MEMS and waveguides

1. Introduction

Laser endpoint detection is a valuable technique for accurately determining the endpoint of the dry etch processes [ref. 1, ref. 2]. It is widely used in the processing of semiconductor, MEMS, 'lab on a chip' devices and integrated optical devices (e.g., waveguides). The basic principle is the generation of an interference pattern between reflections from the etched surface and one or more buried layers. For a single buried interface and non-absorbing material to be etched the situation is fairly simple (figure 1).

Figure 1: Interference, the basic principle of laser endpoint detection.



The phase shift (δ) between the two reflected waves is,

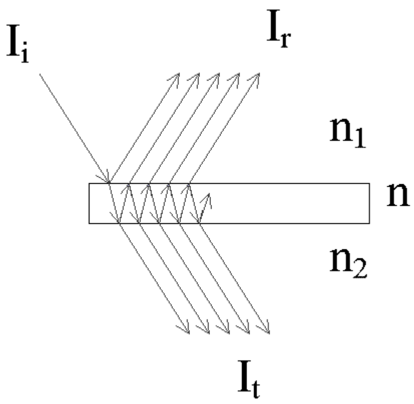
$$\delta = \frac{4\pi n d}{\lambda}, \tag{1}$$

where n is the refractive index of the etched material, d is the physical thickness of the layer and λ is the probing wavelength.

The reflected two waves will interfere constructively whenever they are in phase and destructively when they are out of phase. That is we have a maximum or minimum whenever $\delta = m\pi$ where m = 0, 1, 2, 3, 4, etc.

Part of the wave reflected at the buried interface is subsequently reflected at the air interface in addition to the transmitted component. Consequently, a series of internal reflections are established inside the film (or cavity) (figure 2).

Figure 2: Internal reflections within the monitored layer.

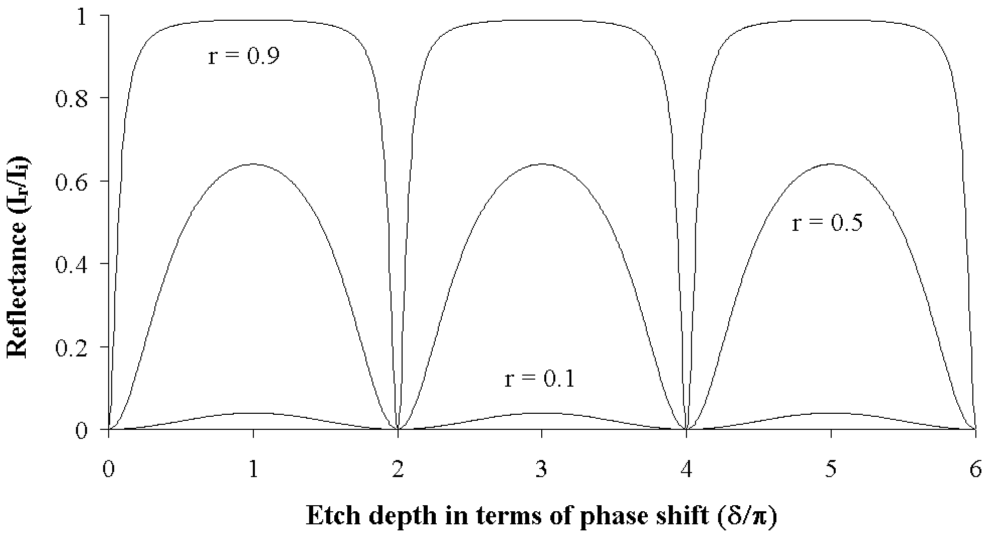


The resultant reflected intensity (I_r) for a beam on normal incidence and intensity (I_i) is described by,

$$\frac{I_r}{I_i} = 1 - A(\theta) = 1 - \frac{1}{1 + F\sin^2(\delta/2)}, \tag{2}$$

where A(θ) is the Airey function and F is the coefficient of finesse [ref. 3]. As the thickness of the film changes, as during an etch, the reflected signal intensity oscillates (figure 3).

Figure 3: The reflected signal as a surface is etched.



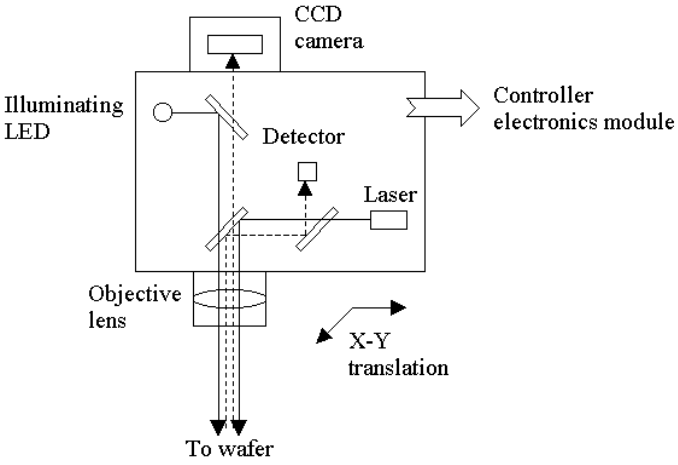
The period of the oscillation is determined by the refractive index of the material and the wavelength of the incident light. The etch depth between subsequent turning points ($\delta = \pi$) corresponds to the removal of an optical thickness of a quarter of a wavelength. When working with interferograms it is common to discuss thickness in terms of 'quarter waves'. The shape and amplitude of the reflected signal is determined by the coefficient of finesse, which is a measure of the reflectivity of the film interfaces (r).

$$F = \left(\frac{2r}{1 - r^2} \right)^2 . \tag{3}$$

2. Practical application of interferometry as a monitoring technique

The interferometer optical head, (figure 4) contains a coherent light source (laser), a lens arrangement to focus the beam on to the wafer and a photodetector to monitor the reflected signal strength. In addition, there is a confocal vision system, consisting of an ultra bright LED to illuminate the wafer pattern and CCD camera, and X-Y translation to allow the operator to select the measurement position.

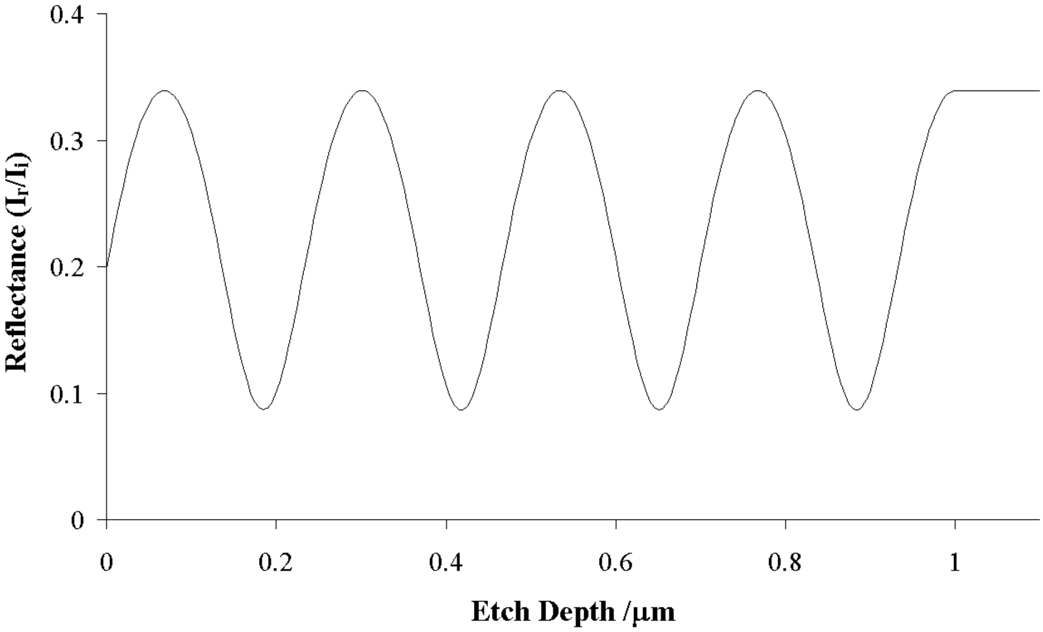
Figure 4: The light path within the Laser Endpoint Detector.



The endpoint system is controlled using dedicated Windows®-based software running on the electronics module. The software detects the endpoint by comparing the measured signal level against a user-defined model trace. The user can specify the structure of the wafer including film thicknesses and refractive indices and the software calculates the predicted interference waveform for the etch [ref. 1]. Then during the process the software will use shape comparison algorithms to calculate the etch depth and signal when the specified end point is reached

Figure 5, shows a sample model trace, taking the simple case of removing a micron of etch resist from a silicon wafer. As the etch resist is removed the calculated interference signal of the reflected light can be seen to pass through successive maxima and minima, until the bulk wafer is exposed and the incident laser light is reflected from only one surface, resulting in a constant signal level. The laser wavelength used in this model is 670nm, a widely available semiconductor laser diode.

Figure 5: The calculated interference waveform for the etch of 1 mm of photoresist on silicon.



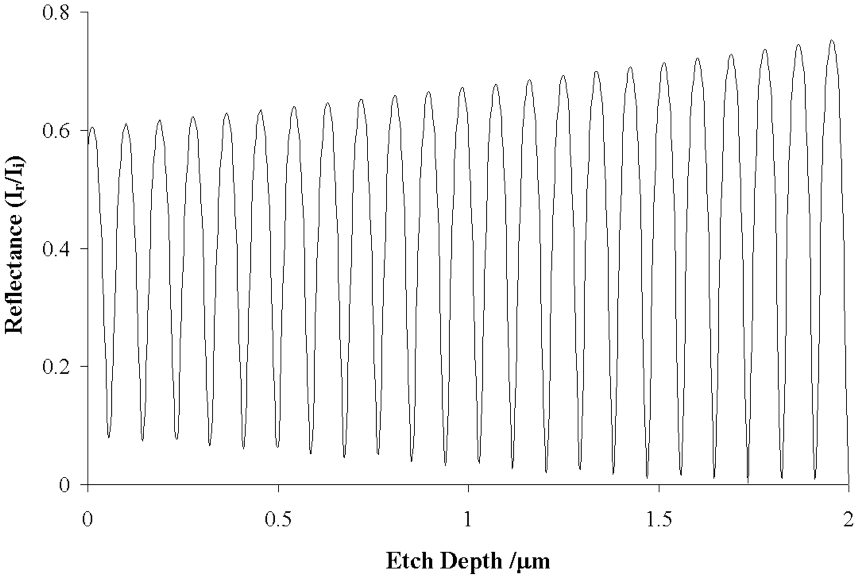
The application of predictive modelling is particularly useful in multiple layer etches, where the reflected signal level can be complex, for example MQW (Multiple Quantum Well) structures, Bragg gratings and VCSELs (Vertical Cavity Surface Emitting Lasers). Some of these laser structures can have hundreds of layers. The modelling software eliminates the need for calibration etches to be done, which can be expensive and time-consuming.

3. Absorbing materials & the application of infra-red probing wavelengths

However in many etches the situation is not this simple. For applications such as MEMS, ‘lab on a chip’ devices and integrated optical devices we may wish to etch tens or hundreds of microns into the wafer (typically silicon for these applications). However, silicon is absorbing to probe wavelengths in the visible spectrum, so interference fringes will not be observed when monitoring the etch of thick layers.

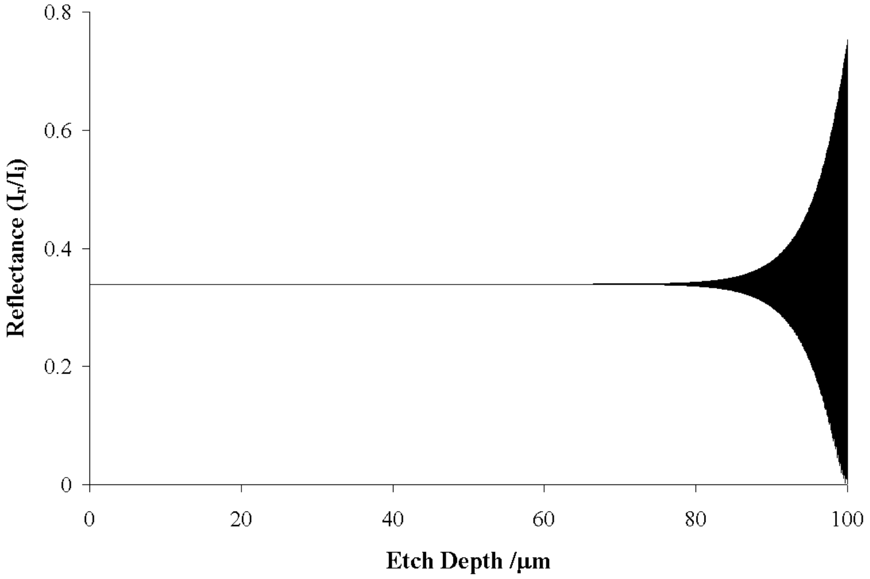
Modelling the theoretical curve for a 2 µm film of silicon monitored at 670nm shows the effect of absorbance on the measurement. The signal amplitude is significantly smaller at the beginning of the etch, but increases as the process progresses and the layer, as it gets thinner, becomes more transparent (figure 6).

Figure 6: Monitoring at 670nm, the effect of absorption is seen with only 2 mm of silicon.



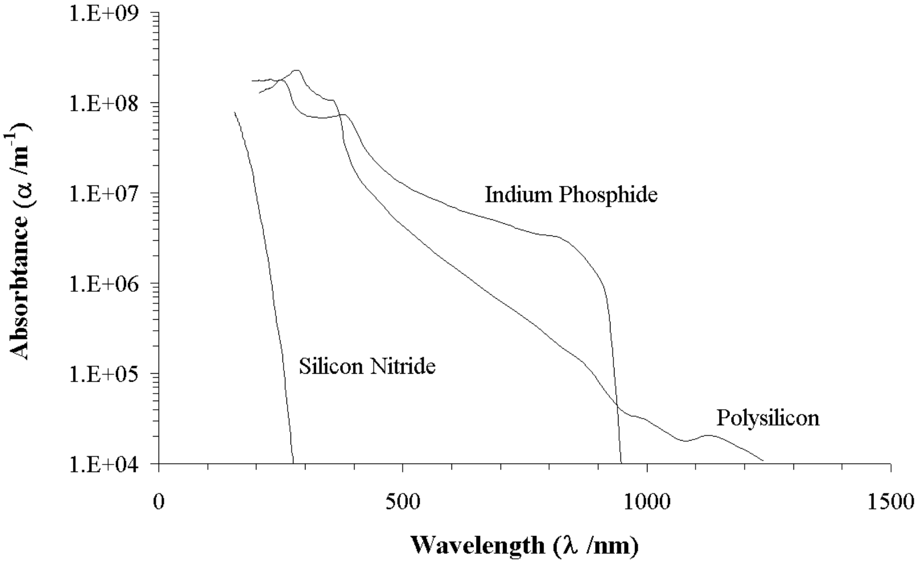
However, when considering a 100 µm layer of silicon, a more realistic case for MEMS applications, the effect is more significant (figure 7). For the majority of the etch the layer is opaque, so the etch rate and depth cannot be calculated and an endpoint cannot be found within the layer.

Figure 7: In 100 mm of silicon the absorption reduces the amplitude of the 670nm monitor signal to zero (only the envelope of the oscillations is seen here).



A common solution adopted to the problem of endpointing in an absorbing material is to incorporate an etch stop layer in the wafer structure at the desired end point depth. The material of this layer will usually be highly selective to the main etch chemistry. The endpoint can then be identified using optical emission spectroscopy, simple reflectometry or possibly just by timing, but no information can be obtained about the etch rate or etch depth as the process progresses. The exposed stop layer is then removed usually with a wet etch. However, the use of an etch stop layer is inefficient, since in order to use this method additional fabrication steps are required. More critically, the stop layer material left behind (beneath the masked region) can affect the performance of the device being manufactured. This is the case in the dual damascene etch [ref. 4], where the relatively high dielectric constant of the stop layer, increases the capacitance, so reducing the device speed [ref. 5]. Therefore it would be advantageous to utilise a probing wavelength where the material is transparent. Figure 8 shows the absorbance coefficient for several materials commonly processed in dry etches.

Figure 8: The absorption coefficient of several commonly etched materials [ref. 6].

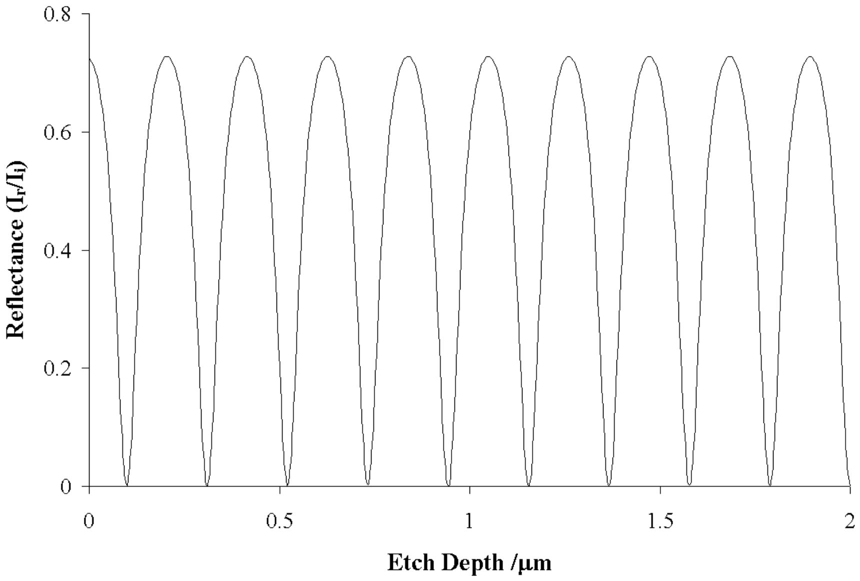


Clearly to 670nm silicon nitride is transparent, but materials like indium phosphide and silicon are not transparent until the probing wavelength is in the near infra red. Indium phosphide becomes transparent above 980nm and silicon above 1250nm.

In order to monitor silicon etches, Intellemetrics has developed an IR interferometer endpoint detector capable of utilising probing wavelengths between 1390-1640nm. Since optical telecommunications operate within this wavelength range there are numerous suitable components available for the opto-mechanical design and the refractive index of silicon is well defined enabling greater accuracy in physical depth measurements. However, since silicon is transparent in this wavelength range, standard silicon CCDs and photodetectors cannot be used. Therefore, an InGaAs detector and a phosphor coated CCD were employed.

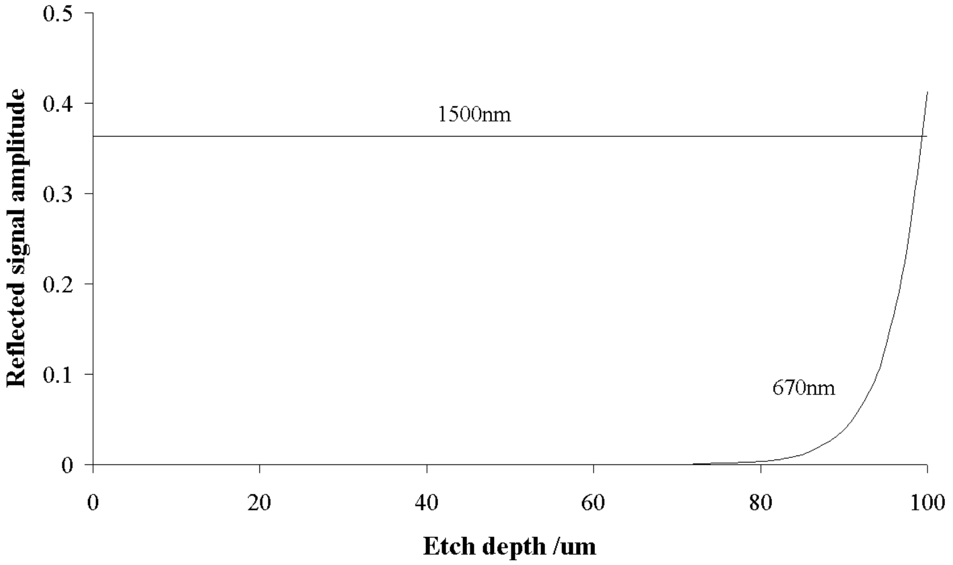
The theoretical interference signal for a 2 μm silicon etch monitored at 1500nm is shown in figure 9. This does not show the decreasing signal seen in figure 6 as there is now negligible absorption of the laser wavelength within the silicon.

Figure 9: A constant amplitude interference pattern seen when modelling at a wavelength of 1500nm, where silicon is not absorbing.



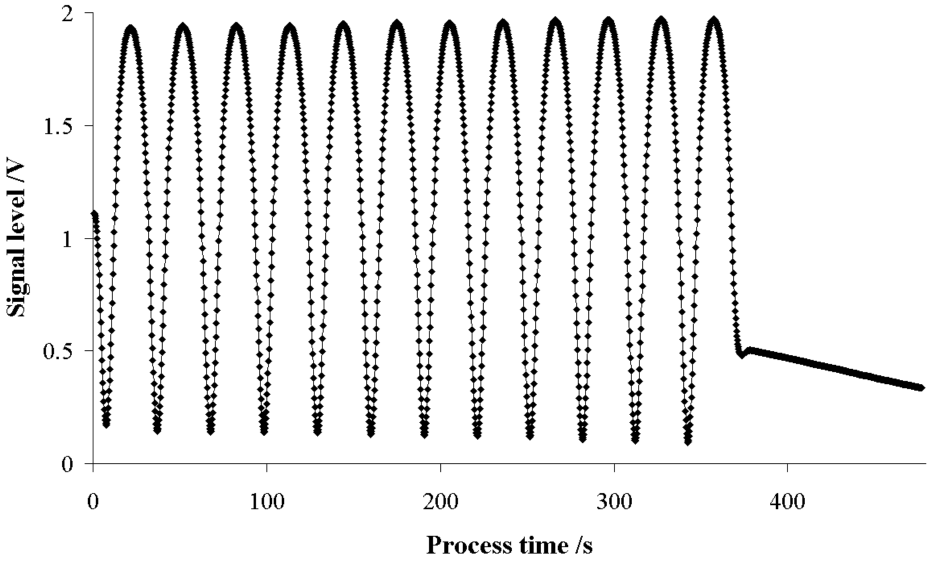
We saw in figure 7 that for etching 100 µm of silicon the amplitude of the interference pattern is below a measurable level once more than 15 µm of silicon is probed with a 670nm laser. Figure 10 compares this amplitude to that calculated when the etch is probed using a 1500nm source. This clearly shows there in no effect of absorbance on the reflected signal at 1500nm, thus enabling etch depth information to be extracted throughout a process.

Figure 10: A comparison of the reflected signal amplitudes in modelled etches of 100 mm of silicon probed at 670nm and 1500nm.



The endpoint system has been used to monitor several shallow and deep (see section 5) silicon etches, on both SOI and double polished bulk silicon wafers. Figure 11 shows the measured interference trace obtained from monitoring the etch of 2.5µm of epitaxially grown silicon above a buried silicon dioxide film using a probe wavelength of 1500nm.

Figure 11: The interference trace from an SOI etch monitored using Intellemetrics' IR end point detector [ref. 7].



Clearly, the amplitude of the signal does not undergo any significant change, as opposed to what is observed in a visible wavelength system. This allows the etch rate and depth to be continually calculated enabling an endpoint anywhere in the silicon layer to be targeted. The etch rate (R_E) is calculated using measured process data from which the time between turning points (quarter wave time, t_{QW}) can be extracted and the calculated model, which holds information about the optical thickness at any depth.

$$R_E = \frac{\lambda}{4nt_{QW}}. \tag{4}$$

For the process in figure 11, the silicon etch rate is approximately 0.4µmmin^{-1}. Once the oxide layer is exposed, the measured signal level changes less rapidly, due to the lower refractive index and high selectivity of the buried layer. This marked change in behaviour can be repeatabley identified by using non-linear filters in order to endpoint at this interface, as is required in some process steps for the fabrication of waveguides and MEMS devices.

The termination accuracy of Intellemetrics' IR laser endpoint detector has been compared with the measurements taken using an offline metrology tool. Four etches were performed on SOI wafers with a top silicon layer of approximately 10µm. The end point target depth in each case was set close to 5µm. After the etch, the mask material was removed using a wet process and a step profilometer used to obtain four depth measurements around the wafer feature on which the endpoint laser had been focussed. The results, displayed in table 1, show very good levels of accuracy and repeatability (< 0.2%).

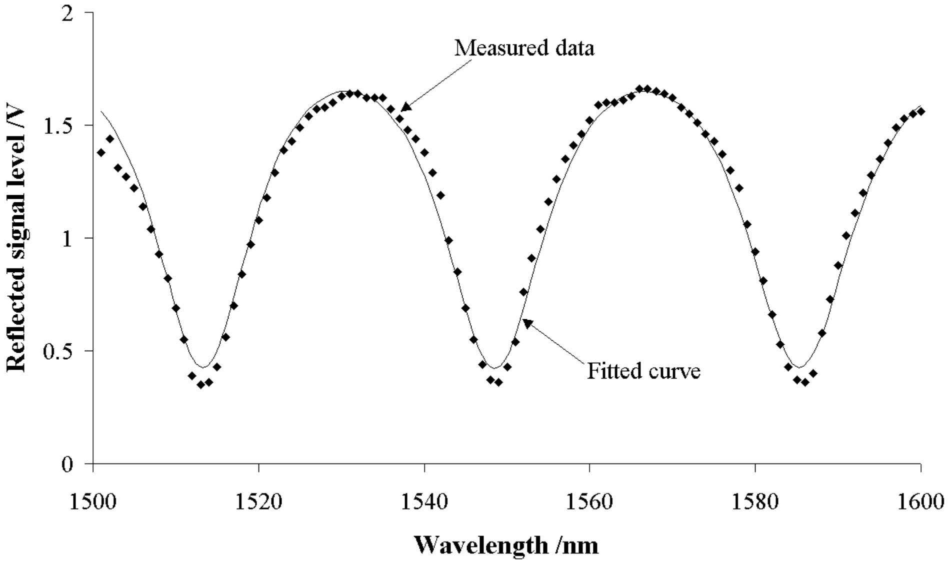
Table 1: A comparison of the endpoint target depth against ex-situ profilometer measurements [ref. 7].

Endpoint target depth /nm	Mean profilometer measurement /nm	Difference /nm	Difference /%
4993	4989	4	0.08
5000	4995	5	0.1
4959	4969	10	0.2
4978	4980	2	0.04

4. Wavelength scanning

In our introduction we showed that a maxima or minima in the reflected signal intensity occurred when $\delta = m\pi$, where m = 0, 1, 2, 3, etc and $\delta = 4\pi.n.d / \lambda$. Standard end point interferometry uses a fixed wavelength source to generate an oscillatory reflected signal as the film thickness is reduced during an etch (that is we track changes in phase shift δ as the thickness d changes). Now, similarly, if the layer thickness is constant (i.e. pre- or post- etch) the wavelength can be varied to obtain an interference pattern characteristic of the film thickness (that is we are now looking at changes in phase shift δ as the wavelength λ is changed). In practice, this has been achieved using a tuneable IR laser, fibre-coupled to the interferometer optical head. An example scan is shown in figure 12.

Figure 12: Interference pattern generated by scanning the probe wavelength focussed on an SOI wafer [ref. 7].



Using the same modelling approach as before, a fitted curve can be applied to the data points. The best fit is achieved when the thickness used in the equation is closest to the actual film thickness. Therefore, the scanning wavelength technique provides film thickness measurement in-situ.

However, several considerations need to be taken into account when taking this measurement. The scan in figure 12 is of an epitaxial silicon layer approximately 10μm thick, obtained by sweeping the probe wavelength over a 100nm range. A small change in the actual output wavelength from the set value can result in a considerable change to the calculated thickness. Therefore an external cavity laser was used with internal wavelength referencing to provide a wavelength accuracy of ±40pm.

'Smart' curve fitting algorithms are also used to obtain accurate fits to the scan data. This is important, as for every scan a family of curves can be generated; each providing a good visual fit, but corresponding to thickness values a quarter wave apart. The accuracy of the thickness measurement has been compared with an offline instrument. Table 2 shows the results obtained from measuring a batch of 12 SOI wafers using the IR endpoint system in-situ and an ex-situ FTIR apparatus.

Table 2: Comparison of endpoint thickness measurements with an offline FTIR technique. [ref. 7].

Wafer no	**Endpoint thickness measurement /mm**	**FTIR thickness measurement /mm**	**Difference /mm**	**Difference /%**
1	9.3310	9.3669	0.0359	0.38
2	9.3433	9.3579	0.0146	0.16
3	9.3415	9.3676	0.0261	0.28
4	9.3008	9.3238	0.0230	0.25
5	9.3298	9.3640	0.0342	0.37
6	9.3310	9.3652	0.0342	0.37
7	9.3347	9.3627	0.0280	0.30
8	9.3356	9.3564	0.0208	0.22
9	9.3279	9.3552	0.0273	0.29
10	9.3077	9.3372	0.0295	0.32
11	9.3605	9.3889	0.0284	0.30
12	9.3405	9.3794	0.0389	0.42

The data in table 2 shows the endpoint system measurements to be, on average, within 28nm (0.3%) of the FTIR value, so the variation between the two techniques is less than the variation between wafers. This level of agreement implies that the scan curve fitter has found the true optimum, i.e. it is not out by a multiple of a quarter wave, which is approximately 107nm. The difference between the two measurements is similar for all wafers; standard deviation of the difference is 7nm. This offset could be due to differences in the measurement location or different values of the refractive index being used to calculate the physical thickness.

The total scan and fit time is less than a minute, so the procedure can take place during the pre-etch chamber preparation stages of the process (i.e. gas stabilisation), thereby not increasing the overall throughput time. Indeed, time is saved by not using an ex-situ metrology system.

Knowledge of the film thickness also enables an etch to be terminated at a remaining thickness. Interferometry provides etch depth information, so if the starting film thickness is known then the target depth can be set to achieve the required final material thickness. However, the starting thickness may vary from batch to batch and wafer-to-wafer, so any one endpoint depth cannot be set for a remaining thickness etch to be accurately terminated on every wafer. Using the wavelength scanning endpoint detector enables the starting thickness to be calculated for every wafer in turn and the correct target depth set to leave the required remaining film thickness. The process can be automated, so the scan is started when the wafer is clamped in position in the chamber, the best scan fit curve is found, the thickness calculated and the target depth is adjusted accordingly to terminate at the pre-set remaining thickness.

The film thickness can then be remeasured after the etch too. This can be useful for fine tuning the endpoint set up, for example, adjusting for a depth offset caused by thermal expansion.

We have now gained a new tool – the ability to monitor the remaining thickness. The infra red endpoint detector can now control the etch process to give either

a) a specific etch depth
b) a specific remaining thickness.

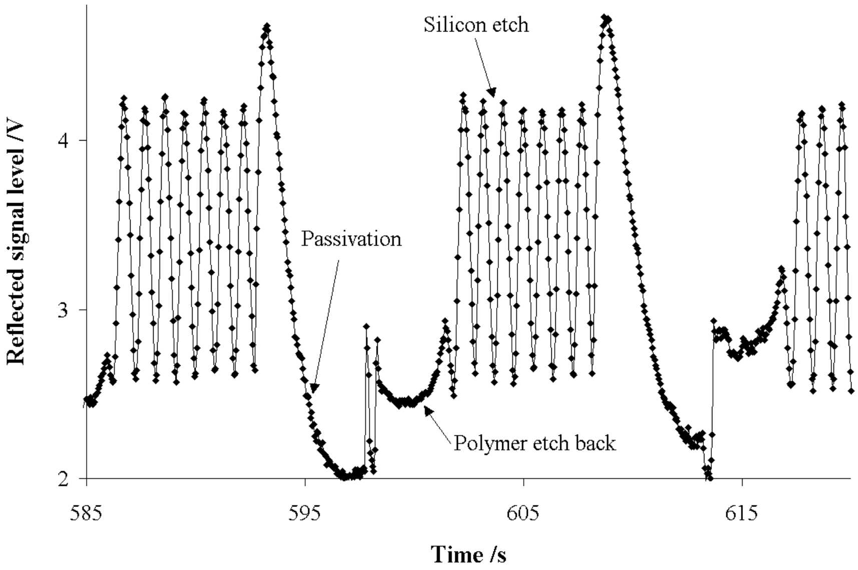
5. Switched etch processes

For deep silicon etches a ‘switched’ or Bosch process [ref. 8] is commonly used. Alternate etch and passivation cycles of several seconds each allow anisotropic trenches to be machined while maintaining high etch rates. This further complicates the monitoring of a reflected interference signal; since the controlling software needs to separate the silicon etch phases from the rest of the process.

Part of a typical process run is shown in figure 13, taken from an etch on a Surface Technology Systems High Rate ICP. The silicon etch is shown by the fast modulation part of the trace. In order to obtain a curve fit and accurate endpoint detection, fast data acquisition speeds are required, typically at least 20Hz. The polymer deposition gives rise to a less marked change in signal level. From the data in figure 13, the silicon is etched at rates of up to $14\mu m.min^{-1}$ in the etch phase, providing an overall etch rate, over etch and passivation phases, of $6.5\mu m.min^{-1}$.

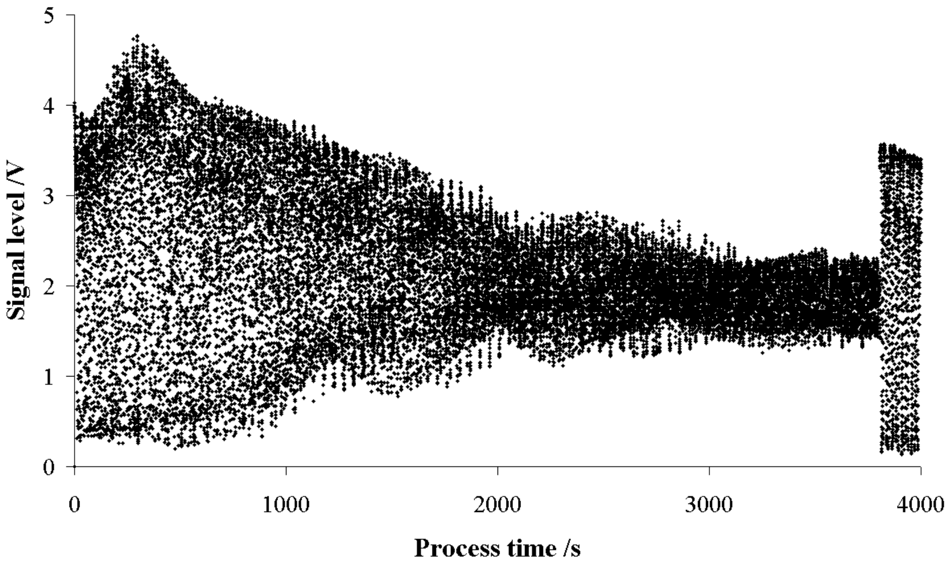
Separating the two phases is not as simple as synchronising with the process phases, using the changes in gas flow and RF levels, as only part of the etch cycle is required. At the start of the etch phase the measured signal is due to the polymer removal, so is not required. Due to the marked change in signal variation when silicon is being etched, patented shape recognition techniques can be used to gate measurement, so only the silicon etch is monitored.

Figure 13: Part of an interference signal measured during a Bosch etch process, showing the rapid data acquisition and the distinct process phases [ref. 9].



The IR LEP300 has been used to monitor etches all the way through a double-polished silicon wafer, an example is shown in figure 14.

Figure 14: The interference trace obtained from a thru-wafer silicon etch monitored at 1500mn [ref. 9].



Due to the thickness of the wafer (400μm) there are many interference fringes (approximately 4000 quarter waves), so individual fringes are not clearly visible on this scale, but the change in amplitude throughout the process is evident. The signal amplitude can be seen to decrease throughout the etch. This is most likely due to changes in the condition of the wafer surface in the locality of the laser spot, in particular roughness and parallelism with the back surface. However, there is still significantly large signal measured at the end of the etch, enabling the depth measurement capability to be maintained. There is an increase in the signal at end of the etch as we break through to the oxide layer at the back of the wafer (due to the change in reflectivity).

Conclusions

Standard laser endpoint detection is not suitable for controlling very deep etches (depths > 10 - 15μm) into silicon. This is due to absorption of the monitoring wavelength, which is typically in the visible region of the spectrum. By utilising probing wavelengths in the near infrared, it has been demonstrated that the etch depth can be monitored during an etch through a wafer, unaffected by absorption. This ability offers new monitoring and endpointing capabilities in the fabrication of MEMS and optical devices. In addition, real-time depth monitoring could eliminate the need for an etch stop layer, simplifying the manufacturing process and improving device operation.

In order for this technique to work, the wafer must contain two or more reflecting interface, such as a polished rear surface or buried layer(s) and the top surface must remain sufficiently smooth during the etch. The results from typically applications presented here, show the modification of the wafer surface during the etch do not restrict the measurement capability of the instrument.

In addition, new capabilities have been demonstrated. The application of a tuneable laser source enables in-situ thickness measurements to be made and the process to be endpointed on a remaining thickness of wafer material as well as etch depth.

Intellemetrics’ LEP300 is also able to monitor switched processes, using fast data acquisition to cope with high etch rates and image recognition to synchronise the measurement with the silicon etch phases of the process.

The IR laser endpoint detector shows a clear development in in-situ metrology for silicon etch applications. The instrument has demonstrated capability to provide real time etch depth information, previously not obtainable using other techniques. Such increases in the performance of monitoring equipment could help improve process control and device performance.

Acknowledgements

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