A New Polarimetric Camera for Real-time Trench Depth Monitoring in Micromachining Applications

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Abstracts

A New Polarimetric method for trench depth monitoring in micromachining applications is presented. As compared to the previous innovative and patented Twin-Spot interferometric technique developed by the Thin Film Division, this new method allows an absolute and accurate trench depth monitoring.

1 Introduction

Micro electromechanical systems (MEMS) is a rapidly growing field driven by micro machine devices and components for automotive, medical and industrial system application. To meet the challenge of manufacturing this generation of devices, precise and novel control techniques are required.

Considerable progress has been made during the last few years in the control of deep trench processes, thanks to the sensor technology evolution and the long experience acquired through semiconductor technology. One of the technique extensively used in dry etching processes is Laser interferometry. Easy to implement and non-destructive, its use is very well adapted to etch of trenches with features size closer to the probing beam wavelength. Due to the large features of the MEMS structure (usually higher than 100 µm), the simplest Laser interferometry technique is not applicable, and thus new techniques are developed like polarised interferometry based on interfering two beams. Nevertheless, like all interferometric techniques the sensitivity is limited to depth comparable to the probing wavelength.

In order to achieve high aspect ration in micromachining applications, complex processes involving etching and passivation steps (Bosch process) are commonly used. The cycles of these steps are becoming shorter and shorter and led to etch depth during one cycle much smaller than the probing wavelength. Thus the monitoring becomes impossible if the reproducibility of cycles is not enough accurate.

To overcome this issue a new sensor based on the absolute measurement of the trench depth was developed. This new sensor which is described below, do not require a special data treatment and is applicable to any process.

2 Polarised Interferometers

2.1 General Formalism of Polarised Interferometers

The optical set-up of the Twin-Spot Interferometer systems is displayed in Fig. 1.

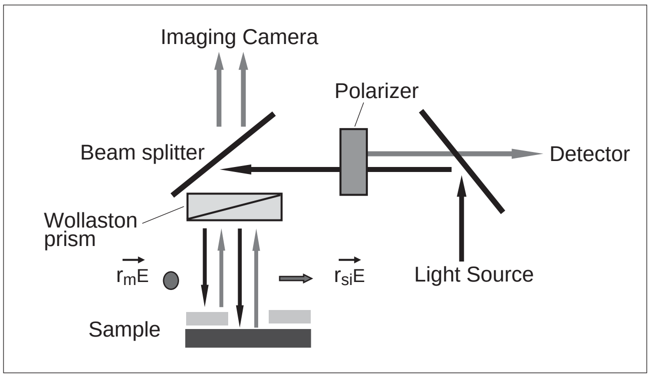

Fig. 1 Optical Set-up of Twin-Spot Interferometer

The light emitted by a laser diode or white light source is first linearly polarized with a Glan-Thompson polarizer. The output beam is then splitted into two linearly polarized beam with a Wollaston prism. The first beam is then reflected by surface 1 and the second beam by surface 2. Let's assume that the complex reflection coefficient is respectively r_1 and r_2. After reflection by the sample, these two beams are then recombined by the same Wollaston prism coupled to the polarizer.

The total electromagnetic field reaching the detector is then :

$$E = E_0 (r_1 \cos P + r_2 \sin P\, e^{-i\Phi})$$

where $\Phi = 4\pi\, T_d / \lambda$ is the phase shift introduced by the trench depth T_d and P the relative orientation of the polarizer

respectively to the eigen-axes of the Wollaston prism.
As in Ellipsometry let's define the following complex ratio :

$$\rho = r_1 / r_2 = \tan(\Psi) \exp i\Delta$$

If we assume that the relative orientation of the polarizer is 45°, then the detected intensity is :

$$I(t) = EE^* = E_0^2 r_2^2 (1 + \tan^2\Psi + \tan\Psi \cos(\Phi - \Delta))$$

The reflection coefficients of the beam reflected (r_1) by the masked area will depend on the thickness and the complex optical properties of the mask layer. If we assume that N_1 and d_1 are respectively the complex refractive index and thickness of the mask layer ($N_1 = n_1 - i\,k_1$: n_1 the index of refraction and k_1 the extinction coefficients), $r_1 = f(N_1, \lambda)$. The complex reflection coefficient of the etched area will depend only on the optical properties of the material being etched. By consequences tan Ψ and Δ will be a complex function of (N_1, N_2, d_1, λ), which can be modelled as in Ellipsometry.

2.2 Classical Twin-Spot Interferometer

For classical twin-spot interferometer where the detected intensity is recorded, during an etch process the only parameter which is time dependant is the phase shift Φ. If we define as ω the etch rate, the detected intensity will have the following time dependence:

$$I(t) = a + b\cos(4\pi\omega t/\lambda - \Delta)$$

Which is a simple time dependence function. In order to get the etch rate and an accurate determination of trench depth, one has to extract the frequency ω from the signal with the assumption that we are in the ideal situation where the process is a highly selective process and the mask material is stable during the process which means that Δ is stable over time.

2.3 Twin-Spot Polarimeter

The optical set-up of the Twin-Spot Polarimeter systems displayed in Fig. 2 is similar to the twin-spot classical interferometer. The main difference is related to the incorporation of an optical device which modulate the polarisation at a frequency ω_m. Thus the detected intensity is given below.

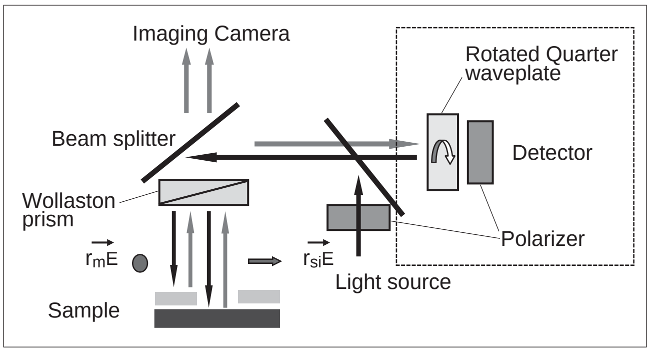

Fig. 2 Optical Set-up of the Polarimetric Camera

$$I(t) = EE^* = E_0^2 r_2^2 (a + b\sin(\Phi - \Delta)\sin 2\omega_m t + b\cos(\Phi - \Delta)\sin 4\omega_m t + c\cos 4\omega_m t)$$

The detection of the second and forth harmonic of the signal at a frequency ω_m, will lead to the direct and absolute measurement of :

$$\mathrm{Tan}(\Phi - \Delta) = H_2\omega_m / H_{4s}\omega_m$$

H_2 is the amplitude of second Fourier's harmonic. H_{4s} is the amplitude of the sine part of fourth Fourier's harmonic. With the assumption that the time variation of Φ is much slower than ω_m , a fast Digital Fourier analysis of the signal allows the extraction of :

$$\Phi = 4\pi\omega t/\lambda = \arctan(H_2\omega_m / H_{4s}\omega_m) + \Delta$$

With the same assumptions as above, ideal processes, the value of Δ can be measured when the etch process start and kept constant during all the process.

3 Calibration and Setting

The calibration and setting procedure of the Twin-Spot Polarimeter consists of two steps. The first one is the calibration of the system, and the second one is the spatial positioning of the two beam on the specific areas.

3.1 Calibration

In order to get an accurate measurement of the phase shift between the two beams, several parameters like the relative orientation of the polarizer to the Woolaston prisms, electronics coefficients and the optical transfer function of the total system needs to be determined.

Thanks to the work which has been done on polarized light during these last decades, a calibration method was developed. This method which will be described in an other paper, allows an accurate calibration of the system.

3.2 Spatial Positioning

In order to have an accurate positioning of the two beams, a set of objective lenses is placed on the beams path after the Wollaston prism. These objectives will focus the two beams on the surfaces to be analysed and by reflection will image their positions on a CCD camera Fig. 3.

This imaging capability coupled to a motorized X-Y stage allow the positioning of the two spots with a high accuracy. A more automated version including a frame grabber for the read-out of the camera signal and a commercially available software for pattern recognition , has been developed. The spot size of the two beams will depend on the distance between the top-window of the chamber and the sample , and the magnification of the objectives lenses . Their separation will depend on the deviation angle of the Wollaston prism . Spot size from 25 μm to 60 μm were achieved with a spacing going from 150 μm to 560 μm.

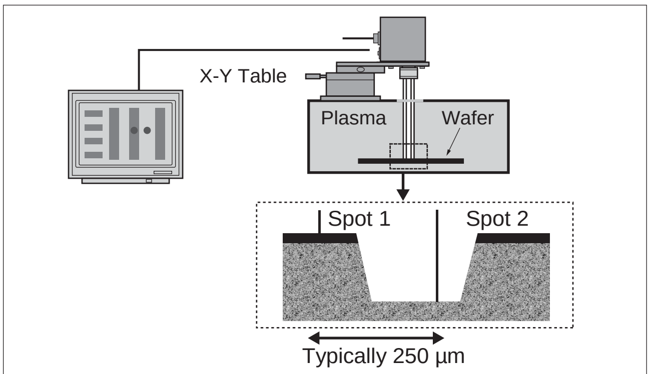

Fig. 3 Spatial Positionning with a Camera

4 Experimental Procedures

4.1 Experimental Description

Different experiments were performed on an Inductively Coupled Plasma dedicated to deep anisotropic etching of silicon following the Bosch process. The Bosch Process involves a pulsed plasma combining an etch step of silicon followed by a deposition step of polymers. The etch rate was 5 μm/min and the selectivity to resist was higher than 30 :1.

4.2 Deep Trench Monitoring by using the Twin-Spot Interferometer

In Fig. 4 is displayed the real time detected intensity recorded during the etch of silicon using the Bosch Process. The analysis of the signal shows clearly, the different steps of the process.

The determination of the trench depth in the Bosch Process by the Twin-Spot camera requires a careful data treatment and signal analysis. A real time discrimination of the silicon etch step is required. This is done by signal processing based on real time triggering and interpretation of the data.

Despite its powerfulness the Twin-Spot interferometer can be used only when the cycles between the passivation and etch step are long enough to allow the determination of the etch rate trough the interference fringes. When these cycles are very short, and combined with the non reproducibility of the triggering function, the measurements will become non reliable.

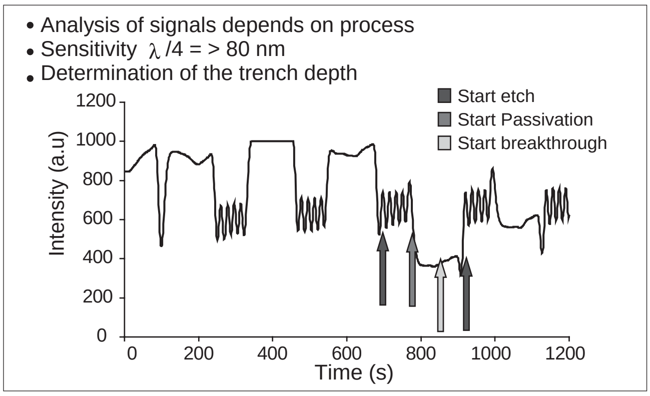

Fig. 4 Recorded Signal with the Twin-Spot Interferometer

4.3 Deep Trench Monitoring by using the Twin-Spot Polarimeter

In Fig. 5 and Fig. 6 are displayed the real time detected trench depth recorded during the etch of silicon using the Bosch Process, for two types of mask Photoresist and Aluminium. Since this new method allows a direct measurement of the trench depth no special signal treatment is required for the discrimination of the etch and passivation process. The sensitivity is clearly shown in Fig. 7 and Fig. 8 by the analysis of the passivation step of these two processes involving two different type of mask.

As compared to the classical Twin-Spot interferometer, this new sensor allows the measurements of a trench depth whatever is the dimension shallow or deep. The sensitivity achieved is comparable to the sensitivity of the Spectroscopic Phase Modulated Ellipsometers which are currently used for film thickness measurement (monolayer level).

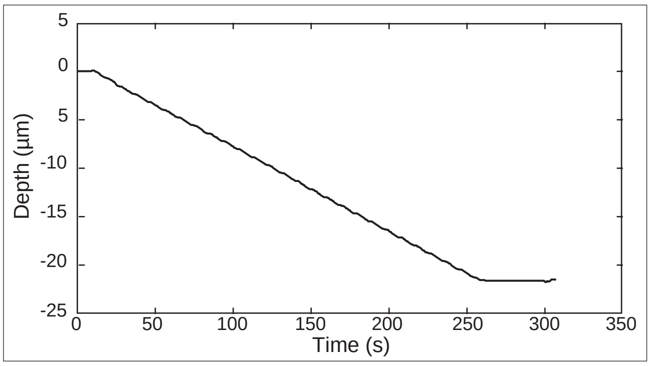

Fig. 5 Trench Depth Monitoring of Silicon Etch by using a Bosch Process and a Photoresist Mask

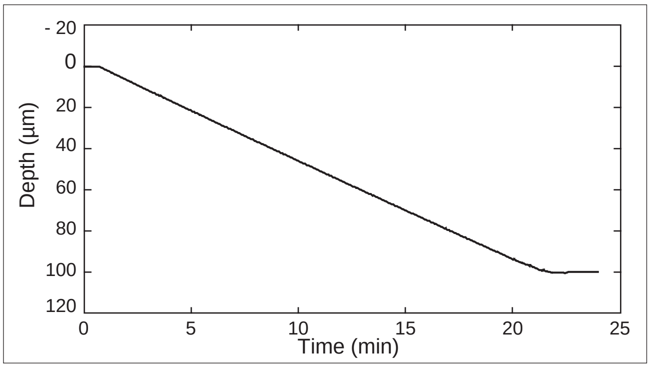

Fig. 6 Trench Depth Monitoring of Silicon Etch by using a Bosch Process and an Al Mask

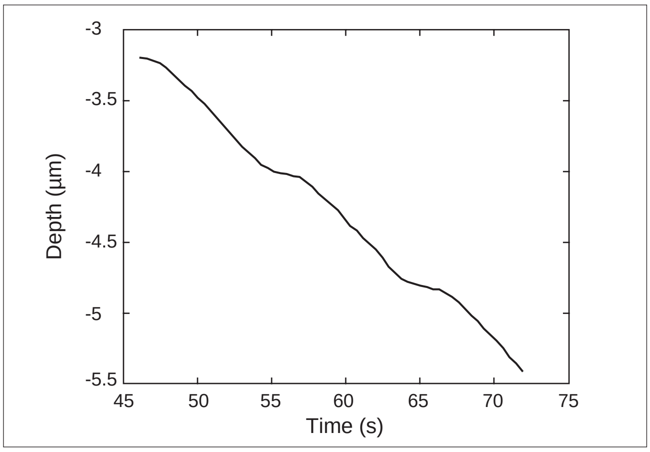

Fig. 7 Trench Depth Monitoring of Silicon Etch by using a Bosch Process and a Photoresist Mask during the Passivation Step

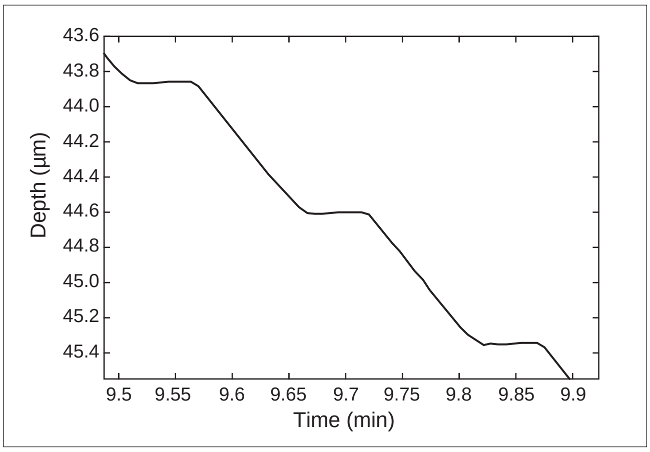

Fig. 8 Trench Depth Monitoring of Silicon Etch by using a Bosch Process and an Al Mask during the Passivation Step

4.4 Results

In the Table 1 are summarized the results obtained for different trench depth obtained by using the Polarimetric Camera for devices produced following the technology of Bosch process. After each process, the trench depth was checked ex-situ with a profilometer and compared to the fixed target.

Table 1 Comparison between Controlled Target and the Measurement of Trench Depth

Mask	Controled target (μm)	Profilometer	Accuracy (%)
Photoresist	21.8	21.6	1
Aluminium	110	109.5	0.5

5 Conclusion

A New Polarimetric Interferometer based sensor for trench depth monitoring, in the fields of MEMS application has been described. As compared to other interferometric techniques, this new sensor takes advantages of the generation of two coherent and polarised beams by a Wollaston prism and due to the modulation of the polarisation allows the absolute measurement of the Phase Shift between these two beams. This polarisation based interferometer allows an accurate trench depth determination at the monolayer level, whatever the process.

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