Novel Low Coherence Metrology for Nondestructive Characterization of High Aspect Ratio Micro-fabricated and Micro-machined Structures

Wojciech Walecki*, Frank Wei, Phuc Van, Kevin Lai, Tim Lee, SH Lau, and Ann Koo

Frontier Semiconductor, 1631 North 1st Street San, Jose CA 95112

ABSTRACT

Novel nondestructive method based on low coherence optical interferometry for measurement of deep etched trenches in MEMs structures is presented. The proposed technique proves to provide very reproducible results and can be easily extended to metrology of other materials such as metals and dielectrics. We present results in real life semiconductor structures and discuss practical and fundamental limits of this technique.

Keywords: Deep trench, low coherence interferometry, optical metrology

1. INTRODUCTION

The low coherence optical interferometry has been proven to be an effective tool for characterization of thin and ultrathin semiconductor wafers. It is particularly valuable for measurement of thickness of wafers thinner than 150 mm, or wafers mounted on dielectrics materials such as tapes or sapphire plates. For these applications standard well-established non-contact thickness gauges such as air pressure of capacitance gauges do not provide direct physical results, which meet industry process window or require introduction of additional experimental parameters. While bulk of effort was concentrated in the area of metrology for manufacturing of utrathin Silicon wafers, other very promising areas include metrology of III-V materials mainly for opto-electronics and microwave applications and metrology of MEMs structures, which is subject of this paper.

One of the main challenges in metrology of MEMs structures is measurement of the depth of fabricated samples, which allow determining time of etching for the fabrication. Most commonly used methods are based on scanning electron microscope (SEM) techniques. They are destructive and require quite extensive sample preparation involving cleaving or cutting samples across deeply etched trenches. Furthermore SEM measurements are performed in vacuum, which is further complication prolonging time of measurement. The alternative techniques may involve X-ray based methods, which also involve evacuation of samples and are relatively time consuming.

The common optical methods have very limited application for metrology of such samples. These methods are based on measuring position of the bottom of the trench by means of observing image of the bottom of the trench. For structures characterized by high aspect ratio, the numerical aperture of the microscope system is limited by aspect ratio of the etched structures. The high aspect ratio implies that small walls of the trench vignette rays emanating from the bottom of the trench. Therefore the entrance aperture of the optical system is determined by the geometry of the measured structure rather than by the objective of optical microscope used in the experiment. This results in reduction of the numerical aperture of the system, reduction of the lateral resolving power of the optical microscope, and increase of the apparent depth of focus (DOF). The depth of focus is given by following simple formula [1]:

$$DOF = \lambda / (NA)^2 \qquad (1)$$

* fsm100@aol.com; phone: 1 408 452-8898; fax 1 408 452-8688; frontiersemi.com

where λ is wavelength of observed radiation. For example in case of structure having aspect ratio of the order of 5, the numerical aperture of the system is of the order of NA = 0.1, which results in depth of focus DOF = 10 μm, assuming wavelength of 500 nm. For the structure having aspect ratio 10 Equation (1) leads to DOF = 40 μm. The accuracy of measured depth is of the same order as DOF. The process window for most of commonly encountered MEMs applications is of the order of 1 μm. From the above-described numerical examples we see that standard optical microscope methods are not adequate for metrology for high numerical aspect structures. Optical triangulation suffers from the same limitations as optical microscope when probing high aspect ratio structures.

We propose solution, which does not suffer from limitations related to microscope and triangulation based metrologies and at the same time is nondestructive. This described below method is based on low coherence optical interferometry. Low coherence interferometry has been proven to be an effective tool for characterization of ultrathin silicon structures such as pressure sensor membranes and ultrathin wafers [2], and it has been also demonstrated to be a powerful tool for metrology of layered materials [2]. Low coherence interferometry has been also used in conjunction with spectral interferometry for metrology of buried dielectric layers, and in conjunction with scatterometry to characterize grinding process. In this paper we extend this technique to metrology of deeply etched structures.

2. APPARATUS AND METHOD OF MEASUREMENT

Experimental apparatus used in the measurement is fiber optics interferometer shown in Figure 1, [2], which represents low coherence Michelson interferometer [2]. Light emitted by low coherence source A is split by means of beam-splitter 50% transmitting, and 50% reflecting beam-splitter C into two beams: first called later reference beam propagates in the reference arm of the interferometer D, second portion of the beam later called signal beam propagates in the signal arm E. The polarization of the reference beam is controlled by means of polarization controller F, and is collimated by means of lens G on mirror H. Mirror H resides on delay stage such that the length of the optical path of the reference beam is controlled by means of optical delay stage. The reference beam is reflected from the reflective element, passes again through polarization controller F is partially transmitted by beam-splitter C and directed to detector B. The signal beam E is collimated by lens I and impinges sample J. The reflected portion of the signal beam is directed by means of beam splitter C towards detector B.

The intensity of the optical beam impinging detector surface I_d is given by:

$$I_d = \tfrac{1}{2}\left(I_r + I_s\right) + \mathrm{Re}\left\{\left\langle E_r^*\left(t+\tau\right)\cdot E_s\left(t\right)\right\rangle\right\} \qquad (2)$$

where I_s and I_r are signal and reference beam combined by beam-splitter C shown in Figure 1, τ is delay equal to difference of the optical paths of the signal and reference beams, t is time, E_r and E_s are electric fields of reference and signal beams respectively, and angle $\langle\ldots\rangle$ bracket means averaging over t .

When optical paths of the signal and reference beams differ by much more than coherence length of the source the intensity detected by detector is simply equal to the first τ independent term in the Equation (2), however when the path of the reference and signal beams are different within the coherence length than the second term becomes comparable to the first term. This phenomenon is well known and was applied in past for distance ranging since the optical delay time is related to difference in length Δl between the reference and signal beams by simple formula:

$$\tau = 2\cdot n\cdot\Delta l \qquad (3)$$

where n is refractive index of the medium. The Equation 3 implicitly assumes that medium is non-dispersive within the bandwidth of the light source.

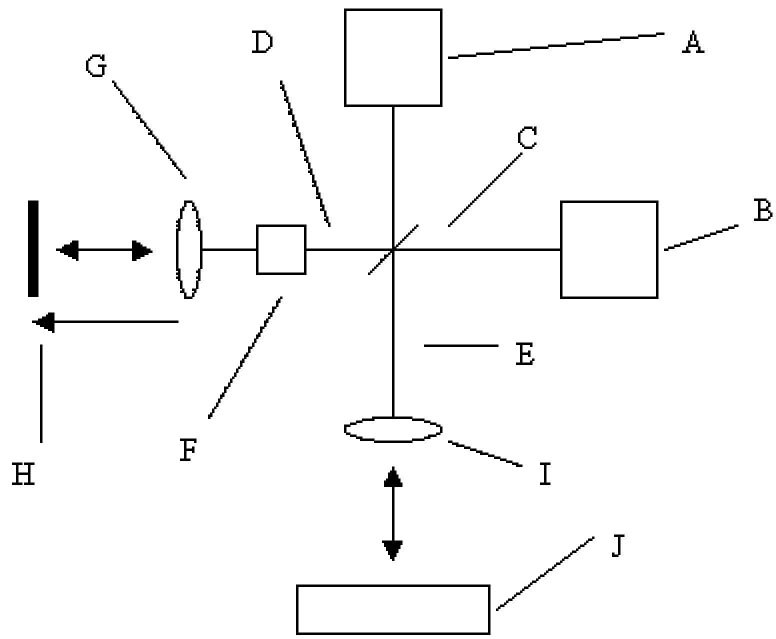

Figure 1: Apparatus used for measurement of the deep comprising of A low coherence source, broad bandwidth infrared source A, detector B, beam-splitter C reference, arm D and signal arm E. Reference arm D comprises of polarization controller F, collimating lens G, and mirror mounted on delay stage H. Signal arm E comprises collimating lens I and sample J.

Example of the interferogram of light reflected from the surface of reflective (and nontransparent) sample is shown in Figure 2. When optical paths of the signal and reference beams are approximately equal strong interference feature is observed. This feature is referred sometimes in Fourier transform interferometry as "center burst". It comprises of several oscillations spaced by approximately half of the wavelength of incident radiation $\lambda/2$ as shown in Figure 3 presenting another interferogram. The width of the observed center burst is determined by the coherence length of the incident radiation.

When sample is transparent (as shown in Figure 4), the low coherence beam is reflected from both first and bottom surfaces of the wafer. The interferogram of the reflected beam from sample 3 is shown in Figure 4. It reveals two smooth surfaces two interference features are observed: first corresponding to reflection from the first surface, and second corresponding to reflection from the second surface.

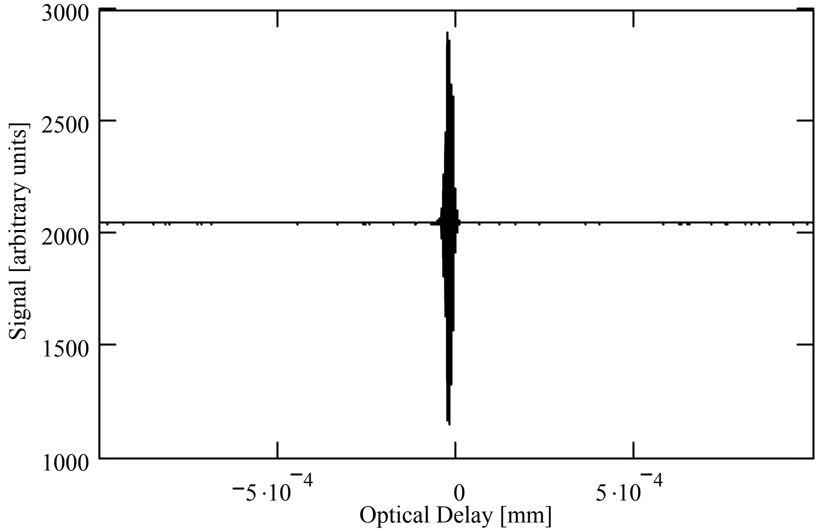

Figure 2: Interferogram of light reflected from reflective and nontransparent sample

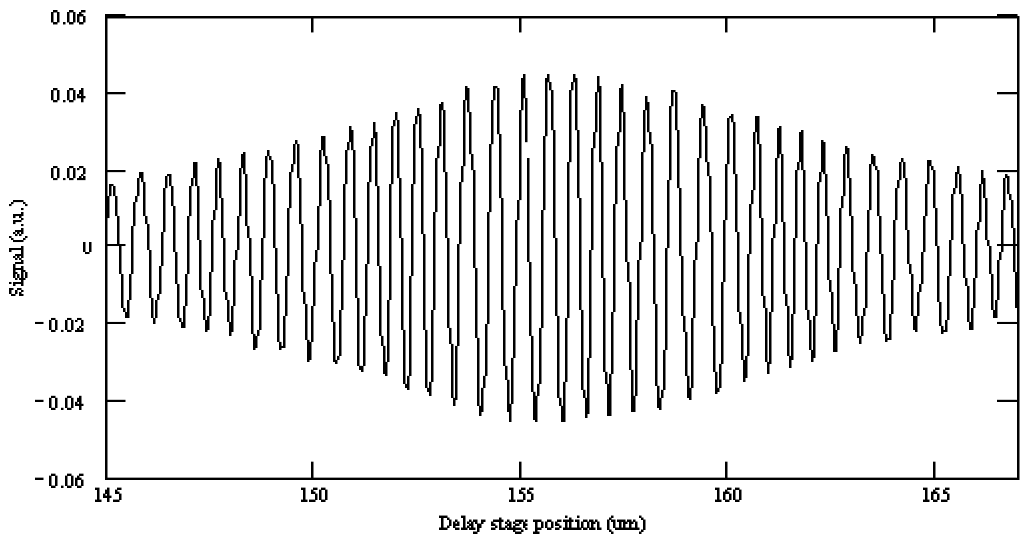

Figure 3: Example of interferogram (expanded scale)

The delay between interference feature corresponding to reflection from the front surface (feature 1 in Figure 5) and interference feature corresponding to reflection from the bottom surface of the sample (feature 2 in Figure 5) is proportional to thickness of the sample. In this paper we extend this simple concept to measurement of the etched deep aspect ratio samples.

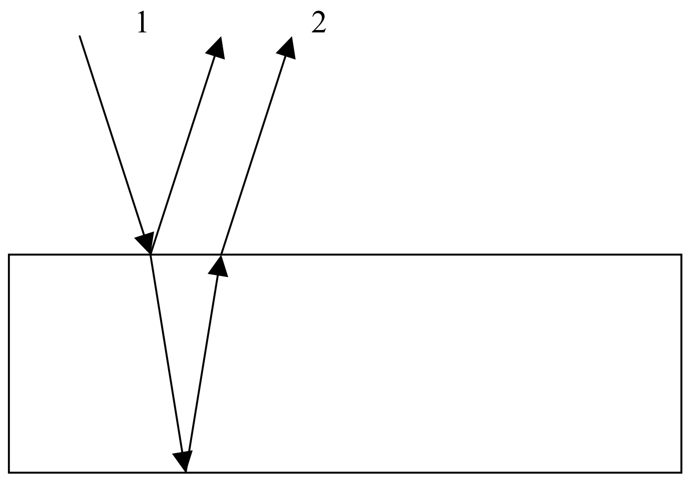

Figure 4: Transparent sample illuminated by low coherence beam. The reflected beam contains contribution resulting from the reflection from top surface 1 and bottom surface 2.

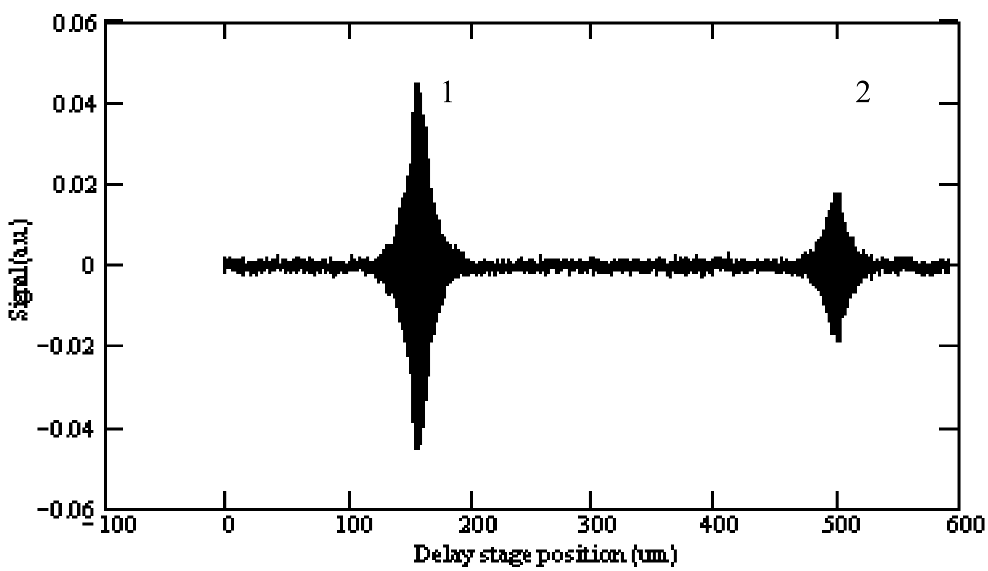

Figure 5: Interferogram of the low coherence beam reflected from transparent shown in Figure 4. The interference features 1 and 2 correspond to reflections from top and bottom

3. EXAMPLE OF EXPERIMENTAL RESULTS

In order to demonstrate our method lets consider very deep cylindrical holes structure defined by dry etching process presented in Figure 6 (a). Sample used to develop experimental method described The nominal diameter and depth of the high aspect ratio hole were 10 µm and 200 µm respectively, as measured on identically processed samples by SEM. In order to measure nondestructively depth of this

structure, we positioned micro-machined sample perpendicularly to signal beam of the low coherence optical interferometer. The wavelength and bandwidth of the radiation used to probe sample were 1.3 µm, and 40 nm respectively. The measured interferogram presented in Figure 6 (b) reveals three features A, B, C corresponding to

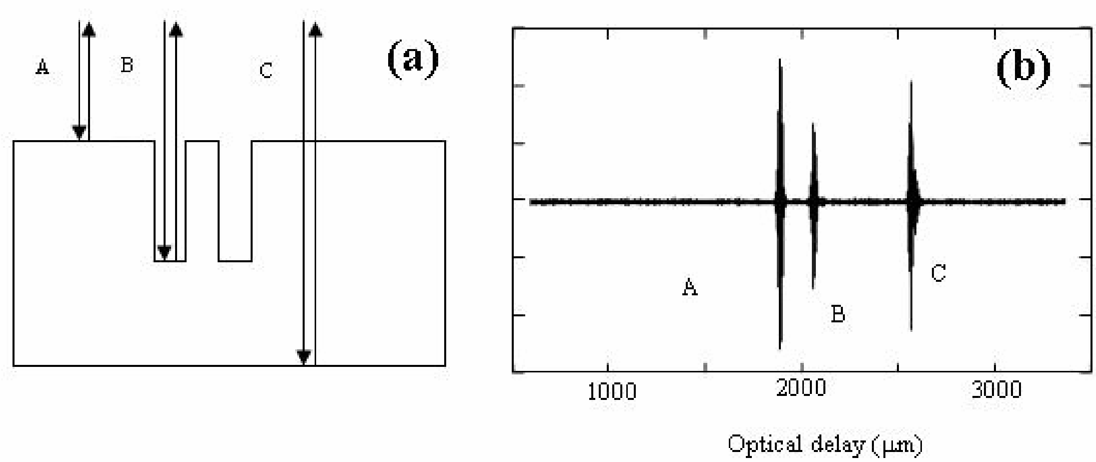

Figure 6: (a) Structure of deeply etched Silicon sample, and three surfaces contributing to reflection: A top surface of the sample, B bottom surface of trenches, C backside of the sample. Please note that optical paths corresponding to each of these three processes are different, (b) Structure of deeply etched silicon sample, and three surfaces contributing to reflection: A top surface of the sample, B bottom surface of trenches, C backside of the sample.

reflection from top of the sample, bottom of the hole, and backside of the sample respectively. Spacing between features A and B is equal to depth of the trench. Spacing between features A and B after taking into account refractive index of the substrate material can be used to measure thickness of the sample.

In commercial implementation of this method sample resides on motion stage connected to computer, allowing measurement in prescribed locations on the sample. Time needed to perform measurement depends on particular technical implementation of the delay stage and data acquisition and processing algorithms, as well as other components such as motion stages. In presented system time needed measure and analyze an interferogram measurement is of the order of 0.1 – 0.5 sec.

The results of typical measurement measurements are summarized in Table 1.

No	Position (x, y)	Trench Depth	Uncertainty in averaging mode
	(mm, mm)	(μm)	(μm)
1	-31.4,80.7	198.2	0.12
2	-10.3,80.7	201.6	0.12
3	10.3,80.7	195.9	0.08
4	31.4,80.7	197.1	0.07
5	-52.5,58.7	198.2	0.14
6	-31.4,58.7	195.9	0.08
7	-10.3,58.7	195.1	0.13
8	10.3,58.7	194.0	0.07
9	31.4,58.7	195.2	0.07
10	52.5,58.7	199.5	0.15

Table 1: Trench depth measurement results, collected in several locations on micro-machined sample. The uncertainty in averaging mode corresponds to standard deviation of arithmetic average taken over population of 30 single shot measurements

Data shown in Table 1 corresponds to measurements where wafer was moved between measurements. From presented data we see that reproducibility of the measurement in averaging mode is better than 0.15 μm. When data is collected without moving wafer the reproducibility is improved by about factor of 2. The data shows that repeatability of the measurement is suitable for measurement of variation of the trench depth on the wafer and exceeds process window, which in case of this particular micro-machining process was about 2 μm.

4. OTHER APPLICTAIONS AND LIMITATION OF THE METHOD

The above described method for nondestructive aspect ration measurement can be effectively used for nontransparent materials such as metals, as for transparent isolators. The measured material does not have to be uniform in composition. Since method does not rely on refractive index homogeneity of the material from which trenches and deep holes are defined it can be applied to quite highly in-homogenous media.

The described above method is quite robust, however it has obvious limitations imposed by the wavelength of the radiation. The first and obvious limitation is imposed by size of aperture of the hole. For most commonly encountered holes characterized by similar lateral width W and lateral length L method is quite exact when each of these dimensions is much larger then the half of the wavelength of the radiation $W >> \lambda/2$ and $L >> \lambda/2$. In this case the optical radiation propagating in the hole or trench can be treated as free space wave, and is not significantly affected by properties of the walls of trench or hole.

When $W \approx \lambda/2$, $L \approx \lambda/2$ but $W \geq \lambda/2$, $L \geq \lambda/2$ the optical radiation propagating in trench cannot be treated as free space propagating wave. The boundary conditions imposed on propagating guided wave result in finite group velocity dispersion, and broadening of the observed feature B in interferogram shown in Figure 6. In principle it is possible to calculate needed corrections using methods of wave-guide theory [3], [4] and references within. This topic is however beyond the scope of this short communication.

When $W < \lambda/2$ and $L < \lambda/2$ hole and trench does not support propagating modes. Limited experiments may be possible using evanescence waves propagating along such structures but these types of experiments are limited to very shallow trenches (characterized by depth of the order of λ) and therefore are not applicable for metrology of high aspect ratio structures. In the special case of very narrow trenches when $W < \lambda / 2$, and $L >> \lambda / 2$ the low coherence interferometry may be applied for measurement of the trench depth when polarization of signal beam is linear and oriented along the longer lateral dimension of the trench. Such measurement of course requires additional care.

For sufficiently wide trenches ($W >> \lambda / 2$ and $L >> \lambda / 2$.) roughness of the walls does not affect measurements. The detailed topography of the bottom surface of the sample may affect however the width and details of the interferogram.

5.CONCLUSIONS

The low coherence interferometry has been demonstrated to be accurate, fast and reproducible tool for measurements of trench depths in micro-machined semiconductor structures. It is fast and nondestructive alternative to complicate and time consuming methods based on electron microscope or X-ray scattering techniques.

REFERENCES

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, J. G. Fujimoto, "Optical coherence tomography," Science 254, 1178-1181 (1991).
2. W.J. Walecki, R. Lu, J. Lee, M. Watman, S.H. Lau, A. Koo, "Novel non-contact wafer mapping and stress metrologies for thin and ultrathin chip manufacturing applications" 3 rd International Workshop on Thin Semiconductor Devices – Manufacturing and Applications November 25, 2002, Munich, German
3. S. O. Konorov, A. B. Fedotov, O. A. Kolevatova, V. I. Beloglazov, N. B. Skibina, A. V. Shcherbakov, A. M. Zheltikov., JETP Letters, Vol. 76, No. 6, 2002, pp. 341–345. Translated from Pis'ma v Zhurnal Éksperimental'no i Teoretichesko Fiziki, Vol. 76, No. 6, 2002, pp. 401–405.
4. A. B. Mironov, N. I. Platonov AND Y. 0. Shlepnev, Radiotekhnika i elektronika, No. 2, 1990, pp. 281-286.