Application of ellipsometric and interference methods in MOS structures investigations

W Rzodkiewicz, L Borowicz and K Piskorski
Institute of Electron Technology, Al. Lotnikow 32/46, 02-668 Warsaw, Poland
E-mail: rzodki@ite.waw.pl

Abstract. Changes in some electrical and photoelectric parameters in the plane of aluminum gate, particularly in the effective contact potential difference (ECPD or \(I_{MS}\) factor) have been observed in MOS System Studies Department of Institute of Electron Technology for the first time. It has been found that the \(I_{MS}\) distribution over the gate area has a characteristic dome-like shape, with the highest values at the center of the gate, lower at the gate edges and still lower at gate corners. In order to find out why these values were changed in such way, we have investigated optical properties of the dielectric in the neighborhood of metal gate. Hence, in this work, interferometry and spectroscopic ellipsometry as well as scattered Raman radiation analysis have been used in the investigation of metal-oxide-semiconductor (MOS) structures. The above mentioned methods turned out to be very useful for the possible explanation of changes in photoelectric characteristics of MOS structures with aluminum gate.

1. Introduction
Interferometric methods described here are old. Namely, description of more popular Fizeau interferometer origins from 1862. A long description of constructions and numerous applications of modifications of Michelson interferometer [1] one can find in Twyman [2] and Candler [3] books. Even, Foucalt knife edge method [4] usually used to do an estimation of mirrors of big diameters, found application for the estimation of usefulness of illuminators of MOS structures at photoelectric properties investigations and Raman analysis.

In this paper, we worked on two issues:
- detection of expected stresses in the vicinity of gate edges (i.e. in the area of several tenths millimeters diameter) by spectroscopic ellipsometry,
- interference investigations of stresses on silicon substrates of several inches order diameters, on which metal and poly-silicon gates are deposited.

In connection with above, a question emerges: what can be a source of stresses in both silicon substrates and neighborhood of gates? It can be caused by chemo-mechanical treatment of silicon substrates. In technology of flat optical elements such as mirrors, focusing plates, compensators for Michelson type interferometers, one can obtain the high flatness not going beyond 0.05 of visible wavelength (it can be usually 546.8nm green mercury line or 632.8 nm red line of He-Ne laser) at element diameter to its thickness ratio not less than 1:12. In the case of silicon substrate, the ratio is equal to the order of 1:200. Therefore, we can observe deformations on the order of several tens of wavelengths on the substrates surfaces after their chemo-mechanical treatment. These surfaces do not have axial symmetry (it is evidently shown in Fig.1).
Figure 1. Interferograms of polished surface of two silicon substrates of 4 inch diameter. In these pictures we can evidently see distribution asymmetry of normal deviation of reflected wave beam surface from substrate surface. The interferograms were taken by means of Fizeau interferometer.

As the shape of interferograms shown in Fig.1 is concerned a question emerges: is such kind of surface shape can be represented by one value of curvature radius which is important term of Stoney formula or its derivatives extending applicability of this formula into cases not only infinitesimal small but also considerable surface deformations.

Calculations of curvature radiuses determined from the interferograms of silicon substrate surface before and after oxidation as well as stresses determined on the basis of these calculations by Stoney formula do not yield so such a big stress of substrates and thin dielectric layer. Assuredly, they do not cause characteristic changes in the electric characteristics of MOS structures. Therefore, these phenomena should be caused possibly by changes in refractive index of the dielectric layer (and silicon substrate) in the neighborhood of the gate.

2. Phenomena indicating existence of stresses in MOS structures

We have been observing characteristic distribution of some electrical parameters of MOS structures in the plane of square gate for several years [5, 6]. The example of such distribution was shown in Fig. 2, where the results of voltage measurements $V_G^0$ in the plane of the aluminum gate ($V_G^0 = \phi_{MS} + C$, $C$ - constant) were portrayed. Hence, distribution of effective contact difference potential is the same as $V_G^0$ voltage distribution with the highest values of $V_G^0$ at the center and lower at the corners of the square gate [7].

Figure 2. Typical dependence of the $(\phi_{MS} + C)$ voltage measured at the wavelength $\lambda = 244$ nm on the position in Al–SiO$_2$–Si(n$^+$) structures with aluminum gate thickness $t_{Al} = 35$ nm and SiO$_2$ layer thickness $t_{OX} = 60$ nm. The direction is either (1) along the diagonal of the square gate, or (2) through the center of the square gate and parallel to its edges.

This distribution is attributed to mechanical stresses occurring in the oxide under aluminum gate (see Fig. 3 [8-10]).
Figure 3. The expected one-dimensional distribution of stress $\sigma_{OX}(z)$ in the oxide layer under the aluminum gate.

As we can see that compressive stress has uniform, constant value at the center of the gate and then suddenly decreases and transforms to tensile stresses at the gate edges. Suggested hypothesis that stresses can be reason for changes of some parameters in the area of surface gate, stimulated us to further investigations on this topic [8, 9]. First step was elaboration of mathematical model describing distribution of the effective contact difference potentials $\phi_{MS}$ and its experimental verification [5, 6]. In Fig. 4, distribution of $\phi_{MS}$ factor in the plane of square gate of MOS structure was presented.

Figure 4. Two-dimensional distribution of $\phi_{MS}(x,y)$ calculated using model [5] for MOS structures with square gates of side length $L = 1$ mm.

It seems that the above mentioned results of our works confirm hypothesis that mechanical stresses existing in the oxide under aluminum gate are reason for irregular distributions of some electrical parameters in MOS structures ($U_G$, $\phi_{MS}$).

3. Results

In this work, interferometry and spectroscopic ellipsometry as well as scattered Raman radiation analysis have been used in the investigation of metal-oxide-semiconductor (MOS) structures.

3.1.1. Ellipsometric investigations in the neighborhood of the gate edge. Four inch diameter wafers with the MOS structures were investigated by spectroscopic ellipsometry (SE) at angles of 65° and 75°, and at the wavelengths $\lambda = 360$-1000 nm. In these studies, MOS structures with both aluminum and poly-silicon gate have been used. Although, the diameter of an incident light beam (obtained by means of focusing probes) was not sufficiently small (c.a. 0.2mm), the changes in SiO$_2$ layer thickness and refractive index have been detected (see Fig.5 and Fig. 6).
Figure 5. SiO$_2$ layer thickness (a) and (b) refractive index vs. distance from the gate edge for SiO$_2$/Al and SiO$_2$/poly-Si systems.

In both Fig.5. and Fig.6, we observe increase of the oxide thickness and decrease of the oxide refractive index (at 630 nm) in the direction of the gate edge. These studies could indicate existence of stresses in the investigated area. For each investigated wafer, determined values of the oxide refractive index were rough the same order.

Figure 6. SiO$_2$ layer thickness (a) and refractive index (b) vs. distance from the gate edge for different thicknesses of aluminum gate (t$_{Al}$).

3.1.2. Micro-interference investigations. On the basis of previous considerations presented in this paper (subsection 3.1.1), it concludes that SiO$_2$ layer under metal gate (from Al) can have other value of refractive index than in the case of the layer absence. Moreover, one can suppose there to exist considerable stresses which overpass possible elasticity limit, and even cause cracking of substrate surface.

In Fig. 7. The interferogram of 500nm thick aluminum gate surface deposited on the 56 thick SiO$_2$ layer was portrayed. Thickness of the silicon substrate was 0.7mm.

Figure 7. An interferogram of Al gate surface (annealed) and the vicinity of two edges in the light beam of 540nm wavelength (a). The interferogram in contours of 6 order (b).

On the basis of the interferogram, radius of curvature of gate surface was determined. Next, stresses in the dielectric layer under the gate by Stoney formula were calculated. Before the calculations, interference fringes needed to be presenting in the form of contours since that visual observation does not give possibility to precious estimation of their deflection better than 0.1 of the distance between neighboring interference fringes [11], what corresponds 27 nm optical path difference. It is necessary
to remember that in the case of elements investigated during reflection, doubling of the optical path
difference occurs. Hence, deflection of the fringe c.a. of 0.1 inter-fringe distance does not correspond
54 nm (0.1x540nm) optical path difference, but only 27nm (0.1x270nm). It seems that application of
interferogram contouring requires reference to multi-beam interferometry in respect of the
investigation of optical microstructure surface.

Contouring method allows to improve the accuracy of determination of the fringes deflection to the
value of 0.01 their scale for contours of the first order. It is assuming that both equidense lines go
symmetrical according to extremum of blackening or brightening of the fringe. E. Lau and W. Krug
estimated the accuracy of equidensometry technique [12]. It was equal to 0.001 of wavelength. These
data were concerned photographic equidensometry relying on coping of image to itself, obviously not
going beyond resolution of photographic material, behaving proper value of gamma factor during its
chemical treatment and dimple resolution of microinterferometer. At taking interference images by
digital camera, graininess of photographic materials corresponds dimensions of pixels forming
detection matrix.

In our paper, compressive stresses determined by Stoney formula were the order of several tens of
GPa. It is a shocking value, however, cracks of the substrate surface (Si) sometimes observed after
removal gate and SiO2 layer confirmed such a big value of stresses under gate surface.

3.1.3. Scattered Raman radiation analysis. Finally, the ellipsometric and interference results for
Si-SiO2 system have been confirmed by Raman analysis. Shift of 520 cm⁻¹ line (characteristic for
relaxed silicon substrate) as a function of distance from the gate edge was observed.

4. Conclusions
On the basis of our investigations, we concluded as follows:
- two phenomena for wafers with both aluminum and poly-silicon gates were detected: increase of the
oxide thickness and decrease of the oxide refractive index in the direction of the gate edge;
- optical path (product of refractive index and thickness) for given SiO2/Si system was almost the
same;
- value of stress in SiO2 layer under aluminum gate determined by interference method was the order
of several tens GPa;
- the increase of stresses in the vicinity of gate edge was confirmed by the increase of 520 cm⁻¹ line
shift (characteristic for relaxed silicon) obtained by scatter Raman analysis in the unavailable zone for
ellipsometric measurements due to significant dimensions of the light spot.

Results of these investigations can be useful for developing of the model of stress distribution in
MOS structures which will allow explanation of the observed changes in both electrical and
photoelectric parameters in the plane of metal gate.

References
[1] Michelson A A 1881 Am. J. Sci. 22 120
[2] Twyman F 1952 Prism end Making (Hilger & Watts)
[3] Candler C 1954 Modern Interferometers (Hilger & Watts)
[4] Furlan W D, Munoz-Escriva L, Pons A and Martinez-Corral M 2002 Am. J. Phys. 70 857
[5] Przewlocki H M, Kudla A, Brzezinska D and Massoud H Z 2004 Microelectronic Eng. 72 165
[6] Kudla A, Przewlocki H M, Borowicz L, Brzezinska D and Rzodkiewicz W 2004 Thin Solid Films 450 203
[7] Przewlocki H M 2001 Sol. State Electronics 45 1241
[8] Bjorkman c H, Fitch J T and Lucovsky G 1990 Appl. Phys. Lett. 56 1983
[9] Hu S M 1991 J. Appl. Phys. 70 R53
[10] Przewlocki H M and Massoud H Z 2002 J. Appl. Phys. 92 2198
[11] Pluta M 1982 Mikroskopia Optyczna (Państwowe Wydawnictwo Naukowe)
[12] Lau E and Krug W 1957 Die Aguidensitometrie (Verlag Akademie)