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Characterization of stress in semiconductor wafers using birefringence measurements

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Abstract. — The nondestructive optical method for quality control based on measurement of birefringence in semiconductor wafers is described. The influence of crystallographic orientation and multiple reflections in wafers on measured parameters are discussed. Also the full description of the device used for investigation of commercial semiconductor wafers is given. The last part of the article is devoted to the results of experimental investigations of semiconductor wafers during manufacturing of semiconductor devices and IC.

1. Introduction.

Stress in semiconductor wafers used in microelectronics does not attract any particular attention of researchers and production engineers. The stress however gives rise to warping and cracking of wafers and also indicates enhanced dislocation density that affects electrophysical properties of wafers and consequently quality and reliability of semiconductor devices. Stress control at various stages of the fabrication process would give an opportunity to reject deficient wafers in due time and to optimize individual operations in processing technology. To answer this need the measuring procedure should be rapid, contactless and non-desctructive. Commonly used methods, i.e. X-ray structural analysis and evaluation of stress from the wafer curvature according to Stoney formula, do not meet the above requirements since the former procedure is time-consuming and the latter is not sufficiently reliable because the wafer curvature can result from plastic as well as elastic deformation. The best suited method of stress control is conceivably the measuring of induced birefringence in semiconductor wafers that is directly concerned with stress.

First studies on application of photoelasticity for controlling semiconductor materials appeared over 30 years ago [1-4]. In subsequent publications (see, e.g. [5-7]) theoretical

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description was developed for measuring of piezobirefringence and examples of application were given usually on specially prepared samples. The method however has practically not been used to control standard semiconductor wafers since it requires to measuring an area distribution of extremely small magnitude of birefringence.

In this paper results are presented for controlling stress in standard semiconductor wafers by means of measuring stress-induced birefringence. In part 2 analysis is given for the particular features of measurements applied to standard wafers concerned with crystallographic orientation of stress, with interference at multiple reflections from polished surfaces of wafer, and with quality of surface finishing. Part 3 describes experimental setup which provides the possibility to measure distribution of magnitude and orientation of stress as small as $1 \times 10^5$ N/m$^2$ in the wafer up to 6 inches in diameter. Part 4 deals with the results of stress studies performed with standard silicon wafers, original as well as subjected to several processing operations. In part 5 similar data are presented for semiconductor wafers from III-V and II-VI compounds.

2. Special features of stress measurements on standard semiconductor wafers.

2.1 BASIC PRINCIPLES OF METHOD. — Materials mainly used in microelectronics, i.e. silicon, germanium and gallium arsenide, have a cubic symmetry and are optically isotropic. Elastic stress induces in them optical anisotropy; in general cases the axes of optical indicatrix ellipsoid do not coincide with directions of principal stresses. Tensor of piezo-optical coefficients for cubic crystal contains three independent components and in a coordinate system, oriented along 4-fold symmetry axes of the crystal, takes the form:

$$\pi_{mn} = \begin{bmatrix}
\pi_{11} & \pi_{12} & \pi_{12} \\
\pi_{12} & \pi_{11} & \pi_{12} \\
\pi_{12} & \pi_{12} & \pi_{11} \\
0 & \pi_{44} \\
0 & \pi_{44} \\
\pi_{44} & \pi_{44} 
\end{bmatrix}.$$  (1)

The stress-induced variations of the components of refractive index $n_i$ are related to stresses $\sigma_i$ as follows:

$$\Delta \left( \frac{1}{n_i^2} \right) = \sum_j \pi_{ij} \sigma_j.$$  (2)

Birefringence is characterized by a quantity

$$\Delta n = \frac{n^3}{2} \left[ \Delta \left( \frac{1}{n_1^2} \right) - \Delta \left( \frac{1}{n_2^2} \right) \right]$$  (3)

which is related to the difference of the principal stresses $\Delta \sigma = \sigma_1 - \sigma_2$ through photoelastic constant $C$:

$$\Delta n = C \Delta \sigma.$$  (4)

The magnitude of $C$ in cubic crystals is determined by two parameters: $(\pi_{11} - \pi_{12})$ and $\pi_{44}$. 
In experiment, one measures the phase difference $\Delta$ for the light with two different linear polarisations oriented along principal axes of optical indicatrix:

$$\Delta = \frac{2 \pi d \Delta n}{\lambda}$$  \hspace{1cm} (5)

where $d$ is the thickness of the wafer under study and $\lambda$ is the wavelength of the probe light. In order to calculate $\Delta \sigma$ at a given point on the wafer from the measured phase difference $\Delta$ it is necessary to know the magnitude of the photoelastic constant $C$.

2.2 Dependence of Photoelastic Constant on Stress Orientation. — In crystalline materials the $C$ value depends on the direction of stress and on the direction of light propagation in crystal [5, 7]. Generally, expressing the $C$ constant in terms of components of the piezo-optical coefficients tensor leads to complicated equations. Standard wafers of monocrystalline silicon have orientation along (111) or (100) planes. In cubic crystals as Si or GaAs the (111) plane is the only one which is isotropic as concerns photoelastic properties, i.e. the $C$ constant value is independent of stress direction in this plane:

$$C = \frac{n^3}{6} [ (\pi_{11} - \pi_{12}) + 2 \pi_{44} ] .$$  \hspace{1cm} (6)

Accordingly when $\Delta$ is measured it is possible to calculate at once $\Delta \sigma$ using (4).

The $C$ value for wafers of (100) orientation depends on stress orientation in this plane with respect to crystallographic axes:

$$C = \frac{n^3}{2} \frac{(\pi_{11} - \pi_{12}) \pi_{44}}{[(\pi_{11} - \pi_{12})^2 \sin^2 \beta + \pi_{44}^2 \cos^2 \beta]^{1/2}}$$  \hspace{1cm} (7)

where $\beta$ is the angle between the [001] axis and one of the principal axes of the optical indicatrix.

It is interesting to determine variation limits of the $C$ value in the plane when the direction of stress action changes in the interval from [001] to [010] and also to estimate the error in measured $\Delta \sigma$ introduced by substituting anisotropic photoelastic constant $C(\beta)$ by average quantity $\bar{C}$

$$\bar{C} = \frac{2}{\pi} \int_0^{\pi/2} C(\beta) \, d\beta .$$  \hspace{1cm} (8)

The angle $\beta$ is related to angle $\varphi$ between the stress direction and [001] axis by the following expression:

$$\operatorname{tg} 2 \beta = \frac{\pi_{44}}{\pi_{11} - \pi_{12}} \operatorname{tg} 2 \varphi .$$  \hspace{1cm} (9)

The $C$ value as a function of $\varphi$ for Si and GaAs was calculated using formulae (7) and (9). The magnitudes of components of the piezo-optical coefficients tensor $(\pi_{11} - \pi_{12})$ and $\pi_{44}$ for these materials are listed in table I. The results of calculations are shown in figure 1. It is obvious that the photoelastic constant of silicon does not change significantly with orientation. If this dependence is neglected and the calculation of $\Delta \sigma$ is performed using constant value $\bar{C} = 1.8 \times 10^{-11} \text{ m}^2/\text{N}$ the relative error introduced to measured values does not exceed 11 %. This decrease in accuracy is counterbalanced by a notably easier procedure of measurement.

The dependence of $C(\varphi)$ for gallium arsenide is much stronger.
Table I. — Component values of piezo-optical coefficients tensor for Si and GaAs [5].

<table>
<thead>
<tr>
<th>Material</th>
<th>$\pi_{11} - \pi_{12}$ (10$^{-12}$ m$^2$/N)</th>
<th>$\pi_{44}$ (10$^{-12}$ m$^2$/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.57</td>
<td>1.55</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.35</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Fig. 1. — Photoelastic constant $C$ as a function of $\phi$ angle between the direction of stress and [001] axis in the (100) plane: (-----) for Si; (---) for GaAs.

2.3 STRESS DIRECTIONS DEVIATING FROM ORIENTATION OF OPTICAL INDICATRIX AXIS. — Birefringence measurements allow us to determine the orientation of principal axes of optical indicatrix in any given point of the sample under study. However for analysis of the stress in the wafer it is essential to know the orientation of stress. Since the stress is related to the refractive index by a tensor, the orientation or the optical indicatrix axes and that of stress directions coincide only in special cases. Thus it is interesting to estimate probable magnitude of $\alpha$ angle between the stress direction and the axis of refractive index ellipse in the plane of the wafer. Figure 2 demonstrates the plot of $\alpha$ angle versus direction of stress for Si and GaAs wafers with (100) and (111) orientation calculated using the following expression [8]:

$$
tg 2 \alpha = -\frac{1}{2} \frac{\pi_{11} - \pi_{12} - \pi_{44}}{\pi_{44} \cos^2 \beta + (\pi_{11} - \pi_{12}) \sin^2 2 \beta} \sin 4 \beta
$$

(10)

In the case of silicon the $\alpha$ angle is not greater than ± 2.5°. Consequently the direction of stress can be evaluated with sufficient accuracy by measured orientation of the axes of optical indicatrix. The misorientation in gallium arsenide is more significant reaching in maximum, a value of 15°.

2.4 INTERFERENCE. — The wavelength of radiation for probing the semiconductor wafers should fall into a spectral region of optical transparency in the samples under investigation, i.e. into near infrared for principal semiconductor materials like Si, Ge, GaAs. Suitable for measurements is the radiation of He-Ne laser with generation wavelength $\lambda = 1.15$ μm. However in case of wafers with two polished surfaces the measurements are strongly impeded by interference that arises from multiple internal reflections of light from polished surfaces.
Interference results in significant amplitude and phase distortions of radiation passing through the wafer. Procedures commonly used to reduce the effect of multiple reflections, namely, low-reflection coating or dipping samples into immersion liquid, are unfit in our case. Consequently, we tried other methods to reduce this unwanted effect.

Under conditions of multipath interference the intensity $I$ of radiation passed through a wafer and phase difference $\delta$ of two components of the light wave are described by the following expressions [9]:

$$ I = \frac{I_0}{2\left[1 + (N^2 - 1)\sin^2 \Delta_x\right]} + \frac{I_0}{2\left[1 + (N^2 - 1)\sin^2 \Delta_y\right]} $$

$$ \tan \delta = \frac{N (\tan \Delta_x - \tan \Delta_y)}{1 + N^2 \tan \Delta_x \tan \Delta_y} $$

where $I_0$ is the intensity of radiation source, $\Delta_x = \frac{2 \pi dn_x}{\lambda}$, $\Delta_y = \frac{2 \pi dn_y}{\lambda}$, $n_x$ and $n_y$ are components of the refractive index of material, $N = \frac{1 + R}{1 - R}$, $R$ is reflection coefficient. At small $\Delta = \Delta_x - \Delta_y$ it is reasonable to assume that $\sin^2 \frac{\Delta}{2} \ll 1$ and $\cos^2 \frac{\Delta}{2} \approx 1$. The (11) and (12) are transformed into

$$ I = \frac{I_0}{1 + (N^2 - 1)\sin^2 \left(\frac{\Delta_x + \Delta}{2}\right)} $$

$$ \tan \delta = \frac{N \sin \Delta}{1 + (N^2 - 1)\sin^2 \left(\frac{\Delta_x + \Delta}{2}\right)} $$
As seen from (14) the measured phase difference $\delta$ in this case is at variance with the value of $\Delta = \Delta_x - \Delta_y$ since the intensity $I$ of passing light as well as the measured phase difference $\delta$ are functions of the optical thickness of the wafer ($\Delta_x$ and $\Delta_y$).

Non-uniformity in the optical thickness of wafer results in strong variations in $I$ and $\delta$ values (Figs. 3a and b).

We obtain from (13) and (14):

$$\sin \Delta = \frac{I_0}{IN} \tan \delta. \quad (15)$$

If $I$ and $\delta$ are measured simultaneously it is possible to exclude the effect of interference by means of relation (15) and to obtain the $\Delta$ value (cf. Fig. 3c). It is obvious that the real value of $\Delta$ significantly differs from the directly measured $\delta$.

Direct determination of $\Delta$ from the measurements would certainly be preferable. A known method of interference suppression consists in using a beam with a large angle of convergence. Actually, on averaging (14) over the interference period $T$ and assuming $\Delta \ll 1$ we get

$$\overline{\tan \delta} = \frac{1}{T} \int_0^T \frac{N \sin \Delta \, d\Delta_x}{1 + (N^2-1) \sin^2 \left(\Delta_x + \frac{\Delta}{2}\right)} \quad (16)$$

Fig. 3. — Variations in intensity of passing radiation (a) and in registered phase difference (b) on scanning wafers non-uniform in thickness. (c) is $\Delta$ recalculated from (a) and (b) measurements according to (15).

In our studies to suppress interference we focussed the laser beam using the short-focus objective with aperture $A = \sin \gamma = 0.21$, the $\gamma$ angle being that of the beam convergence. $(I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \leq 0.01$ in this case. Strictly speaking, a measuring difference of light paths from a beam with a large angle of convergence results in reduced accuracy of measurements. To estimate this error we measured the path difference $\tau$ introduced by attested
ellipsometric plates using an objective for focussing the probe radiation at two aperture values, $A_1$ and $A_2$. The results of measurements are presented in table II. Each value in the table was obtained as a number average from ten readings. The beam aperture was changed by means of a diaphragm. The data of table II show that maximal relative error, in measuring the light path difference which is caused by using light beam with strong convergence amounts for the plates, under study to $\sim 3\%$. This precision is sufficient to control the quality of semiconductor wafers.

Table II. — Dependence of measured path difference on beam convergence angle.

<table>
<thead>
<tr>
<th>Wafer number</th>
<th>$\tau$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_1 = 0.21$</td>
</tr>
<tr>
<td>1</td>
<td>91.6</td>
</tr>
<tr>
<td>2</td>
<td>398.6</td>
</tr>
<tr>
<td>3</td>
<td>116.2</td>
</tr>
<tr>
<td>4</td>
<td>416.1</td>
</tr>
</tbody>
</table>

2.5 Effect of etched surface of wafer on results of measurements. — Standard semiconductor wafers used in microelectronics are of two types: either polished on both sides or with one side polished and the other one etched. In the second case the roughness of the mat surface can lead to depolarisation of light thus distorting results of measurements. Therefore it is interesting to investigate whether the stress measurements might be performed on wafers with an etched back surface. The roughness of the surfaces is described by parameter $R_a < 1.0\ \mu m$. On comparison of the maximum $R_a$ value ($1.0\ \mu m$) with probe radiation wavelength $\lambda = 1.15\ \mu m$ it should be expected that such roughness would not appreciably influence the measurements results. This assumption was subjected to an experimental test by measuring the extent of depolarization of linearly polarized radiation with $\lambda = 1.15\ \mu m$ on passing through a standard monocrystalline silicon wafer with an etched back surface. The depolarization was evaluated according to formula

$$p = 1 - \frac{I_1 - I_\perp}{I_1 + I_\perp}$$

where $I_1$ and $I_\perp$ are intensities of light passed through the wafer under study for polarization parallel and perpendicular to that of an incident light wave. In a series of measurements performed on various wafers obtained from different producers the $P$ value did not exceed $1\%$.

The above discussion shows that the main source of error in measurements of stress in standard semiconductor wafers is the neglect of dependence on orientation of the photoelastic constant $C$. The loss of precision in this case is however counterbalanced by an appreciable simplification of the measuring procedure. It should be noted also that the piezo-optical coefficients obtained in various studies strongly differ (cf. e.g. Tab. 3 in [5]). What is more, the principal interest of stress control does not lie in measuring absolute magnitude of stress at any definite point on the wafer surface but in obtaining data on distribution of relative stress values over the wafer area and changes produced in the distribution after subjecting the wafer to technological operations. High-temperature treatment can result in many-fold changes in stress on the wafer surface and thus precision of the method under discussion is sufficient for
quality control of semiconductor wafers and for optimizing the manufacturing procedures despite all the above mentioned sources of errors.

3. Apparatus.

We have considered the pros and cons of various optical schemes for a polarimeter aimed at quantitative measurements of stress in standard semiconductor wafers, and we have chosen a modification complying a circular polarization of probe radiation and a rotating analyzer (Fig. 4). The scheme is advantageous since it does not require top quality polarizers and the magnitude and direction of stress are easily determined from the measured signal. Plane polarized radiation passes a quarter wave phase plate with axes at 45° to the plane of polarization and is thus transformed to circular polarized radiation:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
1 & 0
\end{pmatrix}
\]

(18)

Fig. 4. — Functional scheme of polarimeter with rotating analyser. 1) laser; 2) phase plate \( \lambda/4 \); 3) optical system for expanding radiation beam; 4) objective; 5) sample under study; 6) double-coordinate scanning table; 7) rotating analyzer; 8) angular coder; 9) pulse formator; 10) radiation detector; 11) amplifier; 12) analogue-to-digital converter.

Next the radiation passes through the semiconductor wafer under study. In case the wafer is subject to stress it becomes anisotropic and may be described as a phase plate with phase difference \( \Delta \) and with fast axis at \( \theta \) angle:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & c_2^2 + s_2^2 \beta & c_2 s_2(1 - \beta) & -s_2 \mu \\
0 & c_2 s_2(1 - \beta) & s_2^2 + c_2^2 \beta & c_2 \mu \\
0 & s_2 \mu & -c_2 \mu & \beta
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
1 & 0
\end{pmatrix}
\]

(19)

The following designations are used: \( c_2 = \cos 2 \theta \); \( s_2 = \sin 2 \theta \); \( \beta = \cos \Delta \); \( \mu = \sin \Delta \). The resulting radiation becomes elliptic polarized.
Let us present the rotating analyser as a polarizer which has a transmission plane depending on \( \omega t \) where \( \omega \) is the angular velocity of rotation and \( t \) is the time interval.

\[
\begin{pmatrix}
1 & c & s & 0 \\
\frac{1}{2} & c^2 & cs & 0 \\
s & cs & s^2 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
1 \\
- s_2 \mu \\
c_2 \mu \\
B
\end{pmatrix}
= \begin{pmatrix}
1 - cS_2 \mu + SC_2 \mu \\
c - c^2 S_2 \mu + CC_2 \mu \\
s - cSS_2 \mu + s^2 C_2 \mu \\
0
\end{pmatrix}
\]

(20)

where \( c = \cos \omega t \); \( s = \sin \omega t \).

The intensity of radiation transmitted by the rotating analyser is determined using the first element of Stokes vector. The expression for the alternating part \( \Delta f \) of radiation intensity \( f \) reaching the photodetector is derived from (20):

\[
\Delta f = f \sin \Delta \sin 2(\omega t - \theta)
\]

(21)

\( \Delta \sigma \) can be therefore expressed by measured data using (4), (7) and (21):

\[
\Delta \sigma = \frac{\lambda}{2 \pi dC} \arcsin \frac{\Delta f}{f}
\]

(22)

The measured values of \( \Delta f/f \) for standard semiconductor wafers usually do not exceed 0.1. In this case approximation \( \sin x \approx x \) is sufficiently accurate and (22) is simplified to

\[
\Delta \sigma = \frac{\lambda}{2 \pi dC} \frac{\Delta f}{f}
\]

(23)

Thus using (22) it is possible to calculate the stress magnitude \( \Delta \sigma \) from the modulation \( \Delta f/f \) of the signal measured by photodetector. The direction of stress is determined from phase of the alternating component \( \Delta f \). One should also take into account that the phase is present by orientation of the long axis of polarization ellipse which forms a 45° angle with the axes of refraction index. Besides it can be seen from (21) that the phase difference between the measured and reference signals is \( 2 \theta \) where \( \theta \) is the angle between the long axis of polarization ellipse and the initial direction of reading since the recording is done at 2 \( \omega \) frequency. The direction corresponding to \( \theta = 0 \) can be changed by varying the phase of the reference signal.

The optical scheme described above was used to construct a scanning automated laser polarimeter designed for stress measurements in standard semiconductor wafers. The polarimeter is schematically illustrated in figure 4. A He-Ne laser (1) with generation wavelength \( \lambda = 1.15 \, \mu\text{m} \) is used as radiation source. A 1/4 wave phase plate assured that the circular polarization of radiation in our device attained very high degree (better than 0.999). Then the light beam passes through an optical system (3) that expands it and afterwards the beam is focussed by lense (4). These parts assure aperture of the beam convergence \( A = 0.21 \) sufficient to suppress interference (1). The diameter of the probe light spot is 200 \( \mu\text{m} \). The semiconductor wafer to be tested (5) is placed on a double-coordinate scanning table (6). To reduce the size of the moving part the table was made to move in polar coordinates. The rotating analyser (7) is rigidly linked to an angular coder (8) which can preset 360 or 1 pulse per 1 revolution of the analyzer. An electric signal from the load of photodetector (10) is then selectively amplified at 2 \( \omega \) frequency, and detected. The signal is

---

(1) Theoretical consideration presented in this part is based on the matrix (19), which is valid for parallel nonconverging light beam perpendicular to the surface. But as it was demonstrated experimentally (see Part 2.4 and Tab. II) the relative error due to convergence of the light beam in our set up doesn't exceed 3%. So within this error we can neglect the effect of convergence.
next transmitted to the input of analogue-to-digital converter (12) which is switched on by the coder pulses 360 times per 1 revolution of the analyzer. The resultant values of the signal are used to digit Fourrier coefficients $a_0$ and $\sqrt{a_1^2 + b_1^2}$ that characterize its average magnitude and amplitude of its alternating component at $2\omega$ frequency respectively. The relation of the Fourrier coefficients to the values $\Delta$ and $\theta$ is as follows:

$$\sin \Delta = \frac{\sqrt{a_1^2 + b_1^2}}{a_0}$$

$$\theta = \frac{\pi}{4} + \arctg \frac{a_2}{b_2}$$

Apparatus control and data processing was done by computer.


Distribution of stress in monocrystalline silicon is determined by the symmetry of temperature field during growing and cooling of ingot. This field has usually axial symmetry with the axis common to the ingot. A series of wafers placed in a quartz holder during high-temperature processing operations is also located in axial temperature field. Consequently the residual stress is essentially due to this temperature gradient in a cooling wafer. In such model the residual stresses are directed along the wafer radius ($\sigma_R$) and normal to it ($\sigma_\tau$) and their values change according to parabolic law [5]:

$$\sigma_R = \sigma_0 \left(1 - \frac{r^2}{R^2}\right)$$

$$\sigma_\tau = \sigma_0 \left(1 - \frac{3r^2}{R^2}\right)$$

where $\sigma_0 = \text{Constant}, R$ is the radius of wafer. In this case the measured magnitude of induced birefringence $\Delta$ should also show parabolic dependence on the $r$ coordinate when scanning is done across the diameter of wafer (Fig. 5):

$$\Delta = C d (\sigma_R - \sigma_\tau) = 2 C d \frac{r^2}{R^2}.$$  

The relation is valid for the cut-off of a monocrystalline ingot made perpendicular to its axis of growth.

In the case when radial temperature gradient exists only in peripherial region of the wafer, the birefringence should rapidly decrease when going away from the perimeter towards the center of the wafer. The plot of the $\Delta$ value presents a flat plateau in the center of the wafer (Fig. 5).

Thus stress inherited by wafer from ingot should be radially oriented and $\Delta \sigma$ should increase from the middle to the sides of wafer as follows from (27) and figure 5. However our measurements performed on original wafers obtained from different producers have shown that in all wafers without exception the value and direction of stress are uniform over a wafer. This meant that mechanical treatment during production of wafers induced greater stress in it than that inherited from ingot. The magnitude of $\Delta \sigma$ in original wafers is small and amounts usually to $(3-5) \times 10^4 \text{N/m}^2$. Parallel directions of stress suggest that it possibly results from cutting of ingot since subsequent mechanical operations (grinding and polishing) have no preferential
Fig. 5. — Theoretical representation with birefringences distribution along wafer diameter after heat treatment [5] : 1) in case of uniform radial heat dissipation; 2) in case of radial heat dissipation only from peripheral region of wafer.

directions of processing. The parallel orientation is conserved after coating of wafer with SiO$_2$ or Si$_3$N$_4$ layer although the distribution of $\Delta \sigma$ over the wafer becomes less uniform. (The thicknesses of layers were 4-70 nm for Si$_3$N$_4$ and 120-400 nm for SiO$_2$). Our studies have shown that the stress in wafer is mostly affected by growing an epitaxial layer. Figure 6 shows results on silicon wafer with an epitaxial layer. It can be seen that the stress is $\sim 10$ times stronger than in original wafers and the distribution of stress parameters is symmetric about the center of the wafer. Similar distributions we observed in over 200 of the wafers studied after heat treatment.

The $\Delta \sigma$ distribution presented in figure 6 contains a flat part in the center of the wafer and a

Fig. 6. — Stress in silicon wafer with epitaxial layer after being subjected to several operations, a) $\Delta \sigma$ distribution; b) orientation of stress.
steep rise on the sides. It means that the radial dissipation of heat has occurred mainly in peripherial region of wafer (cf. Fig. 5). It is obvious from the picture of stress directions for the wafer (Fig. 6b) : on circumference they are radially oriented and reproduce the distribution of temperature gradients in the cooling wafer. It can be presumed that the central part was cooled more uniformly with small temperature gradients. The stress in this case is not sufficient to produce dislocations which would fix the picture of high temperature stress. Thus the central part of the wafer retains on cooling the stress characteristics typical for the original wafer.

The results obtained suggest that there is no need for wafer control to measure the area distribution of stress on each wafer. The symmetry of the distribution permits us to use for quality evaluation of a wafer a plot of $\Delta \sigma$ across its diameter that may be regarded as sufficiently informative characteristics of stress in the wafer. The control time thus will be appreciably reduced.

It is interesting to estimate the range of stress influence in a wafer. For this purpose we did several consecutive measurements of $\Delta \sigma$ distribution along a diameter of wafer : firstly, the readings were taken from the diameter of intact wafer (Fig. 7a) ; then the wafer was cut along a chord parallel to above diameter at 5 mm from it and the measurement of $\Delta \sigma$ distribution along the same diameter was repeated (Fig. 7b) ; finally, the wafer was cut once more along a similar chord at 5 mm from the diameter on the other side and the same measurements were performed for the third time, the previous diameter being in the middle of a strip 10 mm wide (Fig. 7c).

The $\Delta \sigma$ distribution in the uncut wafer was characteristic of wafers with heat dissipation on cooling after heat treatment occurring only over peripherial region (cf. Fig. 7a and Figs. 5 and 6).

It is to be noted that the procedure used in measurements yields as a result a difference of « principal » stresses $\Delta \sigma$ and a zero signal indicated in the center of a wafer (Figs. 5 and 7a) is far from meaning that there is no stress in the centre but that the symmetrical distribution of

![Graph](https://example.com/graph.png)

Fig. 7. — Distribution of stress along silicon wafer diameter : a) uncut wafer ; b) wafer cut along a chord parallel to its diameter at 5 mm from it ; c) after second cut symmetric to the first on another side of diameter also at 5 mm from it.
stress leads to equality \( \sigma_R = \sigma_r \). The symmetry is broken by cutting the wafer and the measured signal in the centre grows accordingly (Fig. 7b) since the stress normal to the diameter of wafer cannot any more be compensated by stress in the cut-out. On the other hand, the stress near the sides of the wafer decreases, i.e. \( \sigma_r \) is less, because the principal contribution to the measured signal in this region comes from this component of stress (in the limit on the perimeter of wafer \( \sigma_R = 0 \)).

The stress in the 10 mm strip cut from the wafer remains close to zero all over the diameter (Fig. 7c).

Important conclusions result from data shown in figure 7. Firstly, these findings prove that the measured signals are due really to stress since only stress among all the factors affecting optical properties of crystals can change on cutting the sample. Secondly, the data corroborates that \( \sigma_R \) and \( \sigma_r \), in the center of the plate are comparable in magnitude with one another and also with stress in the peripheral part of wafer. And, thirdly, the result obtained here enables us to estimate experimentally the range of stress influence in wafers: stress at 5 mm from a cut is significantly affected. Further experiments demonstrated that a cut at 10 and even 15 mm from the point of measurements appreciably influenced stress at this point. The results show that the requirements on devices controlling stress in semiconductor wafers should not put too narrow limits on probe localization and should not demand that the diameter of probing beam be of dimensions comparable to that of microcircuit elements since the principal contribution to the measured signal is from macrostress in substrate and not from the microstress caused by topology and character of the microcircuit elements. The distribution of stress in a chip will change notably on scribing of the wafer. To control quality of wafers and their structures and to optimize the high-temperature production operations only the macroscopic picture of stress in a wafer is important.

It is reasonable to presume that the stressed condition of silicon wafers is due not only to the mode of heat treatment but also to their particular crystal structure inherited from an ingot. One experiment was carried out on a series of 10 wafers which were simultaneously subjected to epitaxial growth. The character of \( \Delta \sigma \) distribution along a diameter of wafers clearly defined two groups with similar distributions inside each group. Respective distributions are represented by curves 1 and 2 in figure 8. It should be noted that before thermal treatment all samples in these series had initially very low stress, typical for original non treated wafers. The effect of heat treatment cannot be ascribed either to a particular place taken by a given wafer in

![Fig. 8. — Stress in wafers forming two groups unlike in distribution of \( \Delta \sigma \) along the wafer diameter after being simultaneously subjected to epitaxial growth.](image-url)
the set-up for epitaxial growth since the wafers belonging to both groups have been mixed there.

5. Other semiconductors.

5.1 III-V COMPOUNDS. — Unlike original silicon wafers, stress in gallium arsenide wafers are initially distributed by values and directions as in characteristic for residual stress (Fig. 9). It is due to large density of dislocations \( N_d \) in GaAs wafers \( (N_d = 10^4-10^6 \text{ cm}^{-2} [10]) \) as compared to original Si wafers \( (N_d (10^2 \text{ cm}^{-2})) \) that is caused by low critical stress value for dislocation formation in GaAs and by great thermostress during the growth of the ingot arising mainly from intense convective heat transfer in the liquid flux layer. Thus in GaAs wafers the stress inherited from the ingot is larger than that produced by mechanical treatment of wafers.

![Diagram](attachment:image.png)

**Fig. 9.** — Distribution of \( \Delta \sigma \) (a) and stress orientation (b) in original GaAs wafer.

Distribution of stress values and orientations in GaAs wafer of 0.6 mm thickness cut from a monocrystalline ingot along its axis of growth is represented in figure 10. The distribution symmetry about the growth axis follows the symmetry of temperature gradients distribution during the cooling of the ingot and also indicates that the stress observed is inherited from the ingot.

In GaP wafers of 60 mm diameter and 0.8 mm thickness stress inherited from an ingot was also observed.

5.2 II-VI COMPOUNDS. — Using induced birefringence for stress measurement in this type of crystals is complicated by the circumstances that some of them (CdS, CdSe, ZnS, BeO, ZnO) are crystallized in the hexagonal wurtzite form and thus are characterized by natural
birefringence which presents significant difficulties for interpreting results of measurements. However, a lot of practical applications of II-VI compounds employ wafers that are cut from the ingot perpendicularly to its hexagonal symmetry axis. The plane of these wafers is optically isotropic and the change in polarization of probe beam, incident normally to the plane of wafer, should reflect only the magnitude of stress therein. The probe beam in this case must be parallel and the focussing is impermissible since converging radiation will be subject to natural birefringence and will distort the results of measurements.

Calculations show that in a plane normal to the hexagonal symmetry axis of wurtzite type crystals the photoelastic constant is isotropic and can be expressed using piezo-optical coefficients as follows:

\[ C = (\pi_{11} - \pi_{12}) \frac{n^3}{2}. \]  

The value of \( C = 4.8 \times 10^{-11} \text{m}^2/\text{N} \) for CdS was calculated from elastooptic coefficients \( p_{ij} \) and elastic pliability coefficients \( s_{ij} \) [11].

The study was carried out on round polished monocrystalline plates of CdS, CdSe and CdS_{x}Se_{1-x}/CdS. The wafers were 1.6 mm thick and 60 mm in diameter. In all measured samples stress distribution corresponded to the residual stress inherited from the ingot. Pictures of stress in wafers cut from the same ingot were very similar but an appreciable difference between ingots was observed. It can be seen in figure 11 where the results for two CdS wafers are presented, that they were cut from two different ingots perpendicular to the axis of growth.

It is to be noted that the orientation of wafer must be done very accurately. If a perpendicular to the plane of wafer forms with the hexagonal crystallographic axis an angle of 2-3° the principal contribution to birefringence is from a natural one as is seen from a constant value of it and uniform orientation of axes all over the wafer area.

6. Conclusions.

Distribution of magnitudes and orientations of stress in a semiconductor wafer belongs to the wafers individual characteristics and depends on previous treatment of the wafer. Measure-
ments of these characteristics provide complementary information and the total data are sufficient to evaluate the quality of wafer and of operations performed on it.

The symmetry of stress distribution allows one to limit the measurements at mass control to registering stress distribution along the wafer diameter.

In original silicon wafers the stress inherited from ingot was found to be less than that produced by mechanical operations. The fact is due to a highly perfected structure of single crystals. The stress substantially increases during production of integrated circuit due to heat treatment. The main factors which determine stress in silicon wafers after heat treatment are the following: the rate of heating and cooling, the position of heaters, the mode of heating and the form of wafer holders. Changing these conditions and measuring $\Delta \sigma$ before and after heat treatment, the optimum treatment procedure can be developed to produce minimal stress. It turned out, e.g., that varying the geometry of a substrate holder during the growing of the epitaxial layer can result in changes by an order of magnitude in stress values of the epitaxial structures. Optimization of the form of substrate holder allowed one to decrease substantially the possibility of slip line formation at this stage of the process.

In original semiconductor wafers of III-V and II-VI compounds the residual stress inherited from the ingot predominates since they are substantially larger than those in silicon single crystals. Subsequent production operations do not change notably the extent of stress in these wafers.

Stress measurement provides a possibility of discarding deficient wafers and optimizing high temperature production operations.

The devices used for stress control in wafers is permissable not to strictly limit concerning the localization of probe, since the principal contribution to the measured value of stress is provided by the macrostress in the substrate and not by the microstress from integrated circuit topology.

Fig. 11. — Schematical representation of distribution of $\Delta \sigma$ (a) and stress orientation (b) in CdS wafers 1.6 mm thick that were cut from different ingots.
References