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Semiconductor devices – Micro-electromechanical devices – Part 16: Test methods for determining residual stresses of MEMS films – Wafer curvature and cantilever beam deflection methods

Dispositifs à semiconducteurs – Dispositifs microélectromécaniques – Partie 16: Méthodes d'essai pour déterminer les contraintes résiduelles des films de MEMS – Méthodes de la courbure de la plaquette et de déviation de poutre en porte-à-faux

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SEMICONDUCTOR DEVICES – MICRO-ELECTROMECHANICAL DEVICES –

Part 16: Test methods for determining residual stresses of MEMS films – Wafer curvature and cantilever beam deflection methods

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The text of this standard is based on the following documents:

FDIS	Report on voting
47F/209/FDIS	47F/214/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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SEMICONDUCTOR DEVICES –
MICRO-ELECTROMECHANICAL DEVICES –

Part 16: Test methods for determining residual stresses of MEMS films – Wafer curvature and cantilever beam deflection methods

1 Scope

This part of IEC 62047 specifies the test methods to measure the residual stresses of films with thickness in the range of 0,01 μm to 10 μm in MEMS structures fabricated by wafer curvature or cantilever beam deflection methods. The films should be deposited onto a substrate of known mechanical properties of Young's modulus and Poisson's ratio. These methods are used to determine the residual stresses within thin films deposited on substrate [1][1].

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62047-21, *Semiconductor devices – Micro-electromechanical devices – Part 21: Test method for Poisson's ratio of thin film MEMS materials*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
residual stress

σ_f

stress that remains after the original cause of the stresses (external forces, heat source) has been removed

3.2
curvature

κ

amount by which a geometric object deviates from being flat

Note 1 to entry: In case of a circle, $\kappa = 1/R$ where R is the radius.

3.3
body

object with mass, not only energy, that is three dimensional (extended in 3-dimensions of space), has a trajectory of position and orientation in space, and is lasting for some duration of time

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[1] Numbers in square brackets refer to the Bibliography.

4 Testing methods

4.1 General

The deposition of a film shall make the bi-layer structure to bend together due to residual stresses in the film. The amount of deflection is directly related to the residual stresses of the film.

There are two kinds of test methods such as wafer curvature method and cantilever beam deflection method in order to measure the residual stress.

In the case of tensile residual stress, the substrate bonded to the film becomes concave, whereas for a compressive residual stress, it becomes convex.

4.2 Wafer curvature method

4.2.1 General

Wafer curvature method should be used in a wafer level processing. A wafer should be biaxial symmetric and stress free.

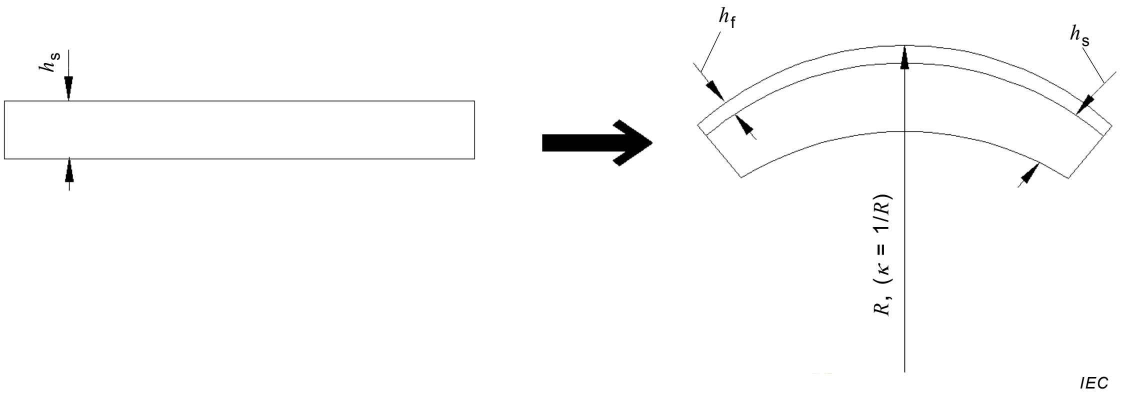
Stoney [2] used a bi-layer plate system composed of a stress bearing thin film, of uniform thickness h_f, deposited on a relatively thick substrate, of uniform thickness h_s, and derived a simple Equation (1), so-called Stoney's equation, relating the curvature, κ, of the system as shown in Figure 1, to the stress, σ_f of the film as follows [3]:

$$\sigma_f = \frac{E_s h_s^2 \kappa}{6(1-\nu_s) h_f} \qquad (1)$$

where

f and s	are film and substrate, respectively;
E	is the Young's modulus;
ν	is Poisson's ratio (see IEC 62047-21)

The formula has been extensively used in the literature to infer film stress changes from experimental measurement of system curvature changes [4].



a) Substrate before depositing thin film

b) After depositing thin film on substrate

Figure 1 – Schematic drawing of compressive residual stress induced curvature after depositing thin film on substrate

The following assumptions should be satisfied in order to use Equation (1) [3]:

a) both the film thickness h_f and substrate thickness h_s should be uniform and small compared with the lateral dimensions;

b) the film shall cover the one side surface of a circular substrate;

c) the strains and rotations of the plate system should be very small;

d) the substrate material should be homogeneous, isotropic, and linearly elastic and the film material should be isotropic;

e) the film stress states should be in-plane isotropic or equibiaxial (two equal stress components in any two, mutually orthogonal in-plane directions) while the out-of-plane direct stress and all shear stresses vanish;

f) the system's curvature components are equibiaxial (two equal direct curvatures) while the twist curvature vanishes in all directions;

g) all surviving stress and curvature components are spatially constant over the plate system's surface, a situation which is often violated in practice;

h) the edge effect near the periphery of the substrate should be inconsequential, and all physical quantities should be invariant under a change in position.

i) in order to measure more accurate residual stress, curvatures of before and after thin film deposition are measured and the stress of thin film is calculated by Equation (2) from the modified Equation (1):

$$\sigma_f = \frac{E_S h_S^2 \Delta\kappa}{6(1-\nu_s)h_f} \tag{2}$$

where

$\Delta\kappa$ is the difference of curvature before and after thin film deposition.

4.2.2 Test apparatus

More than one equipment or tool regarding contact methods (e.g. profilometry) or non-contact (e.g. video, laser scanning) are used for measuring curvature radius (R). Measurement accuracy is in the range of 0,1 nm to 0,1 µm which depends on measurement test apparatus.

4.2.3 Measurement procedures

The measurement procedures are as follows:

a) measure substrate thickness (h_s) and thin film thickness (h_f);

b) obtain the Young's modulus (E_s) of substrate and Poisson's ratio (ν_s) of substrate;

c) measure radius of curvature (R) of system and calculate curvature (κ) or measure radii of curvature (R) and calculate the difference of curvature ($\Delta\kappa$) before and after thin film deposition of system;

d) calculate residual stress(σ_f) according to Equation (1) or (2).

4.2.4 Reports

Calculate σ_f according to Equation (1) or (2) and write the value in Table 1.

Table 1 – Mandatory details for the test of wafer curvature method

Parameters	Values
Number of specimens	
Substrate material and thickness (h_s)	
Young's modulus of substrate (E_s)	
Poisson's ratio of substrate (v_s)	
Film material and film thickness (h_f)	
Substrate thickness (h_s)	
Curvature radius (R) and curvature (κ) of system regarding Equation (1)	
Curvature radii (R) and calculate the difference of curvature ($\Delta\kappa$) before and after thin film deposition regarding Equation (2)	
Stress of the film (σ_f)	

4.3 Cantilever beam deflection method

4.3.1 General

Cantilever beam deflection method should be used in a piece or chip level processing. Given a small deflection compared with the beam length, the radius of curvature in case of wafer curvature method can be substituted by the length of the beam squared, L^2, divided by twice the deflection, 2δ.

$$\sigma_f = \frac{E_s h_s^2 \kappa}{6(1-\upsilon_s)h_f} = \frac{E_s h_s^2}{6(1-\upsilon_s)h_f}\frac{\delta}{L^2/2} = \frac{E_s h_s^2 \delta}{3(1-\upsilon_s)h_f L^2} \tag{3}$$

Equation (3) involves the following assumption: there is no biaxial bending in thin film on beam structure. This method shall be used to determine the residual stresses of thin film materials by using a bi-layered beam structure. All the assumptions applied to the Stoney's equation of (Equation (1)) should be satisfied in this method.

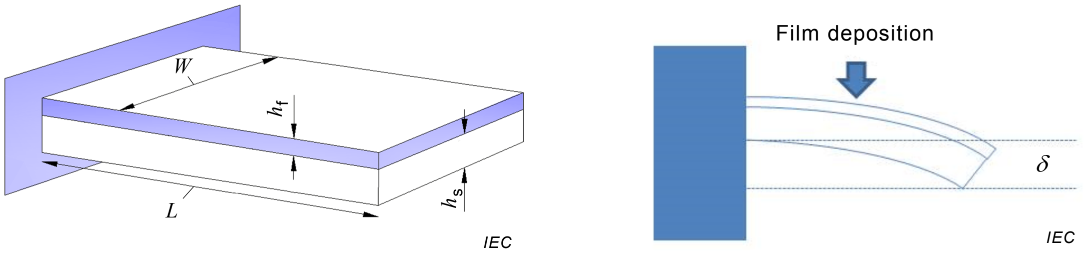
In order to measure more accurate residual stress, cantilever deflections of before and after thin film deposition of system should be measured and the stress of thin film is calculated by Equation (4) from the modified Equation (3);

$$\sigma_f = \frac{E_s h_s^2 \Delta\kappa}{6(1-v_s)h_f} = \frac{E_s h_s^2}{6(1-v_s)h_f}\frac{\Delta\delta}{L^2/2} = \frac{E_s h_s^2}{3(1-v_s)h_f}\frac{\Delta\delta}{L^2} \tag{4}$$

where

$\Delta\delta$ is the difference of deflection before and after thin film deposition.

Figure 2 shows scheme for comprehensive residual stress induced curvature, and Figures 2a) and 2b) show residual state of thin film and beam bending after thin film deposition. Thickness of the film h_f and the substrate h_s are provided in Figure 2a) and deflection δ induced by thin film deposition is provided in Figure 2b).



a) Residual stress free state of thin film b) Beam bending after thin film deposition

Figure 2 – Scheme for comprehensive residual stress induced curvature

4.3.2 Test apparatus

A noncontact surface profiler (e.g. white light interferometric microscope, digital image correlation method, confocal microscope, etc.) should be used to measure the surface profiles and deflection (δ) of a film deposited on a substrate.

4.3.3 Measurement procedures

The measurement procedures are as follows:

a) prepare a cantilever of free residual stress and measure the undeformed surface profiles as a reference;
b) measure the thickness of a substrate (h_s) and beam length (L);
c) search or measure the Young's modulus (E_s) and Poisson's ratio (v_s) of the substrate;
d) deposit a film on the corresponding substrate by using the same fabrication methods as a real MEMS device;
e) measure the deformed surface profiles and the thickness of the film (h_f);
f) measure the deflection (δ) of the free end of system or to measure deflections (R) and calculate the difference of deflections ($\Delta\delta$) before and after thin film deposition of system;
g) calculate residual stresses (σ_f) by using Equation (3) or Equation (4).

4.3.4 Reports

Calculate σ_f according to Equation (3) or (4) and write the value in Table 2.