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OPTICAL MEASUREMENT OF STRESS IN THIN MEMBRANES

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Abstract: Ion Projection Lithography being one of the New Generation Lithography (NGL) techniques, uses Silicon stencil masks. A typical 150 mm stencil mask consists of a thin membrane of 126 mm diameter containing the openings for lithography and a stiff outer ring of bulk wafer material. The thickness of the membrane is in the order of several microns. The membrane has intrinsic stress to keep it flat. To determine the stress of the mask membrane the well known bulging method is used. In the developed equipment an electrostatic force between the membrane and a second electrode replaces the conventionally used gas pressure. The change of curvature of the membrane due to pressure load is determined optically by measuring the change of focal length of an optical system where the membrane serves as a mirror.
Keywords: membrane stress, optical measurement, electrostatic bulging force

1 INTRODUCTION

Ion Projection Lithography (IPL) is one of the promising New Generation Lithography (NGL) techniques in the sub 100nm range. IPL uses Silicon stencil masks, where the patterns are formed as openings in a thin membrane. The thickness of such a membrane may be in the order of several microns, to date it is typically 3 µm. The membrane is formed by etching techniques [1] from a SOI wafer of approximately 700 µm thickness providing a 12 mm wide so-called wafer ring for handling purposes (see Fig. 1). The membrane must have tensile stress in order to stay flat. The fabrication process includes a step where Boron doping induces tensile stress in the SOI membrane layer of the wafer. Establishing proper process parameters a measurement of the stress in unstructured membranes versus doping concentration is necessary.

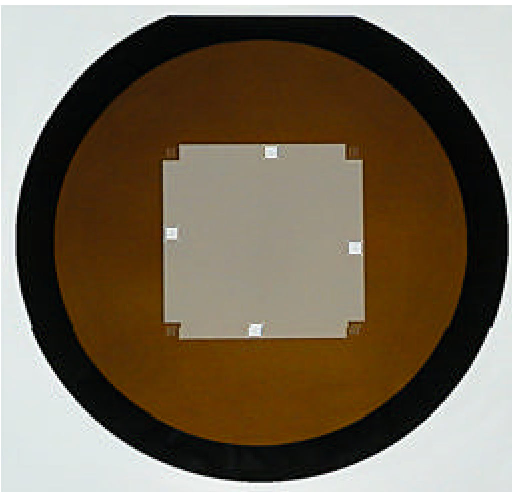

Figure 1. 150 mm stencil mask with pattern area and massive wafer ring

2 BULGING METHOD

The bulging method for stress measurement [2] makes use of the second order differential equilibrium equation

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} = -\frac{p}{T} \tag{1}$$

where x and y are the coordinates of the point of the membrane surface under consideration, p is the acting pressure, perpendicular to the membrane surface and T is the tension force per unit length of an arbitrarily shaped membrane boundary. Eq. (1) assumes small deflections of the membrane. There are several assumptions made for this formula to be valid for the whole membrane and not only for an infinitesimal domain:

a) The thickness of the membrane is uniform
b) Membrane has no openings
c) Elasticity constants are uniform and isotropic
d) The pressure is constant across the whole membrane
e) Boundary conditions are compatible with the membrane deformation

For the current purposes only b) and c) are ideally fulfilled, the other assumptions deviate by some amount and so do contribute to the error of the measurement.

The second order derivatives in eq. (1) can be expressed by the principal radii of curvature R_x, R_y with respect to the orthogonal coordinates

$$\frac{1}{R_x} + \frac{1}{R_y} = -\frac{p}{T} \tag{2}$$

The values of the radii of curvatures can be measured experimentally. The principle of the measurement is shown in Fig. 2. In this simple autocollimation system the membrane acts as a mirror reflecting the impinging light rays. The other basic components of the optical setup are an aberration free objective lens with known focal length and a laser diode point-like source. The point source is located at the focal point of the lens.

Generally, in the case of orthogonally unsymmetric shapes of the membrane the light rays reflected from its deformed surface after passing backward through the lens will create an astigmatic beam of rectilinear rays. As it is known [3], two planes, which contain the shortest and the longest radius of curvature, are perpendicular to each other. The corresponding curvatures are usually called tangential field curvature $1/R_t$ and sagittal field curvature $1/R_s$. The quantity

$$\frac{1}{R} = \frac{1}{2}\left(\frac{1}{R_t} + \frac{1}{R_s}\right) \tag{3}$$

is their arithmetic mean value.

At the experimental measurement the values of both the radii R_t and R_s can be determined by searching of mutually perpendicular tangential, as well as sagital focal lines.

Provided that the membrane surface is flat, the light source and its image are both at the focal point. A deflection of the membrane causes a change of the focal length of the optical system as a whole. It can be expressed by the well-known relation for a system of two centered thin lenses at mutual distance l:

$$\frac{1}{f} = \frac{1}{f_0} + \frac{1}{f_m} - \frac{l}{f_0 f_m} \tag{4}$$

from which the radius of curvature of the mirror-like membrane surface can be obtained,

$$R = 2\left(\frac{f_0^2}{\Delta} + f_0 - l\right) \tag{5}$$

where $R = 2f_m$. The value of f_m is the focal length of the mirror-like membrane surface, f_0 is the known focal length of the lens, Δ is the shift of image (focal) plane of the whole system with respect to the original focal plane, and l is the distance membrane – lens. Using eq. (5) the values of both the quantities R_t and R_s can be evaluated. After insertion into eq. (2) one can solve for the searched membrane force T.

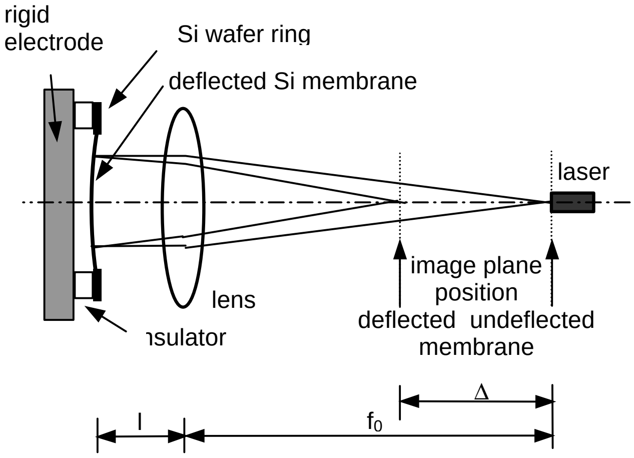

Figure 2. Principle of the optical membrane stress measurement using electrostatic pressure

3 DESCRIPTION OF THE APPARATUS

The optical setup of the apparatus consists of a laser diode source 650 nm / 10 mW, a well corrected telescope doublet f = 1000 mm, ∅ = 152 mm and a small groundscreen movable on a rail with a mm scale. For better searching of the focal plane the focal spot is observed by a simple magnifier or by using a microscope eyepiece. The achievable precision of such a focal plane localization is under 1 mm.

The specimens are unstructured membranes of a circular shape, 126 mm in diameter. They are connected to a massive wafer ring in order to have something that can be handled properly.

The applied pressure bulges the membrane only approximately to a spherical surface. We must be aware of the fact that the actual membrane deformation is not at all spherical even if all assumptions regarding uniformity are fulfilled. The reason for this lies in the boundary condition of the membrane (transition from membrane to wafer ring), that does not satisfy the condition of a free membrane. The closest spherical shape approximation is in the middle of the membrane, so we are forced to use diaphragms as small as possible. But on the other hand, this increases blurring of the focal spot due to diffraction phenomena. Thus, we have chosen the diameter of about 70 mm on the membrane surface illuminated by the laser light.

For actual calculation eq. (2) is now modified in order to distinguish between the intrinsic prestress of the membrane and the stress induced by the bulging force. In the case of an axially symmetric membrane shape and a uniformly distributed pressure load we get

$$\sigma_0 + \sigma_P = -\frac{pR}{2t} \tag{6}$$

where σ_0, σ_P are tensile stresses related to the force T and the membrane thickness t as $\sigma = T/t$, p is the pressure load and R is the mean change of membrane radius of curvature due to the applied pressure. σ_P is the added membrane stress due to the change of deformation with increasing pressure according to

$$\sigma_P = \frac{E}{1-\nu}\frac{a^2}{6R^2} \tag{7}$$

and σ_0 is intrinsic membrane stress, which has to be determined. In eq. (7) E is the Young's modulus of elasticity, ν is the Poisson's ratio and a is the half diameter of the membrane.

An electrostatic pressure between the membrane and a second electrode at different electrical potential was used to deflect the membrane. The electrostatic pressure p between a couple of conductive plates is given by

$$p = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 U^2}{d^2} \tag{8}$$

where U is the applied voltage, d is the gap electrode – membrane and ε_r, ε_0 are the relative permitivity of the medium (air) and the value of the permitivity in vacuum. As can be seen, the generated force is inversely proportional to the second power of the gap distance. In order to guarantee a satisfactory precision of the gap width determination, two distances were used, 1.50 mm and 2.18 mm, respectively, at voltages ranging from 0 to 900 V.

For simplicity, the second electrode is used as holder for the wafer ring. It supports the membrane at three points in horizontal position, so the specimen can easily be placed manually.

Depending on the magnitude of mid deflection of the membrane the first order approximation of (6) may be appropriate, which neglects the pressure induced stress σ_p. This can be of interest, if the elastic constants of the membrane are not known.

4 RESULTS

Depending on the implanted doping concentration Boron doping induces tensile stress in a Si monocrystal. Boron implantation is done with a constant dose across the wafer surface. Fig. 3 shows the resulting relation of membrane stress versus doping concentration. Each experimental value represents the mean value of stress of several individual measurements at different pressure loads. The total error of the measurement has been calculated according to the rules of error distribution. The error of the measured data Δ and U is considered as statistical. The contributions are added quadratically. The error of constants of the apparatus, which are needed for the calculation, are systematic and are summed. Each membrane is measured in two different positions.

From theoretical considerations [4], it is known that stress vs. doping concentration should show a linear relation. Calculating a linear fit through the experimental results does not yield zero stress for zero doping. This has been detected as initial stress due to the SOI wafer production.

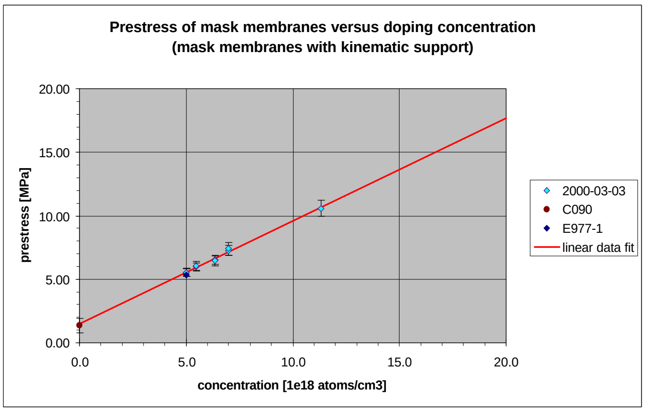

Figure 3. Results of stress measurement on Si membranes vs. Boron doping concentration.

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