MECHANICAL PARAMETER EXTRACTION USING RESONANT STRUCTURES

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ABSTRACT

In order to model and design micromechanical sensors and actuators, it is of crucial importance that thin film mechanical parameters, such as the Young's modulus and the residual stress, are known. In this paper, the parameter extraction method using resonant structures has been used to obtain these data and has been compared with the bulge test. Circular aluminum diaphragms have been used as samples.

INTRODUCTION

Planar integrated circuit technology together with non-IC compatible processing steps such as wet anisotropic etching of silicon is used to fabricate microsensors, microactuators and microsystems. In order to model and design these sensors and actuators, it is of crucial importance that thin film mechanical parameters, such as the Young's modulus, and the residual stress are known. However, it is well known that thin film materials used in microsystem technology can have properties which differ from their bulk counterparts. Besides, thin films exhibit residual stress, which is strongly process dependent. This necessitates explicit determination of the properties. In this paper, the resonance method will be highlighted using circular aluminum membranes. A similar measurement method has been presented in ref. [1] and ref. [2]. However, in this paper the resonance method is compared to the bulge test. Circular membranes are preferred because they are easier to interpret. The method can in principle generate the Young's modulus and the residual stress. The well known bulge test has been applied to the same aluminum membranes, allowing a comparison of the measurement methods.

SAMPLE PREPARATION

Silicon wafers were used as a substrate material for the aluminum deposition. Both sides of the wafer were covered with aluminum using a Varian (3117) E-beam evaporation system. The thickness of the films has been determined by breaking the samples and studying the interface with a Scanning Electron Microscope (SEM). The backside of the silicon wafer has been patterned using standard photolithographic techniques. The circular etch windows are defined by wet etching the aluminum in a 80% H_3PO_4, 11% CH_3COOH, 4% HNO_3, 5% H_2O solution. Reactive Ion Etching (RIE) has subsequently been used to etch through the 380 μm silicon wafer. Depending on the loading effect, the etch rate varied between 4 and 5 μm/min. at a pressure of 150 mTorr, a power of 100 Watt and an SF_6 / O_2 gas mixture with flows of 50 sccm and 10 sccm respectively. The downward direction etched three times faster than the lateral direction.

THEORY AND EXPERIMENTAL SET-UP

Resonance method

In principle, the Young's modulus and the residual stress can both be obtained from resonance data of membranes. Wah [3] determined the first 9 resonance frequencies of circular diaphragms as a function of geometrical and material parameters. He solved the characteristic equation numerically. A functional behaviour, similar to the behaviour of doubly supported beams [4] was used to fit the numerical data. For the fundamental frequency the following equation is obtained:

$$\omega_1 \approx 10.16 \frac{h}{a^2} \sqrt{\frac{E}{12\varrho(1-\nu^2)}\left[1 + 0.794 \frac{\sigma_o(1-\nu^2)}{E} \left(\frac{a}{h}\right)^2\right]} \qquad (1)$$

where ω_1 is the lowest natural frequency, a is the radius of the plate, h is the thickness of the plate, σ_o is the uniform in-plane tension, E is the Young's modulus, ν is Poisson's ratio and ϱ is the density. The correlation coefficient of Wah's numerical data and the fit is close to 0.999. The second term under the square root sign determines the relative contribution of the membrane stiffness compared to the bending stiffness. For our membranes, the membrane stiffness dominates, and equation 1 can be simplified to:

$$f_1 = \frac{\omega_1}{2\pi} \approx 0.416 \frac{1}{a} \sqrt{\frac{\sigma_o}{\varrho}} \qquad (2)$$

The membranes have been excited optothermally by a diode laser or an Ar^+-laser [5]. The aluminum around the membrane has been coated with a black layer in order to enhance the absorption. The vibration has been monitored with a Michelson interferometer (fig. 1).

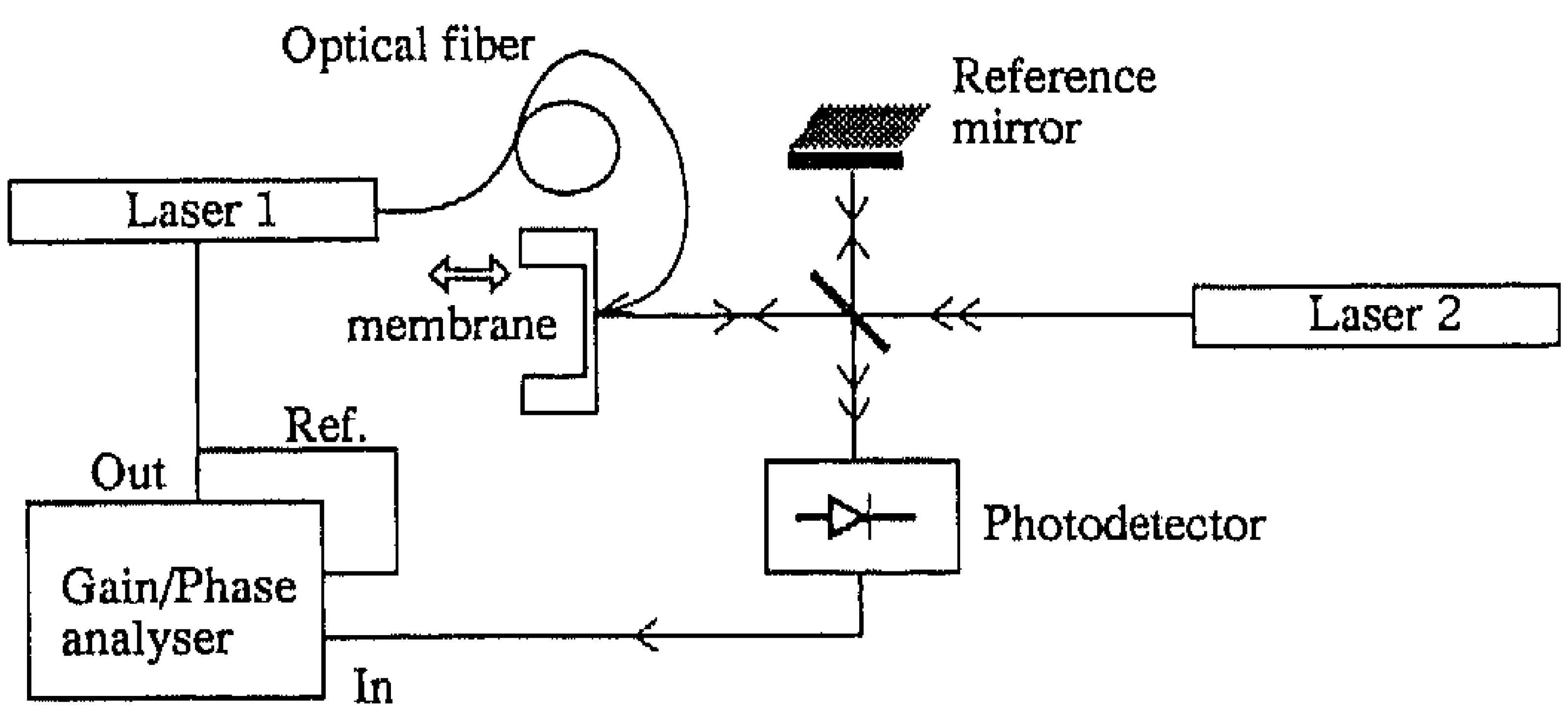

Figure 1. Schematic diagram of the resonance measurement system. Laser 1 (diode- or Ar^+-laser) is used for optothermal excitation [5] and laser 2 (He-Ne laser) is used for the Michelson interferometer set-up, which is used for the detection of the vibration.

Bulge test

By applying pressure to the membrane and measuring the deflection (fig. 2), the biaxial modulus $E/(1-\nu)$ and the residual stress σ_o can be obtained. Small et al. [6] have performed finite element analysis in order to generate a procedure for a correct use of the bulge test. Assuming a spherical cap shape of the deflection, the following equation expresses the pressure (P) vs. deflection (x) behaviour:

$$\frac{P}{x} = \frac{8E_{calc}hx^2}{3a^4(1-\nu)} + \frac{4h\sigma_o}{a^2} \qquad (3)$$

in which x is the total bulge height and P is the pressure. Plotting P/x vs. x^2 results in a line of which the slope is proportional to the biaxial modulus and the intercept is proportional to the residual stress. A correction for the inaccuracy of the spherical cap model should be made, and is expressed in equation 4:

$$\frac{E_{corr}}{(1-\nu)} = \frac{E_{calc}}{(1-\nu)}(1 - 0.24\nu - 0.00027(1-\nu)\sigma_o) \qquad (4)$$

where σ_o is in units of MPa. The total height of the bulge as well as the diameter of the membrane, have been measured using a Dektak surface profilometer.

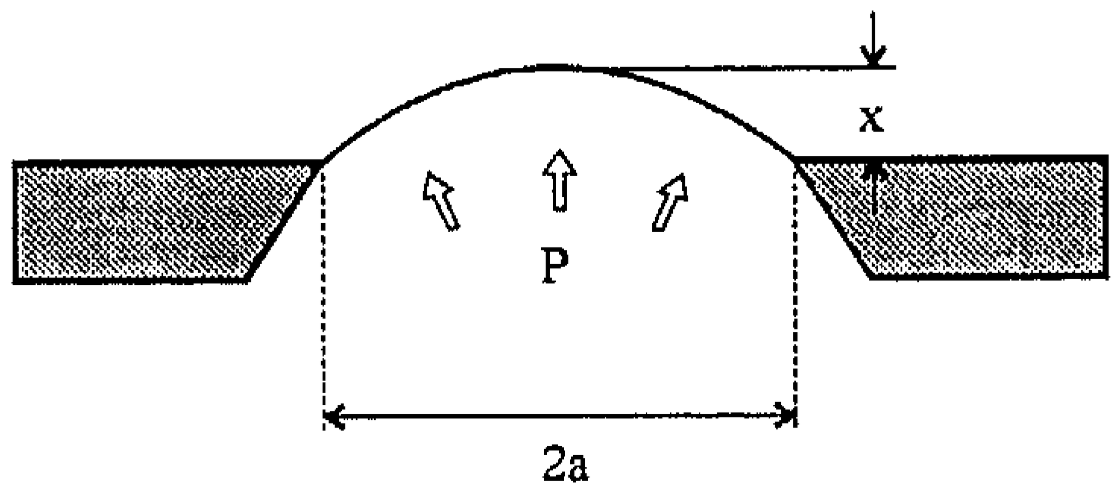

Figure 2. Bulge test schematic.

RESULTS AND DISCUSSION

The results of the resonance method of aluminum membranes with different radii are given in columns 2 and 3 of table I. The residual stress has been calculated using equation 2. The results of the bulge test are given in columns 4 to 6 of table I and are graphically represented in figure 3. The average values of table I are: $\sigma_{o\text{-}res}$=92±10 MPa, $E_{bulge\text{-}calc}$=57 ±5 GPa, $E_{bulge\text{-}corr}$=62±5 GPa, $\sigma_{o\text{-}bulge}$=74±18 MPa.

As can be observed in table 1, the resonance method generates systematically higher values for the residual stress in comparison with the bulge test method. For the first three membranes of table 1, these values are roughly 15 % higher. This may partly be due to the assumed density: the real density will probably be lower, thereby lowering the calculated residual stress. The density does not appear in the equation describing the pressure - deflection behaviour.

Table I. Measurement data of the resonance method and the bulge test.
The thickness of the aluminum membranes is 715 nm, determined using a SEM. The radius is the average of two measurements perpendicular to each other. The residual stress determined by the resonance method has been calculated assuming a density of 2700 kg/m^3 and the Young's modulus has been calculated assuming a Poisson ratio ν=0.345. f_1 denotes the fundamental mode.

Radius a [mm]	Fund. Freq. f_1 [kHz]	σ_0-res [MPa]	$E_{bulge\text{-}calc}$ [GPa]	$E_{bulge\text{-}corr}$ [GPa]	σ_0-bulge [MPa]
1.005	76.8	93	50	55	83
1.521	54.4	107	59	65	89
1.913	39.6	90	56	62	76
2.018	37.8	91	61	67	48
3.133	22.8	79	-	-	-

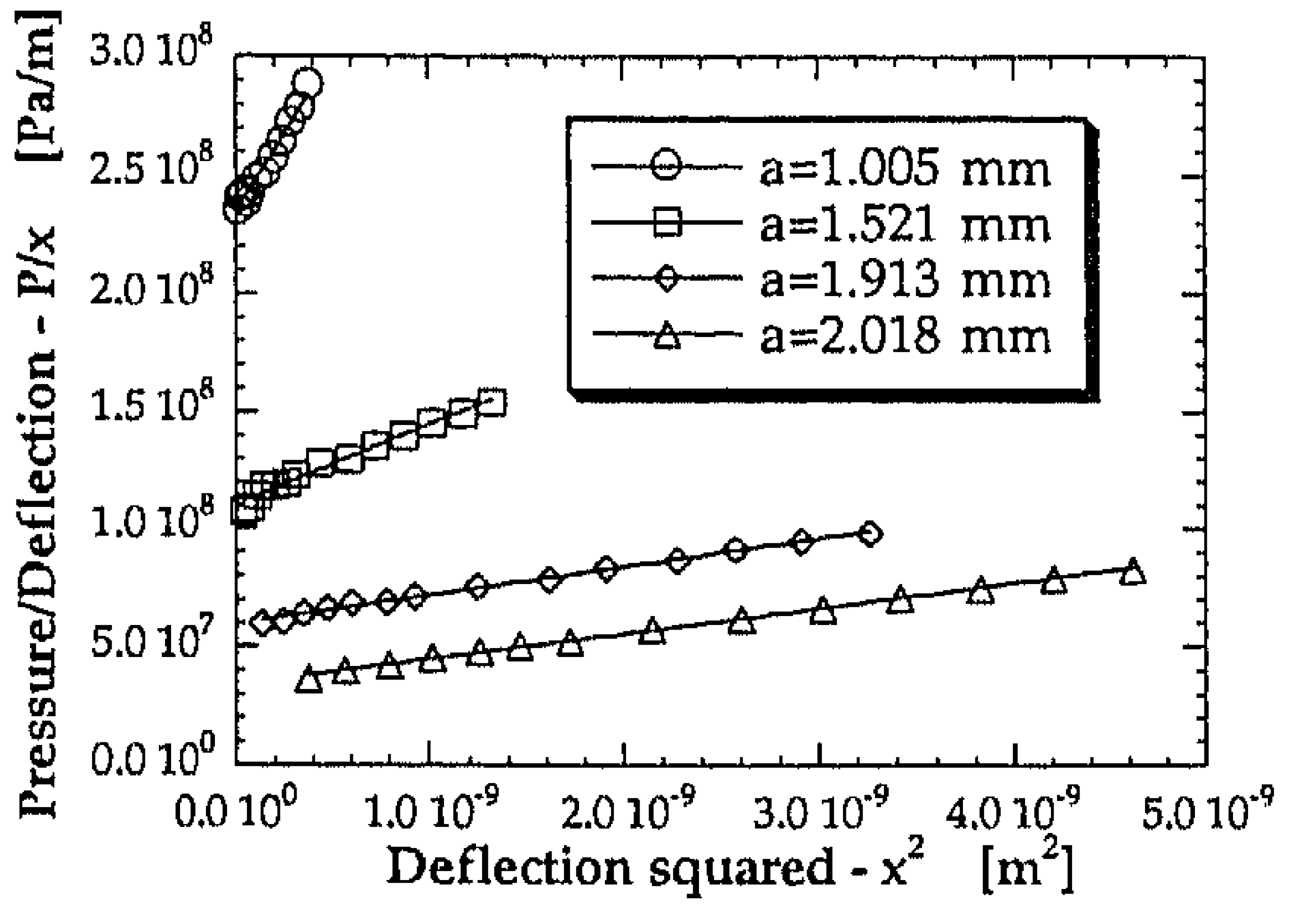

figure 3. Measurement data of the bulge test.

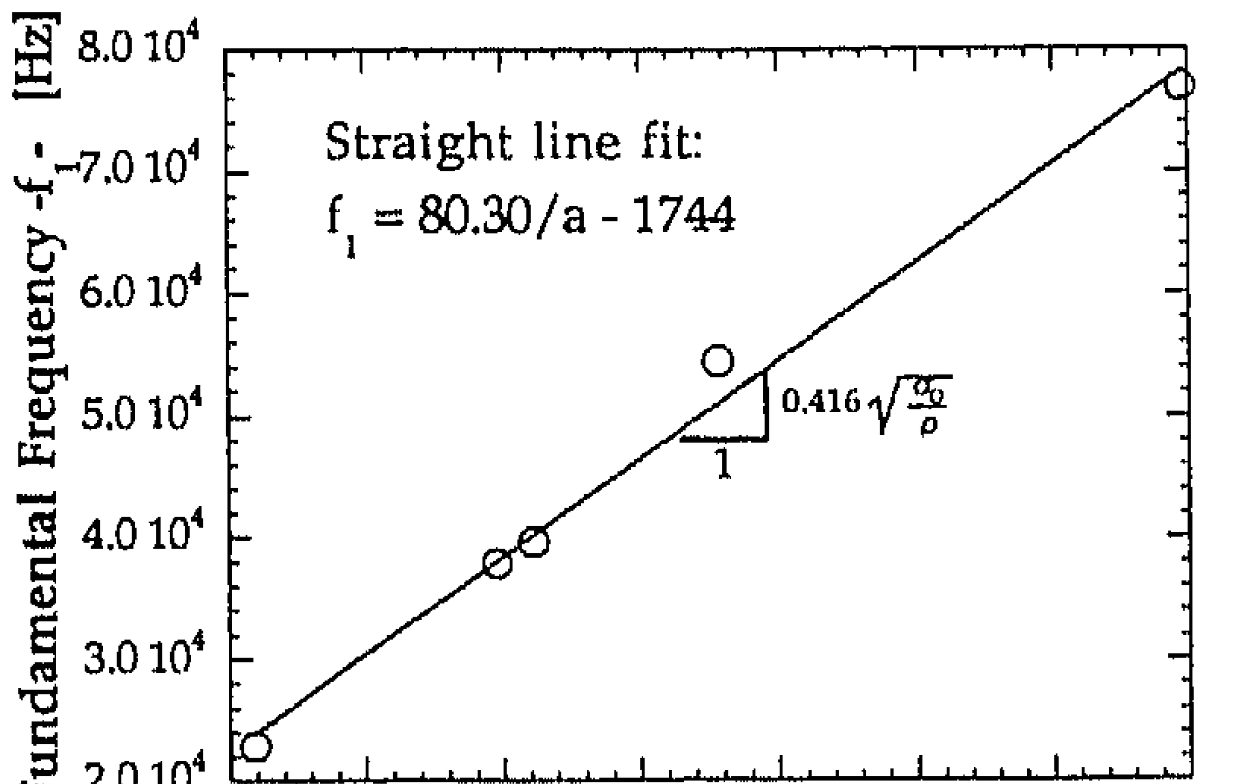

figure 4. Measured resonance frequencies as function of the reciprocal radius.

On the other hand, the thickness will affect the data obtained from the bulge method, while the resonance method is independent from the thickness (see eq. 2). Thickness inhomogeneities may therefore partly explain the higher scatter of the bulge test data in comparison with the resonance method data. The scatter which is observed in the data of both methods, may be due to an inhomogeneous stress distribution across the silicon wafer.

According to equation 2, a linear line should be obtained when plotting the resonant frequency vs. the reciprocal of the membrane radius. In figure 4 it can be observed that the resonant frequency results indeed show a linear behaviour as function of 1/a, confirming the detected resonant frequency peaks. The resulting residual stress is $\sigma_0 \approx 100$ MPa. Besides, for the membrane with a radius of 1.521 mm, the second mode has been detected as well. The second mode has been observed at 77.4 kHz, i.e. 1.5 times the fundamental frequency, which is in accordance with the numerical solution of Wah [3].

Most of the laserlight was reflected because of the high reflectivity of the aluminum membranes. This facilitates the detection of the resonance, but it hinders the optothermal excitation of the membranes. For this reason, it appeared to be necessary to coat the membrane-chip with a black layer. This could only be done in close vicinity of the membrane, not on the membrane itself. Unless if one uses a high power focused laser beam, one excites 'off-membrane'. In order to study this effect, the circular membranes have been excited, besides by means of a diode laser, by an Ar^+-laser as well. It appeared that, at low laser powers, the resonance peak did not shift in frequency, only the amplitude of the vibration changed. When exciting 'on-membrane' with the Ar^+-laser at a power of 0.16 W (losses due to mirrors, fibres etc. are not included), the resonant frequency was the same compared to the diode laser, namely 37.8 kHz (see table I).

With optothermal excitation of the circular membranes, it is possible to heat up the membranes. This leads to a lowering of the tensile stress and thus in a lowering of the resonance frequency. The Ar^+-laser allows us to vary the power and study the influence of the heating as well. When exciting 'on-membrane', it appeared that an increase of the laser power from 0.16 W up to 0.44 W resulted in a slight decrease of the resonant frequency, namely from 37.8 kHz to 37.5 kHz. When the laser power was further increased up to 0.56 W, the resonant frequency drastically lowered to 36.8 kHz. Since we only measured at low powers with the Ar^+-laser or at even lower powers of the diode laser, we are confident that, for the results presented in table I, the heating effect is negligible. In conclusion, the laser power should be high enough in order to excite the membranes above noise level, and at the same time as low as possible in order to avoid the heating effect.

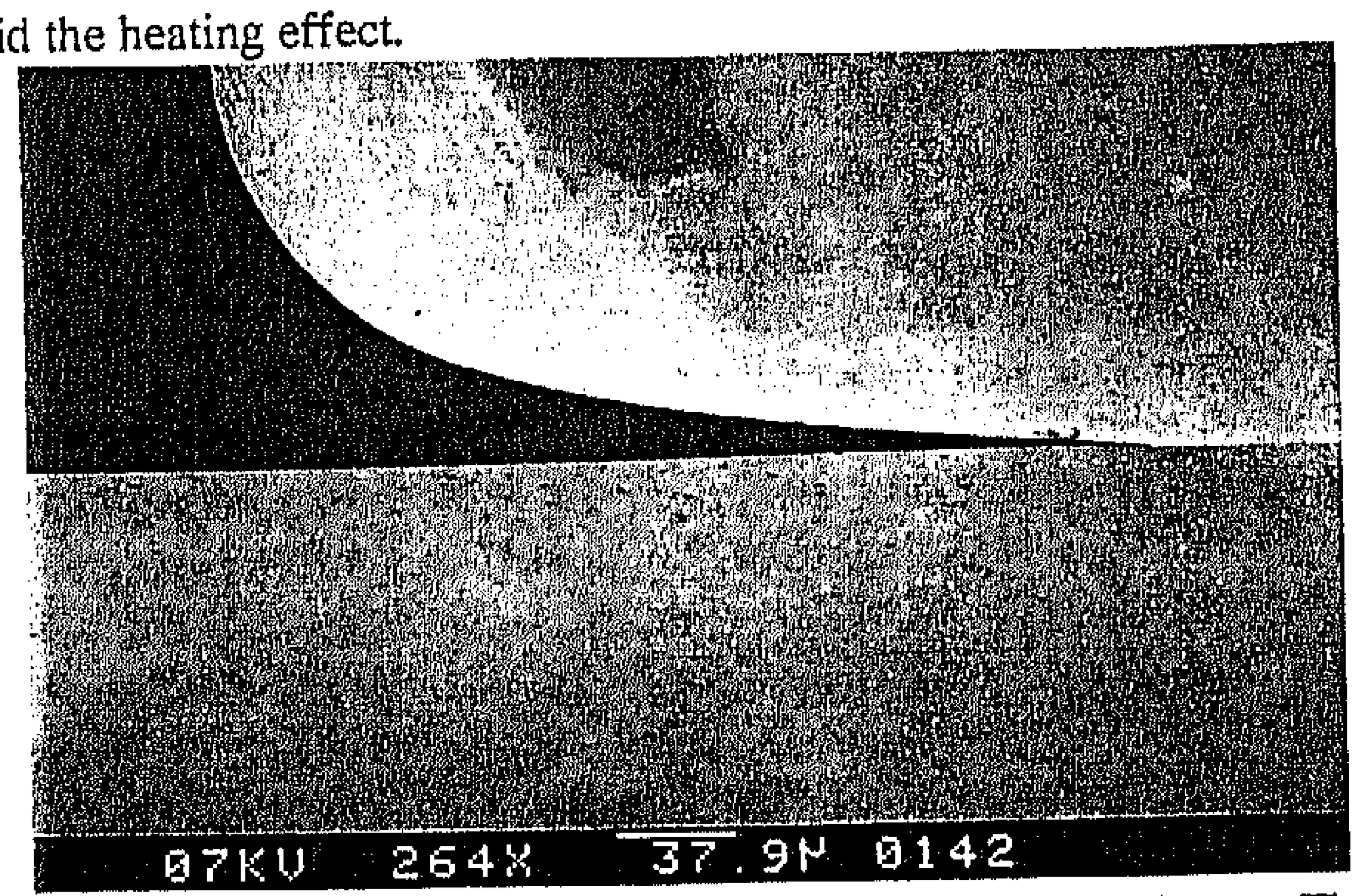

Figure 5. A Scanning Electron Micrograph of the edge of an aluminum membrane. The bar indicates 37.9 μm.

The clamping of the aluminum membranes may affect its mechanical behaviour. The clamping of the membranes is shown in figure 5, and is far from ideal. However, it is unclear whether the clamping changes the mechanical response different in the case of the resonance method with regard to the bulge test.

The resonance method can be used to extract the Young's modulus, as well. Equation 1 should be used to extract the Young's modulus. In this case one should plot $(fa)^2$ vs. $(h/a)^2$. The slope of a linear fit is proportional to the Young's modulus and the intercept is proportional to the residual stress. For our membranes the bending stiffness is negligible compared to the membrane stiffness, and therefore equation 1 can be simplified to equation 2. For the determination of the Young's modulus the geometrical parameters of the membranes should be adapted (thus thicker membranes with smaller radius).

SUMMARY

The resonance method has been used to extract the mechanical properties of thin aluminum films. In theory, the residual stress and the Young's modulus can be determined, although the geometrical parameters should be chosen such that the films have flexural rigidity. Otherwise, solely the residual stress can be determined.

The resonance measurement data of circular films with different radii indicate that the results are consistent. These data have been compared to the bulge test. The comparison shows that the residual stress determined by the bulge test is consistently lower. The scatter of the bulge test data was larger than the scatter of the data obtained by the resonance method which may partly be due to inhomogeneities in the thickness of the aluminum films. It is concluded that the resonance method is a useful method for the extraction of thin film mechanical parameters and residual stress.

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