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NOTCH FRACTURE OF MEMS SENSORS MADE OF SINGLE CRYSTAL SILICON

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ABSTRACT

Designers of silicon microstructures are often facing a so-called notch fracture problem. Anisotropic etching results in corners which are sharp on an atomistic length scale. Neither the stress-based design approach nor the well-established linear elastic fracture mechanics (LEFM) apply for such cases. In analogy to the LEFM for cracks, a notch fracture mechanics can be developed. In the present paper, a simple sensor-type plane-strain bending specimen with 23 μm thick membrane has been manufactured and tested to determine the critical notch stress intensity factor for silicon microstructures with notch opening angle 125.26^o. The resulting critical stress intensity factor has been used to predict the burst pressure test results of the same type sensor structures. Excellent agreement between the prediction and burst tests was observed. It indicates that the critical notch stress intensity factor can be taken as failure criterion for sensor structures with a thin membrane. The critical notch stress intensity factor is, however, about 20% lower than the value from bulk material. For design purpose of pressure sensors, an equation for calculating the notch stress intensity factor as a function of membrane thickness is given. The factors influencing the notch stress intensity factor and the possibility of a unified failure criterion for silicon microstructures with different notch angles are discussed.

KEYWORDS

Notch fracture, MEMS, Single Crystal Silicon, Failure Criterion.

INTRODUCTION

The development of the fast growing micro-electro-mechanical-systems (MEMS) has presented many new technological challenges. One of them is called notch fracture of silicon microstructures. Silicon is an ideal elastic brittle material. For failure analyses of structures made of brittle materials, the stress based strength approach and the LEFM approach can be applied. In the former, a maximum stress in the structure must be found while in the later a crack pre-exists and a stress intensity factor should be calculated. For silicon microstructures used in MEMS, the anisotropic etching process that etches different crystallographic planes with dramatically different speed, results in atomistically sharp reentrant notches. Early analysis by Williams [1] has shown that a stress singularity exists close to the notch tip.

The degree of the stress singularity depends on the notch opening angle. Thus, for silicon microstructures with sharp notches, neither the strength approach nor the LEFM may be applied. Hence, a notch fracture mechanics must be developed. By an asymptotic analysis, the stress field near the notch tip can be expressed by three terms, – a radial single term, an angular term and a stress intensity factor. Intuitively, we may think that the fracture mechanics for crack problems can be directly extended to the notch fracture problem. Because of the special singularity at crack tips, $(r)^{-0.5}$, where r is the distance to the crack tip, there is a mathematically beautiful one-to-one relation between the crack tip stress intensity factor and the surface energy. Irrespective of the local fracture process, the critical stress intensity factor links directly to the surface energy and can be formulated as the fracture criterion. For notch problems, this simple relation does not exist and the notch tip stress intensity factor loses the link to the energy argument. There is no strong theoretical basis and it needs to be proved experimentally that the notch stress intensity factor can be taken as a fracture (initiation) controlling parameter. Even if the critical notch stress intensity factor is a fracture parameter, it should work only for crack initiation and its value is dependent on the notch angle. How to develop a general failure criterion for silicon microstructure - how to link the critical notch stress intensity factors with the critical stress intensity factor is still an open question.

A considerable work has been done in the literature to determine the critical stress intensity factors [2-5], in particular by Suwito [3]. For a fixed angle, Suwito has shown that the critical notch stress intensity factor is a constant. The critical notch stress intensity factor is increasing with the increase of notch angle. The experiments carried out in the literature were mostly for bulk materials. In this paper, a sensor type specimen with thin membrane has been manufactured and tested to determine the critical stress intensity factor. The resulting critical stress intensity factor was then applied to predict the burst pressure of the same type structures. By finite element analysis, a stress intensity factor equation as a function of the membrane thickness is presented for pressure sensor design. The transferability of the critical stress intensity factor for bulk materials to thin membranes and various factors influencing the stress intensity factor are discussed.

NOTCH TIP STRESS FIELDS

Single crystal silicon is an an-isotropic elastic material. The stress fields in anisotropic elastic solids can be conveniently described by the Stroh's formalism [6-7]. For the coordinates system shown in Fig. 1, the general solution for displacements and stress functions can be written as

$$\begin{aligned} u_i &= \sum_{\omega=\pm 1}^{\pm 3} a_{i\omega} f_\omega(z_\omega) \\ \phi_i &= \sum_{\omega=\pm 1}^{\pm 3} b_{i\omega} f_\omega(z_\omega) \end{aligned} \tag{1}$$

where $z_\omega = x + \rho_\omega y$, ρ_ω are Stroh's 3-pair eigenvalues, f_ω are twice-differentiable one-variable functions, a_ω and b_ω are constants. Stroh has shown that eigenvalues can be solved from a standard six-dimensional linear eigenvalue problem. Detailed formulation of the eigenvalue problem can be found in [7]. By conducting an asymptotic analysis of the near tip stress fields , using the traction free conditions and neglecting the higher terms, we can finally write the near tip stress and displacement fields as

$$\begin{aligned} \sigma_{ij} &= K_I^N f_{ij}^I(\theta) r^{\lambda_I - 1} + K_{II}^N f_{ij}^{II}(\theta) r^{\lambda_{II} - 1} \\ u_i &= K_I^N g_{ij}^I(\theta) r^{\lambda_I} + K_{II}^N g_{ij}^{II}(\theta) r^{\lambda_{II}} \end{aligned} \tag{2}$$

where λ^I and λ^{II} are mode I and II degrees of singularity, K_I^N and K_{II}^N are notch stress intensity factors, and f_{ij} and g_{ij} are angular functions. For the notch considered in this paper with notch opening angle between the (001) and (111) planes, $2\beta = 125.26^\circ$, the mode I degree singularity, λ_I, is 0.6257 and mode II, λ_{II}, is 1, (not singular) [3,4]. Thus the near tip field can be written more explicitly

$$\begin{aligned} \sigma_{ij} &= K^N f_{ij}^I(\theta) r^{-0.3743} + F_{ij}(\theta) \\ u_i &= K^N g_{ij}^I(\theta) r^{0.6257} + G_{ij}(\theta) r \end{aligned} \tag{3}$$

where the K^N is the notch stress intensity factor and F and G are angular constants. Here K^N is defined by normalizing the angular function such that $f_{ij}^I(\theta = 0) = 1.0$. By carrying out a finite element analysis for a given geometry and load, the K^N can be determined from either the opening stress along the x axis (θ=0) or from the opening displacement along the notch edge ($\theta = \pm\alpha$) by a least square fitting. In the present paper, the average opening displacement along the notch edge was applied. In finite element calculations, displacements are supposed to be more accurate than stress and strain. It should be noted that for silicon structures considered here, there is a rigid rotation around the notch tip and this rigid rotation has been subtracted prior to the curve fitting.

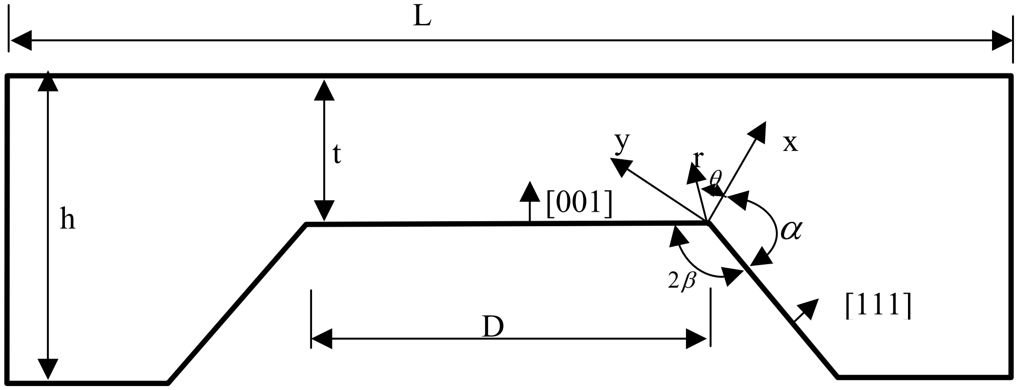

Fig. 1 Sketch of a sensor-type microstructure. The notch angles (2β =125.26°) are determined by crystallographic planes. The coordinates are used for material representation and asymptotic analysis.

SENSOR-TYPE SPECIMENS

MEMS structures are indeed composite. Fig. 2b shows a typical sensor-type microstructure (glass-silicon-glass sealed by anodic bonding). It is not easy to test the silicon microstructure itself. For bending tests, there are basically two possibilities to apply load to the microstructure shown in Fig.1 such that positive singular stress fields are generated at the notches. One way is to apply the load at the non-etched side. In this case the two supporting ends should be simple ends – fixed in vertical direction but free to move horizontally. Another way is to apply the load at the etched side. In this situation the two supporting ends on the top can be fixed in both horizontal and vertical directions. Specially prepared specimens with very thick membranes and loading at the non-etched side have been used in the literature [3-4]. The smallest *t/h* tested by Wuwito [3] was 0.8. For a typical silicon sensor structure, the membrane is very thin and the typical *t/h* value is about 0.02. It is questionable whether the critical notch stress intensity factor from bulk material can be applied to structures with such thin membranes. Furthermore, the fracture strength may be sensitive to the micromachining process and specially prepared specimens may not be representative of sensor structures from mass production. In this paper, bending specimens cut from a generic type sensor have been tested [8]. The dimensions of the generic sensor tested in this paper are *L*=1.95 mm, *D*=0.45 mm, *t*=0.023 mm, *h*=0.4 mm and width W=0.85 mm. Fig 2a shows the 3-point bending specimen.

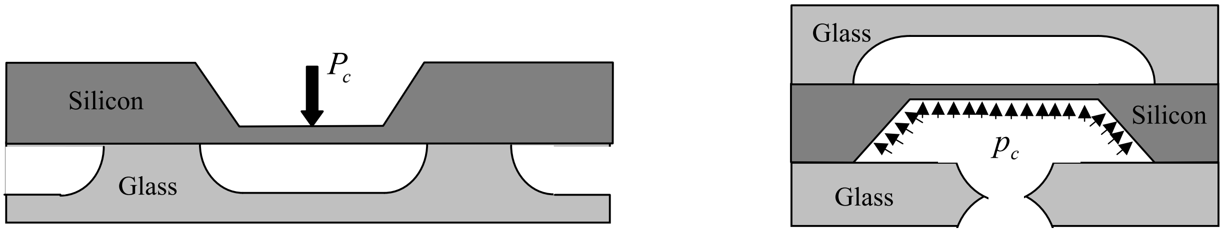

Figure 2: Sketches of a) the three point bending sensor-type specimen and b) the burst pressure specimen.

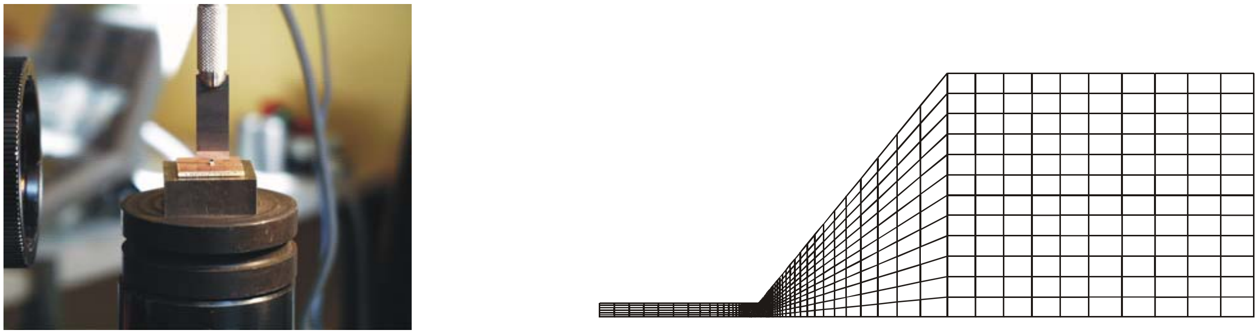

Figure 3 a) Lateral view of the loading blade and bending specimens, b) the finite element mesh used for the analyses.

The tests were conducted on a Darmtec tensile machine with a specially mounted micro load cell of sufficient accuracy. The load was applied through a super sharp flat blade made of quenched high alloy steel, see Fig. 3. The specimen was fixed with silicone glue on a copper layer of a thin resin plate of area 1.5 cm by 1.5 cm. The plate with the specimen was placed on a mobile micro table with four degrees of freedom. The test setup was equipped with an optical microscope for positioning. After accurate positioning of the blade parallel to the desired axis by manipulating the table translation and rotation degrees of freedom, the specimen was loaded with a cross-head speed 0.5 μm/s until its breakup. The details of the experimental technique are reported in [8].

The glass-silicon-glass specimens used for the burst pressure tests are shown in Fig. 2b. The composite structure is attached on top of a holed plate. A controlled increase in time of pressure was applied through the hole in the silicon cavity until the failure. Only the final burst pressure was registered for each specimen. It should be noted that the bending specimens were designed and loaded as 2D specimen while the burst testing specimen is 3D and the membrane has a dimension 1.0mm by 0.45 mm.

TEST RESULTS AND CRITICAL NOTCH STRESS FACTOR

For the bending tests, 9 specimens in total have been tested. Load-cross head displacement was monitored for each test. All showed linear relation up to final failure. Post-test examination shows that all the specimens fractured at the midpoints of the notch tip edges. For the specimens with width 0.85 mm, the averaged critical load of the 9 specimens is 1.04 N with a standard deviation 0.11 N, minimum 0.934 N and maximum 1.23 N. Finite element analyses were carried out to determine the critical notch stress intensity factor. Fig. 3b shows half of the finite element model used. A specially designed, very fine mesh was used at the notch tip. There are in total 3045 4-node plane strain ABAQUS elements in the model. The near tip elements are about 0.11 nm long. The elastic anisotropic constants with regard to the material coordinates shown in Fig. 1 were taken from [2]. As seen in the Fig 3b, the supporting glass was not modeled. Instead, the interface between the silicon and glass was assumed to be rigid. Preliminary analyses have shown that the length of the rigid boundary has little influence on the notch tip stress field, because the membrane considered in this paper is very thin. The average opening displacement along the notch edges under the applied critical load were fitted by a non-linear curve fitting program with the following equation

$$u_{\theta(\theta=\pm\alpha)} = 0.000578^{0.6257} + 0.00056r \qquad (4)$$

The fitting range for the above equation is 3.5 μm which is 15% of the membrane thickness. Please note that in the above equation the unit for displacement and radius is [mm]. By comparing Eq. (4) with Eq. (3) and using $g_{\theta\theta(\theta=\pm\alpha)}$=$7.91\times10^{-6}\,MPa^{-1}$, we obtain the critical notch intensity factor K_C^N=73.0 MPa$\,mm^{0.3743}$ (5.5 MPa$\,m^{0.3743}$).

The same finite element mesh shown in Fig. 3b was slightly modified for analyses of the pressure sensor to take into account the boundary conditions. Analyses have revealed the following relation between the pressure and the notch tip stress intensity factor for the given structure: $p = 0.575K^N$, where the p is the applied pressure [bar]. By applying the critical stress intensity factor from the bending test, we finally predict the burst pressure would be 42 bar.

The burst pressure tests carried out included 8 specimens in total. Three of them failed at 40 bar, three failed below 40 bar with a minimum 38 bar, and two over 40 bar which is beyond the measurement limit. All specimens were reported to fail at the notch tip in the proximity of the one half of the long side of the rectangular membrane (1mm by 0.45 mm). The averaged burst pressure is about 39.7 bar which is very close to the predicted one. It should be noted that the calculations carried out in the paper were based on a 2D stress field, which is well justified for the bending specimens. For the burst pressure specimens, the stress field is clearly 3 dimensional. However, the experimental observation has indicated that the failure occurred in the middle of the long edge of the membrane and the long side is two times as long as the short side. The 2D plane strain calculations may therefore be justified.

For design purpose pressure specimens with different membrane thickness but otherwise identical dimensions have been analyzed. Six cases with membrane thickness, 18, 23, 30, 35, 40 and 50 μm were considered. Following relation between the applied pressure p [bar] and the notch stress intensity factor [MPa$\,mm^{0.3743}$]: $K^N = ph^{0.3743} f_N(t/h)$, where the unit of h is [mm] has been obtained:

$$f_N(\frac{t}{h}) = 6.37 - 0.08502(\frac{t}{h}) + 0.0003281(\frac{t}{h})^2 \,. \qquad (5)$$

DISCUSSIONS AND CONCLUDING REMARKS

A sensor-type specimen made of silicon and glass cut from real sensor has been mechanically tested. The sensors were produced using commercial production technique. The silicon microstructure in the specimens therefore should represent the typical surface conditions of commercial sensor products. The test results show that silicon microstructure fails when the notch has reached a critical notch stress intensity factor 5.5 MPa$\,m^{0.3743}$. This value has been used to predict the burst pressure of the same type of structure, and an excellent agreement was obtained. This finding indicates that this critical value can be used for the design of pressure sensors with thin membrane. It must be noted that this critical notch stress intensity factor is about 20% lower than the value reported in the literature for bulk materials [3]. How the membrane thickness influences the critical notch stress intensity is not quite know to us. There are two other possibilities that might have caused the discrepancy. Firstly, the surface conditions may be different in our specimens and in others. It is known that the notch tip radius has a great effect on the fracture strength of silicon structures. Fig. 4 shows the notch tip geometry of our specimens at high magnification. We can observe that at 10000 magnifications there is no observable notch radius. An additional observation from Fig. 4 is that there are local "steps" close to the notch tip. The influence of the "steps" on the notch tip stress field is not clear to us yet. The notch tip radius in [3] was not reported, therefore it is not possible to compare. Secondly, the presence of residual stress in our specimens certainly contribute to the decrease of the critical notch stress intensity factor, while in [3] the specimens are basically residual stress free. The average thermal expansion of glass in the process temperature range is larger than that of silicon. When the cooling takes place from the bonding temperature of 400 C° to room temperature, a positive stress intensity factor might already have been built up at the notch tip.

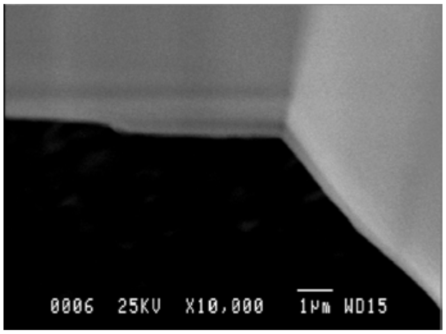

Figure 4: Notch tip geometry at high magnification.

An important question may be raised regarding the validity of the notch stress field for structures with a thin membrane. For our specimens with 0.023 mm thick membrane, the valid area of the K_C^N field at least has a radius of 3.5 μm which is far larger than the physically non-linear range at the notch tip of single crystal silicon. This can justify that the notch tip stress fields at failure are still controlled by the K_C^N.

So far, we have focused on the notch fracture of a fixed notch angle. It has been stated early that for cases with different notch angle, not only the value of the critical notch stress intensity factor will be different, but also the units. It is therefore not possible to transfer the critical notch intensity factor from one case to another. Currently a unified failure criterion for notch fracture based on cohesive model is being developed. In the unified criterion, the critical notch stress factor is linked to the cohesive energy (surface energy) via the material's cohesive strength. Details on this work will be reported elsewhere.

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