ORAL/POSTER REFERENCE: ICF100440OR

NOTCH EFFECT OF MICRO POLYCRYSTALLINE SILICON CANTILEVER

S. Hamada, S. Tani, M. Horikawa, H. Otani, M. Tsugai and E. Yosikawa

Mitsubishi Electric Co., 8-1-1, Tsukaguchi-honmachi, Amagasaki city, 661-8661, Japan

ABSTRACT

A micro polycrystalline silicon cantilever is employed widely as a common structural member for microelectromechanical systems (MEMS). It is necessary to build up the reliability design criterion of the micro polycrystalline silicon explaining the strength of cantilever root area that is regarded as a fracture origin due to stress concentration in general. In this study, the bending tests using the micro scale cantilever beams of polycrystalline silicon with notch of several sizes are carried out in order to obtain the strength database of a micro polycrystalline silicon structures. The bending test results are analyzed by means of maximum peak stress $\sigma_{\max}$ at the notch root calculated by FEM models, and it is found that this approach does not describe the data. Therefore, a reforming approach are taken into account by use of the two parameters that are the peak stress $\sigma_{\max}$ and an area of 0.5 $\sigma_{\max}$, S which indicates the stress extension around the position of peak stress representatively. By this two parameters approach, the test results are explained quantitatively and the limit state describing the fracture of micro cantilever is obtained as $\sigma_{\max} = 4.19S^{-0.212}$.

KEY WORDS

MEMS, Polycrystalline Silicon, Notch effect, Stress Concentration

INTRODUCTION

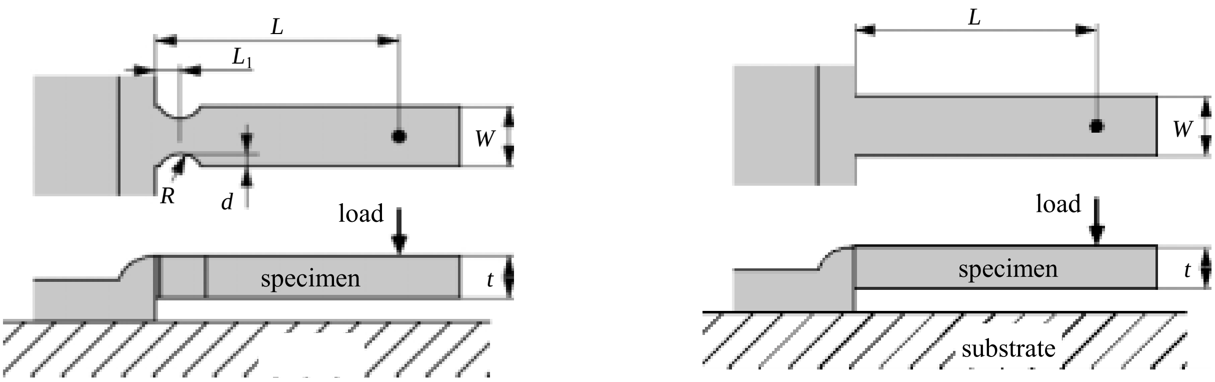
Recently, micron meter order microstructure called microelectromechanical systems (MEMS) [1,2] attracts attentions. The MEMS technologies are applied to an ultra-micro motor, DMD [3], micro sensor [4] and so on. It is well known that a micro polycrystalline silicon cantilever is employed widely as a MEMS structural member in general. From an engineering viewpoint, it is important to establish the reliability design rule of the micro polycrystalline silicon [5-8] involving the explanation of the fracture phenomena of stress concentrated cantilever root area that is regarded as an origin of fracture. In present studies, the bending tests using the micro scale cantilever beams of polycrystalline silicon with notch of several sizes are carried out in order to obtain the strength design criterion of a micro polycrystalline silicon structures considering the notch effect.

TEST METHOD AND RESULTS

Specimen and test method

The bending tests of microcantilever are carried out at room temperature under the atmospheric environment. The specimen is illustrated in Figure 1 and the photographs of specimens are shown in Figure 2. The dimensions of the specimens are shown in Table 1. The specimens are made of 3.5 μm polycrystalline silicon film by a surface micromachining process. The substrate is single crystal silicon and the gap between cantilever and substrate is 2 μm. For the tests, two type specimens are prepared (Type-A and B). In the Type-A specimen, the notch of several sizes (1~5 μm) is introduced in the root area of cantilever on purpose. In the Type-B, although the notch is not introduced on purpose, by the microscopic observation, the notch of 1 μm radius is recognized indeed in the root area of cantilever beam as a result of surface micromachining process.

A dynamic ultra micro hardness tester (Shimadzu Co. DUH-W201) is used for the bending tests of microcantilever beams. Table 2 shows the properties of the test machine. The road conditions in the tests are shown in Table 3. The load conditions are changed corresponding to the length of specimen.



(a) notched specimen (Type-A) (b)no-notched specimen (Type-B)

Figure 1: Schematic diagram of the specimen

(a) notched specimen (Type-A of No. 3) (b) no-notched specimen (Type-B of No. 2)

Figure 2: Top view of examples of the specimen

TABLE 1

DIMENSIONS OF THE SPECIMEN (UNIT: μm) ALL SPECIMEN'S THICKNESS IS 3.5 μm

Type	No.	Width, *W*	Length, *L*	Notch root, *R*	Notch depth, *d*	Notch distance, L_1
A	1	5	15	1	1	1
	2			2	1	2
	3			3	1	3
	4			4	1	4
	5			5	1	5
B	1	5	10	no	no	no
	2		15	no	no	no

TABLE 2.
PROPERTIES OF THE TEST MACHINE

Load range	0.1 to 1961 [mN]
Minimum measurable load	0.2 [μN]
Indentation depth range	0 to 10 [μm]
Minimum measurable displacement	0.001 [μm]
Indenter	Tetrahedral
Notch root radius of indenter	Under 0.1 [μm]
Displacement measure method	Operation transformer
Loading method	Electromagnetic coil

TABLE 3
TEST CONDITIONS

Specimen	Maximum load	Load speed
Type-A No. 1 to 5, Type-B No. 2	1.96 [mN]	1.421 [mN/sec.]
Type-B No. 1	9.8 [mN]	14.21 [mN/sec.]

Test Results

Figure 3 shows examples of the relationship between the load and displacement of the bending tests. In this figure, it is known that the polycrystalline silicon deformed elastically until final catastrophic failure in room temperature, showing a brittle nature. In this figure, the behavior of specimen Type-A of No. 3 differs from other specimens in the part of A. This is because the free edge of microcantilever beam contacts to the substrate surface.

Figure 4 shows the fracture surface of the specimen (Type-A of No. 1) for example. The origin of the fracture surface is clearly shown in this picture. The fracture origin is located in a tensile side and notch root of the specimen. River pattern [9] can be seen on the fracture surface like other brittle materials.

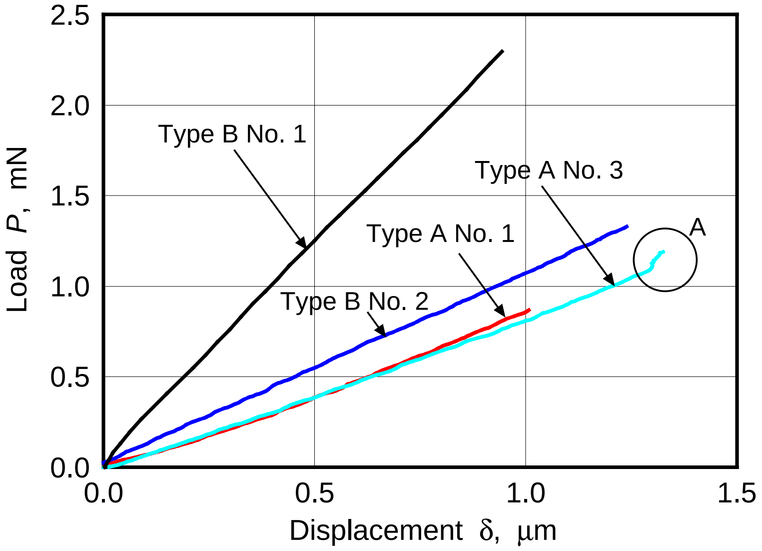
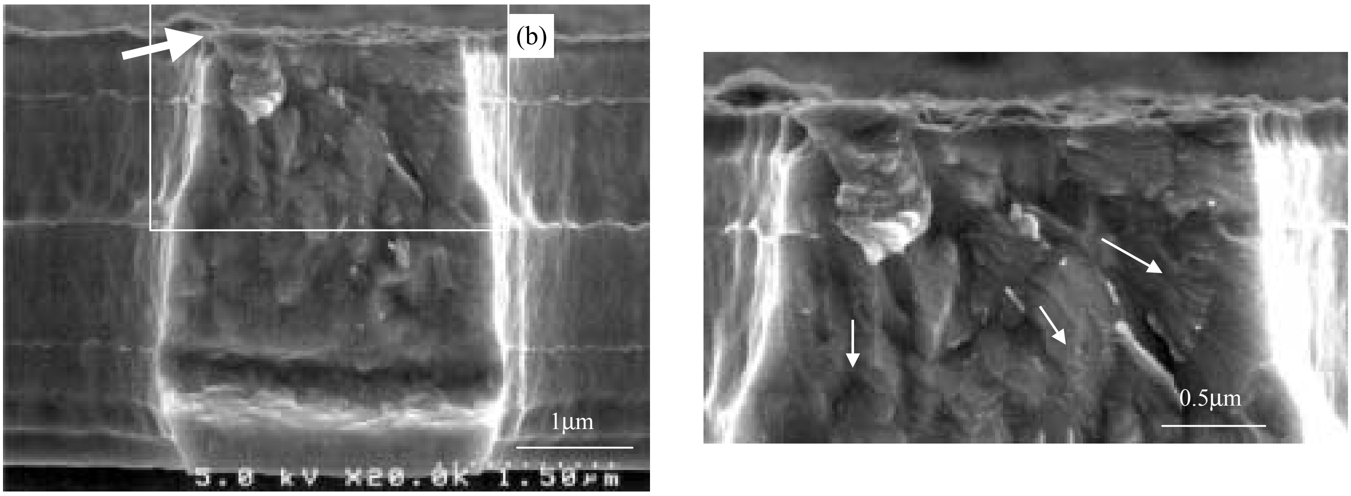


Figure 3: Examples of the relationship between load and displacement of the tests



(a) Macroscopic view of fracture surface (arrow shows the fracture origin)

(b) Magnification of fracture origin (arrow shows the fracture direction)

Figure 4: Fracture surface of the specimen

FEM ANALYSIS OF MICROCANTILEVER BEAM

FEM model and analytical procedure

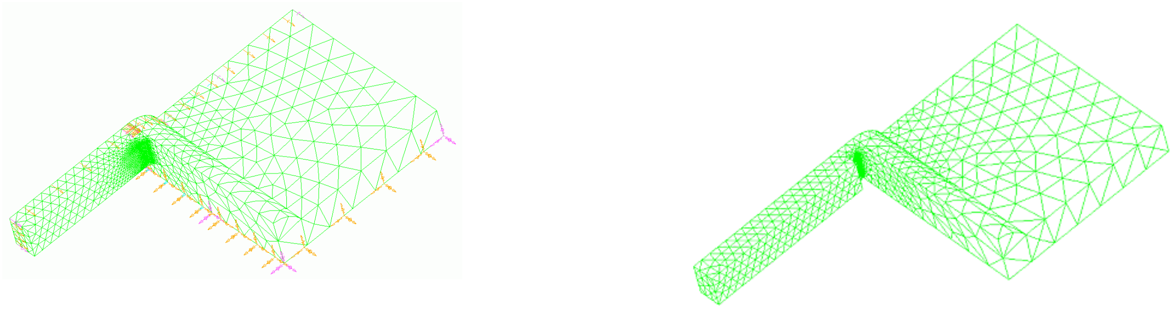
In order to quantify the fracture of specimens by the applied stresses in the tests, the three-dimensional finite element elastic analyses are performed. Table 4 shows the analyses conditions. Figure 5 indicates the examples of FEM models of the specimens (Type-A of No.1 and Type-B of No.1). For the Type-B specimen, the notch of 1 μm radius is taken into the model based on the microscopic observations mentioned above. The element sizes of the models are about 1 μm in the overall region and are about 0.1 μm in the stress concentration area near the notch root. Table 5 shows the material properties used in the analyses. The analyses are carried out under the load condition such as the deformation of loading point is equal to 1 μm.

TABLE 4
FEM CONDITIONS

Elements	3-dimensional 10-node Tetrahedral
Solver	I-DEAS Master Series 7
Load condition	1 μm displacement on the load point
Number of elements	About 6,400
Number of nodes	About 11,000

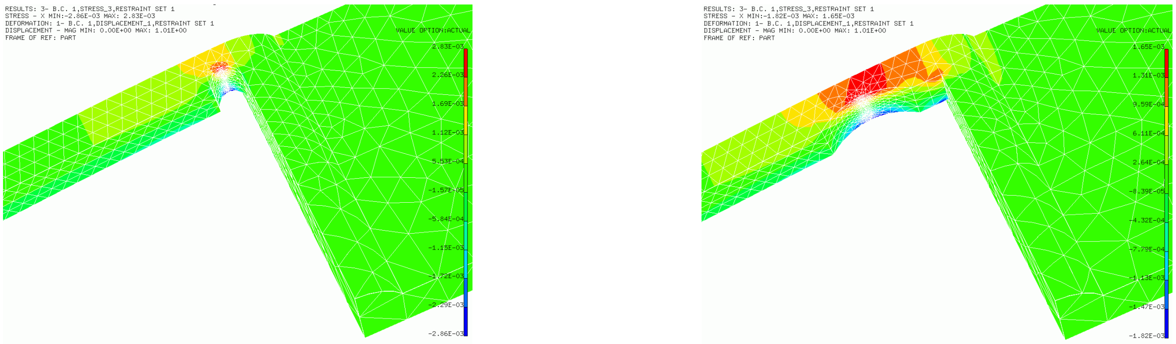
TABLE 5
MATERIAL PROPERTIES FOR FEM ANALYSES

Young’s modulus	148 [GPa]
Poisson’s ratio	0.2 [-]



(a) notched model (Type-A of No. 1) (b) no-notched model (Type-B of No.1)

Figure 5: Examples of the FEM model



(a) Notched model (Type-A of No. 1) (b) Notched model (Type-A of No. 5)

Figure 6: Examples of the stress distribution around the notch roots

Analytical results

Table 6 shows the maximum stress of the longitudinal direction of beam obtained by FEM analyses, and Figure 6 indicates the stress distributions for example (Type-A of No. 1 and Type-A of No. 5). As the location of fracture origin shown in Figure 4 almost corresponds to the maximum stress area of notch root, the validity of analyses is confirmed qualitatively. Moreover, it is found that the area of stress intensity zone near the notch root is different with the each model corresponding to the difference of stress concentration.

TABLE 6
FEM ANALYSIS RESULTS (1μm DISPLACEMENT OF LOAD POINT)

Type	No.	Reaction Force, P [mN]	Maximum Stress, $\sigma_{\max}$ [GPa]
A	1	1.17	4.43
	2	1.19	3.47
	3	1.21	3.00
	4	1.23	2.67
	5	1.24	2.41
B	1	3.90	5.54
	2	1.42	3.08

DISCUSSIONS

Figure 7 shows an expression of the test results by use of maximum peak stress $\sigma_{\max}$ in the notch root. In this figure, the plots of solid mark means the data of fracture specimens and the open mark means the data of non-fracture specimens due to the contact of free edge to the substrate surface. In Figure 7, a tendency can be seen that the plots by the $\sigma_{\max}$ move down with the increase in notch radius because of the effect of the difference on the stress distribution pattern. So, this approach using only maximum stress is not recognized as the criterion for the practical use. Therefore, the another approach are taken into account by use of the two parameters that are the peak stress $\sigma_{\max}$ and an area of 0.5 $\sigma_{\max}$, S which indicates the stress extension around the position of peak stress representatively. Figure 8 shows the results of reforming approach mentioned above. In Figure 8, the mean values of maximum stresses are plotted in consideration of the non-fracture data statistically [10]. The relationship between the maximum stress $\sigma_{\max}$ and the area of $0.5\sigma_{\max}$ is expressed by the following equation.

$$\sigma_{\max} = 4.19 S^{-0.212} \tag{1}$$

In above equation, the unit of S is μm^2 and $\sigma_{\max}$ is GPa respectively. Eqn. 1 represents the limit state of the fracture of microcantilever with satisfaction moderately as the design rule of micro scale structure of the polycrystalline silicon.

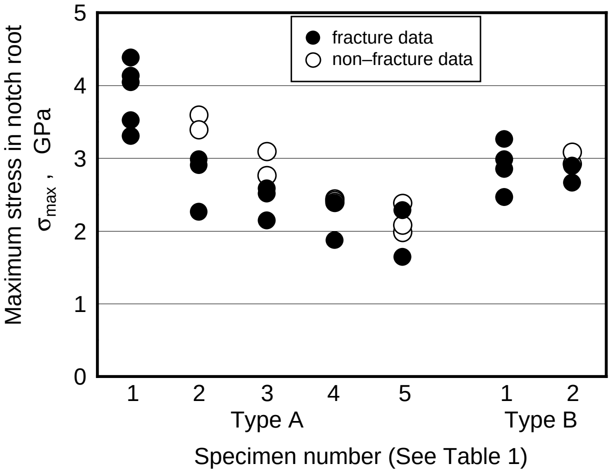


Figure 7: Relationship between maximum stress in notch root and specimen number

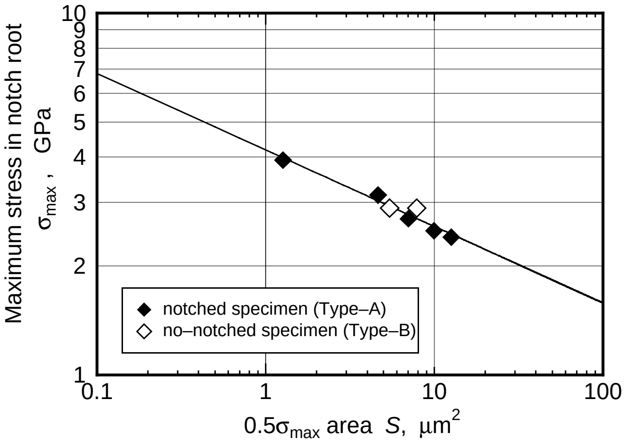


Figure 8: Relationship between maximum stress in notch root and $0.5\sigma_{\max}$ area

CONCLUSIONS

The bending tests using the micro scale cantilever beams of polycrystalline silicon with notch are carried out in order to obtain the strength design rule. The original approaches are taken into account using the two parameters that are the peak stress $\sigma_{\max}$ and an area of 0.5 $\sigma_{\max}$. By this approach, the test results are explained quantitatively and the validity of presented method is confirmed.

REFERENCES

1. Senturia, S. D. (2000). *Microsystem Design*. Kluwer Academic Publishers, Dordrecht.
2. Najafi, K. (2000). *Proc. 2000 Symposium on VLSI Circuits Digest of Technical Papers*. 6.
3. Douglass, M. and Sontheimer, A. (1998). *Texas Instruments Technical Journal*. 15-3, 128.
4. Lűder, E. (1986). *Sensors and Actuators*. 10, 9.
5. Greek, S., Ericson, F., Johansson, S. and Schweitz, J.- Å. (1997). *Thin Solid Films*. 292, 247.
6. Tsuchiya, T., Tabata O., Sakata J. and Taga Y. (1998). *J. microelectromechanical systems*. 7-1, 106.
7. Namazu, T., Isono Y. and Tanaka T. (2000). *Proc. 13th IEEE Int. Conf. Micro Electro Mechanical Systems*. 205.
8. Kapels, H., Aigner R. and Binder J. (2000). *IEEE Trans. Electron Devices*. 47-7, 1522.
9. Hull, D. (1999). *Fractography*. Cambridge University Press, Cambridge.
10. Johnson, L. G. (1964). *The Statistical Treatment of Fatigue Experiments*. Elsevier, New York.