Silicon Flexures for the Sugar-Cube Delta Robot

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Abstract

Fracture tests have been performed on 333 flexure hinges of various shapes machined in monocrystalline silicon by Deep Reactive Ion Etching. The results show the significant effects of stress concentration, crystalline orientation and surface treatments on the fracture stress levels. A Delta-Robot with a size of a sugar cube has been manufactured as a demonstrator.

1 Introduction

The machining of macroscopic compliant mechanisms in monocrystalline silicon leads to decisive advantages [1]: ideal elastic properties of the material, absence of fatigue, machining accuracy (typically one order of magnitude better than that of Wire-EDM), possible integration of sensors and actuators inside the articulated structures themselves, batch production on wafers. Nevertheless, the brittleness of silicon, especially under the effect of stress concentration effects, makes the design and sizing of flexures a delicate issue. This paper briefly presents the results of a test campaign made with 333 flexure hinges machined in monocrystalline silicon by Deep Reactive Ion Etching (DRIE).

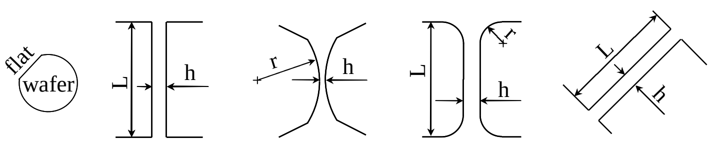


Figure 1: Tested hinges in their real orientation with respect to the flat of the wafer

2 Fracture test campaign

2.1 Test-specimens

Three hinge shapes have been tested (Fig. 1): rectangular hinges (R), circular hinges (C) and rectangular hinges with circular fillets (F). Those three hinges types have been machined in an orientation that is inclined by 45° with respect to the flat of the wafer. To study the effect of the orientation of the hinges with respect to the crystalline structure of silicon, a fourth hinge type (D) has been tested: it is a rectangular hinge (same shape as R) oriented parallel to the flat of the wafer.

For the tests, the hinges have been grouped in sets of five into a dedicated test-specimen (Fig. 2 & Table 1). The latter is composed of a fixed base and two guiding arms producing a circular translation of the mobile block when a displacement (x) is applied to it. This mobile block is connected to 5 levers acting on the tested hinges via decoupling blades that suppress the overconstraints that could stem from geometrical imperfections. This arrangement produces a load case on the tested hinges that is very close to an ideal pure bending. In addition, a removable locking-arm is used to secure the test-specimen during fabrication and manipulation. A microscopic vernier-scale has been etched into the silicon to allow an optical control of the zero position of mobile block.

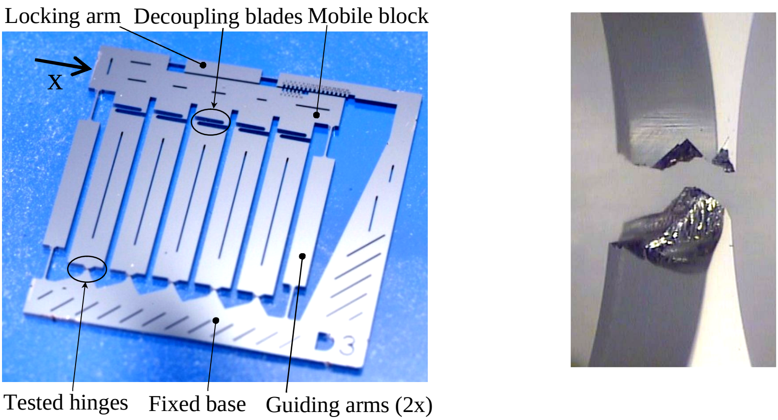


Figure 2: Test-specimen with five identical hinges & photo of a fractured C hinge.

Table1: Overview of the tested hinges; b is the thickness of the wafer; the other geometrical parameters are defined on Fig. 1; 78 of those hinges have been manufactured with the surface treatment T1, 132 with T2 and 123 with T3.

Shape	h [μm]	b [μm]	r [μm]	L [μm]	Number of hinges
C	20 to 100	250 and 350	230 to 1150	-	103
D	10 to 50	250 and 350	-	40 to 200	41
F	10 to 100	250 and 350	10 to 100	40 to 400	116
R	50 to 100	250 and 350	-	200 to 400	73

2.2 Etching surface treatments

Three different surface treatments have been used: raw surface left after DRIE process (T1), addition of a silicon oxide layer after the DRIE process followed by a removal of this layer (T2), addition of a silicon oxide layer after the DRIE process, followed by its removal and then followed by a second oxidation step (T3).

2.3 Fracture tests

The fracture tests themselves consist in pushing gradually the mobile block of the test-specimen until rupture happens in the individual hinges. Knowing the imposed displacement, the corresponding rotation angle of the hinge is calculated. Then, assuming a pure bending load case and knowing the precise geometry of the hinge, the corresponding stress level just before fracture is calculated. This process is performed with each test-specimen, until the fracture of all test-hinges.

3 Test results

Figure 3 (left) shows the average fracture stress level of hinges C, F & R which all have the same orientation with respect to the silicon crystal. The fracture stress level of the R hinges is approximately half of the others. This is probably due to stress concentration effects near the sharp corner of the rectangular shape.

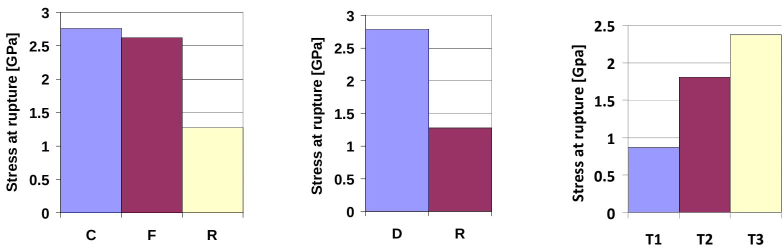


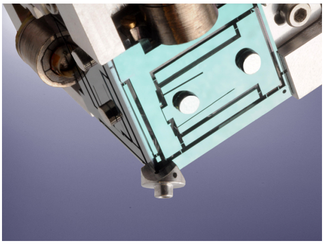
Figure 3: Test results

Figure 3 (middle) shows the average fracture stress level of hinges D & R which have both the same shape, but different orientations with respect to the crystal. The D hinges, which are parallel to the flat of the wafer, have a significantly higher fracture stress level (approx. double) compared to the R hinges which are rotated by 45° on the wafer.

Figure 3 (right) shows the average fracture stress levels of all hinges sorted according to their surface treatment. Treatment T2 leads to a fracture stress level that is approximately twice as high as of the raw etching T1. Treatment T3 leads to a fracture stress level that is approximately three times higher than that of the raw etching T1. Remarks: the average standard deviation of fracture stress level is 320 MPa; the average stress uncertainty is estimated to range between 80MPa for the thickest hinges, down to 230 MPa for the thinnest hinges.

4 Illustrative example of the Sugar-Cube Delta-Robot

To illustrate the potential of this technological approach, a fully three dimensional flexure-based articulated structure has been manufactured. It is the skeleton of a three degrees-of-freedom (DOF) parallel kinematics robot based on the industrially well known Delta architecture (Fig. 4). It has the size of a large sugar-cube (20x20x20 mm) and a stroke of 1.2 mm in all three directions (X-Y-Z). It is composed of three identical monolithic plates. Each plate is articulated by 12 hinges (F shape) with a thickness of 45 microns, 4 of which are allowing an out-of-plane motion (3D compliant structure).



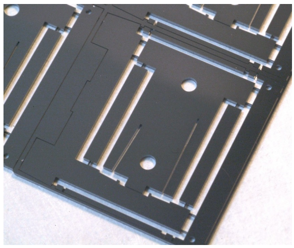


Figure 4: Photos of Sugar-Cube Delta-Robot (left) and one of its plates (right)

5 Conclusion

This study shows the importance of hinge shape (stress concentration effect), hinge orientation with respect to the crystal and surface treatments on the fracture stress levels of thin flexures (20 to 200 microns). This information is essential for the safe design of thin silicon flexure hinges. The acquired knowledge has been successfully used for the design and manufacturing of a novel three dimensional flexure based robot.

Reference:

[1] Design principles for six degrees-of-freedom MEMS-based precision manipulators, D. Brouwer, Ph.D. Thesis, University of Twente, Enschede, NL