MICRO CRACK-FREE SCRATCHING OF SILICON UNDER EXTERNAL HYDROSTATIC PRESSURE

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1. INTRODUCTION

Silicon is widely used in the semiconductor electronic industries for integrated circuits and for optical components in high resolution thermal imaging systems. These precision components require a high degree of surface finish and form accuracy with minimal surface and subsurface damage. It has been observed that the tendency for subsurface defects, such as micro cracks to develop in the case of brittle materials decreases with decrease in the undeformed chip thickness and almost disappear below a critical value of depth of cut, < 1 µm [1-5]. This is because at low depths of cut, the stresses generated by the high negative rake angle tools may not reach the values required to generate median vents in brittle materials. It has also been suggested that at very shallow depths of cut, the energy required to propagate cracks may be larger than the energy required for plastic yielding resulting in material removal by plastic deformation [2].

Alternately, it is possible that such large negative rake angle tools can induce significant hydrostatic pressure to plastically deform the material around the tool [5]. Nakasuji et al. [6] reported that negative rake angle tools enabled higher cut depths before the occurrence of brittle fracture. From Bridgman's work [7] it is well known that the hydrostatic pressure can increase the strain at fracture even in a nominally brittle material, such as chalk, marble, cast iron etc. In the current study, the possibility of generating micro crack-free silicon surfaces under a range of external hydrostatic pressure (0 to 400 MPa) and scratch depths (0 to 1.5 µm) and consequently, increasing the brittle-to-ductile transition (BDT) depth is investigated (both experimental and numerical) in detail. More details are given elsewhere [8].

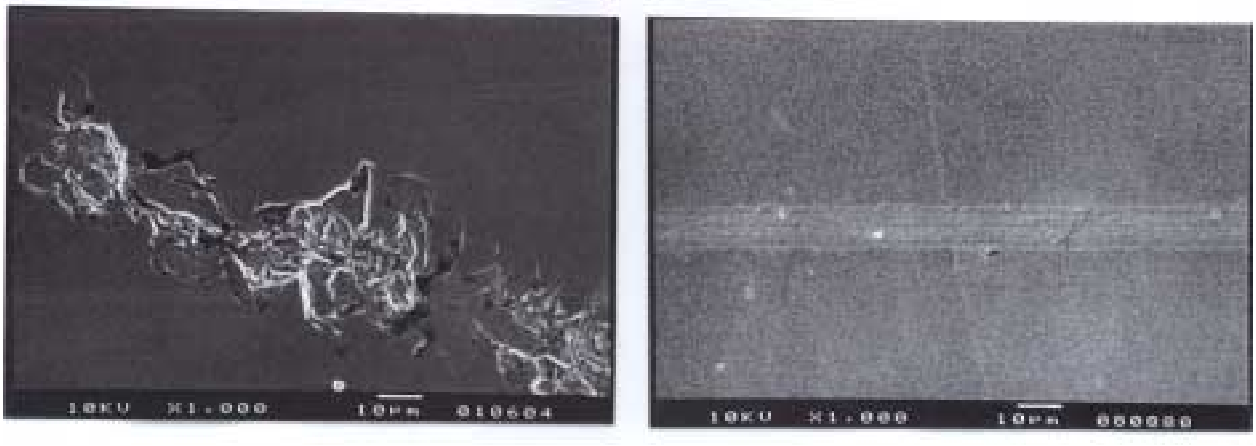
2. EXPERIMENTAL AND NUMERICAL APPROACH

Pin-on-disc type scratch tests were conducted on (111) silicon surface under various external hydrostatic pressures (0 to 400 MPa) and scratch depths (0 to 1.5 µm) using a specially designed high external hydrostatic pressure machining apparatus [4]. The scratch speed was maintained constant at 5 mm/s. A single crystal diamond pin with an edge radius of 17 µm was used in the experiments. The resulting scratches were examined in an SEM and an optical interference microscope (MicroXam) to evaluate the influence of scratch depth and hydrostatic pressure on the nature of the scratches produced (smooth versus fractured surfaces). To simulate dislocation generation and propagation during indentation and retraction of silicon, mesoplasticity FEM technique under plane strain conditions was used [9]. Indentation simulations were performed on the (111) silicon surface for a depth of 2.5 µm. Friction at the interface of indenter and workmaterial was not considered for simplicity.

3. RESULTS AND DISCUSSION

3.1. Scratch Experiments Under External Hydrostatic Pressure (EHP)

Figures 1 (a) and (b) are SEM micrographs of the scratch tracks on silicon at 0 and 400 MPa external hydrostatic pressure (EHP), respectively, at a scratch depth of ~ 0.6 µm. It can be seen that at 0 MPa external hydrostatic pressure (EHP) condition [Figure 1 (a)], the material removal is accompanied by brittle fracture due to the generation of lateral cracks and their growth outside the scratch track. Figure 1 (b), on the other hand, shows a smooth surface on the application of 400 MPa external hydrostatic pressure (EHP). The SEM images indicate that for a given scratch depth, the external hydrostatic pressure (EHP) plays an important role in minimizing machining defects, such as microcracks, and producing smooth surfaces.



(a) (b)

Figure 1 SEM micrographs of scratch tracks on silicon at (a) 0 MPa and (b) 400 MPa

Figure 2 shows the variation of the crack-ratio (ρ) with scratch depth (d) for different hydrostatic pressure conditions where ρ is the total length of the cracks along unit groove length. It can be seen from Figure 2 that the critical scratch depth (d_c) for zero crack-ratio (ρ =0, no defects) increases with increase in the external hydrostatic pressure. For example, the critical scratch depth (d_c) for zero crack-ratio is ~ 0.11 μm at 0 MPa external hydrostatic pressure (EHP). With increasing scratch depth (d), the crack-ratio (ρ) increases and reaches a value of unity (100% fracture) at a scratch depth, d ~ 0.55 μm. When EHP is increased to 400 MPa, crack-ratio (ρ) remains at zero as the scratch depth increases up to ~ 0.4 μm. Beyond this point, crack-ratio (ρ) increases with increasing groove depth and approaches 100% at d ~ 2 μm. It can, therefore, be seen that the critical depth of cut (d_c) can be increased with increase in EHP. The external hydrostatic pressure (EHP) tends to compensate the tensile stresses generated during the scratching process, which in effect suppresses the crack generation and growth.

3.2. Mesoplasticity FEM Simulation - Indentation-Retraction on (111) Silicon Surface

The principal and the hydrostatic stress distributions showed the generation of compressive stresses just beneath the indenter during indentation and tensile stresses outside the perimeter of the indenter during retraction [8]. Dislocations generation was not only observed underneath the indenter but also extending deep into the workmaterial [8]. Figure 3 shows the variation of the maximum tensile principal stress and compressive hydrostatic stress (hydrostatic pressure) with depth of indentation and after retraction, respectively. The retracted depth corresponds to the depth at which the force curve during retraction reaches zero force. Figure 3 shows that the maximum hydrostatic pressure increases at a higher rate than the tensile principal stress during indentation and at maximum indentation depth the hydrostatic pressure is ~ 4 times higher than the tensile principal stress. After retraction, the tensile principal stress increases further. However, the hydrostatic pressure decreases significantly as observed from the stress distribution plots [8]. This combination of stress variation (increasing tensile stress and decreasing hydrostatic pressure) can result in an increase in the defect density in the workmaterial after retraction as will be shown below. To investigate the effect of external hydrostatic pressure (EHP) on the deformation and fracture in the indentation-retraction process, the stress distribution and the defect density distribution (η) were calculated under EHP from 0 to 400 MPa from the FEM simulation. With increasing EHP, the stress distribution in the workmaterial was observed to transform from a tensile stress state to a compressive stress state resulting in a decrease in the magnitude of defect generation [8].

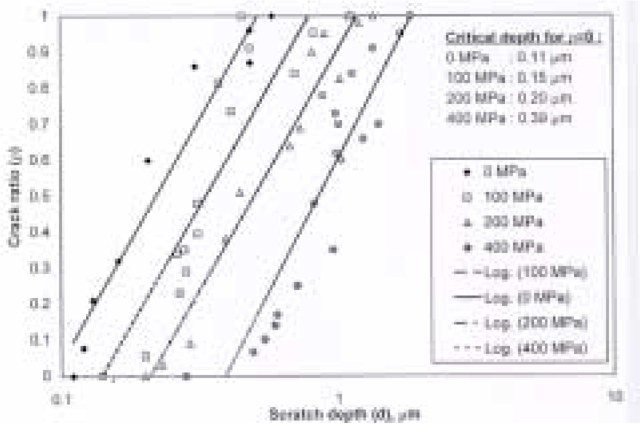


Figure 2 Variation of the crack-ratio with the scratch depth under various EHP

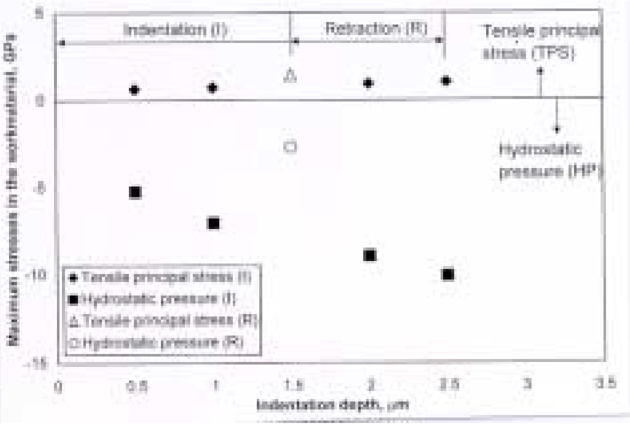
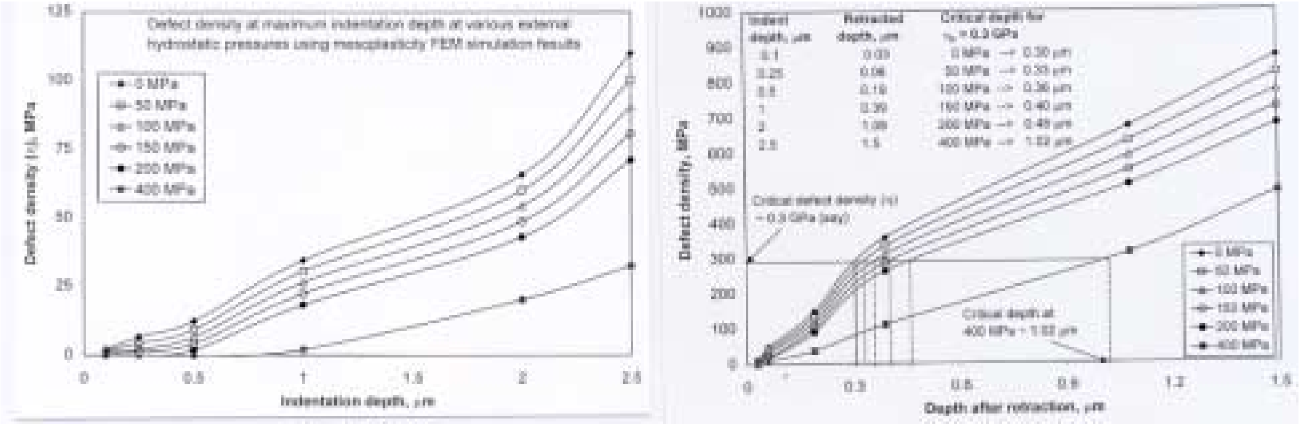


Figure 3 Stress variation in the workmaterial using mesoplasticity FEM results

Figures 4 (a) and (b) show the variation of the maximum value of the defect density (11) in the workmaterial at various depths of indentation (for a maximum indentation depth of 2.5 µm) and after retraction, respectively, for different EHP conditions. The retracted depth corresponds to the point where the indentation-retraction force curve reaches zero force value. The indentation depth and the corresponding retracted depth are given in Figure 4 (b). The defect density for a particular indentation depth and hydrostatic pressure condition is higher after retraction than at maximum indentation depth due to the combination of stress variation [Figure 3]. Figure 4 also shows an increase in the magnitude of defect density with increasing indentation depth and decreasing EHP (both during indentation and after retraction). This can be attributed to the decreasing compressive hydrostatic stress and increasing tensile principal stress in the workmaterial. Thus, at a critical defect density of ~ 0.3 GPa for example, the critical indentation depth after retraction increases from ~ 0.3 µm at 0 MPa EHP to ~ 1 µm at 400 MPa EHP. The increase in the critical depth is ~ 3 times with the application of 400 MPa external hydrostatic pressure. Earlier, the experimental results also showed a similar increase in the critical depth by ~ 3 times on the application of 400 MPa external hydrostatic pressure [Figure 2]. Based on the experimental and simulation results, it appears feasible to increase the brittle-to-ductile transition (BDT) depth in finishing of brittle materials under EHP. A detailed comparison of the experimental and simulation results and verification of the fracture criterion model used in the simulations are given elsewhere [8].



Figures 4 Variation of the defect density (a) with indentation depth and (b) after retraction under EHP

4. CONCLUSIONS

The feasibility of generating micro crack-free silicon surfaces under external hydrostatic pressure was investigated in detail. Scratch experiments were performed on the (111) silicon surface at external hydrostatic pressures (EHP) varying from zero to 400 MPa. On the numerical side, plane strain indentation-retraction simulations were conducted using the mesoplasticity FEM technique. Both, the experimental and the simulation results show that the hydrostatic pressure plays an important role in minimizing fracture and producing smoother surfaces. The results also indicate an increase in the brittle-to-ductile transition (BDT) depth with increasing hydrostatic pressure. The change in the behavior from brittle to ductile of hard and brittle materials with decreasing depth is attributed to the high effective negative rake angle presented by the tool. Such high negative rake angles generate significant hydrostatic pressure around the tool, which in effect reduces the tensile stresses resulting in the generation of smooth surfaces on brittle materials.

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REFERENCES

[1] K. E. Puttick, M. R. Rudman, K. J. Smith, A. Franks, and K. Lindsey, "Single Point Diamond Machining of Glasses," Proc. R. Soc. Lond. A, 426, (1989), pp. 19-30

[2] P. N. Blake and R. 0. Scattergood, "Ductile-Regime Machining of Germanium and Silicon," J. Am. Cer. Soc., 73/4, (1990), pp. 949-957

[3] T. Shibata, S. Fujii, E. Makino, and M. Ideda, "Ductile-Regime Turning Mechanism of Single Crystal Silicon," Precision Engineering, 18, (1996), pp. 129-137

[4] M. Yoshino, T. Aoki, T. Shirakashi, and R. Komanduri, "Some Experiments On the Scratching of Silicon," Int. J. Mech. Sci., (in print, 2000)

[5] R. Komanduri, D. A. Lucca, Y. Tani, "Technological Advances in Fine Abrasive Processes," Annals of CIRP, 46/2, (1997), pp. 545-596

[6] T. Nakasuji, S. Kodera, S. Hara, H. Matsunaga, N. Ikawa, and S. Shimada, "Diamond Turning of Brittle Materials for Optical Components," Armals of CIRP, 39/1, (1990), pp. 89-92

[7] P. W. Bridgman, "The Effect of Hydrostatic Pressure On the Fracture of Brittle Substances," J. Appl. Phys., 18, (1947), pp. 246-259

[8] N. Chandrasekaran, M. Yoshino, T. Aoki, and R. Komanduri, "On the Micro Crack-Free Scratching of Silicon Under External Hydrostatic Pressure," submitted for publication

[9] M. Yoshino, T. Shiina, and T. Shirakashi, "FEM Simulation of Dislocation Behavior in an FCC Metal," Computer Modeling and Simulation in Engineering, 2, (1997), pp. 218-226