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Influence of tool geometry and crystallographic orientation upon ductile response in monocrystalline silicon

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Abstract

The attenuation of brittle response during machining of semiconductor crystals is a desirable aspect. In this paper, the determination of machining cutting conditions that promote ductile material removal and smooth surface finish in monocrystalline silicon was carried out. The objective of this article is to assess the effect of cutting parameters and tool geometry on the material removal response. Single crystal silicon samples with different crystallographic orientations, to know: (100) and (111), were diamond face turned. Tool rake angle showed the most significant influence on the ductile response during machining. Negative rake angles generated the larger ductile thickness of cut. The maximum value of the ductile thickness of cut was estimated to be 0.266 μm when -25º rake angle was used. The effect of the nose radius was also investigated and it was observed that smaller tool nose radius presented a larger ductile response. The comprehension of the phenomena involved in this cutting process in order to achieve ductile response is discussed in terms of the viabilization of application of this process with large material removal rates.

Diamond Turning, crystal anisotropy, single crystal Silicon, brittle-to-ductile transition

1. Introduction

The importance of generating high quality components with semiconductors crystals stands on their optical and electronic applications. Despite of the conventional abrasive machining processes provide fine surface finish and low damage to surface and subsurface, diamond turning has a good response in terms of controlling the fabrication of complex surface forms. The objective of this paper is to present experimental results obtained from single point diamond turning of monocrystalline silicon with different crystallographic orientations. Cutting conditions (federate and depth of cut) as well as tool geometry (nose radius and rake angle) were varied. Optimized machining conditions to cut silicon in ductile regime are shown and discussed as a way of improving the machining process.

2. Experimental procedure

A diamond turning machine, Rank Pneumo ASG 2500 was used to cut the monocrystalline silicon with (100) and (111) surface orientation. The surface roughness of polished samples, measured by AFM, did not exceed 5.82 nm Ra. In this work, three different round nose single crystal diamond tools (Contour Fine Tooling®) with two different rake angles were used as shown in Table 1.

Table 1. Diamond tool characteristics.

Tool code	Rp (mm)	Rake Angle γ	Clear.Angle α
CO30LG	0.76	0°	12°
CO60LG	1.52	0°	12°
CO60WG	1.52	-25°	12°

Facing cuts were performed and Interrupted Cutting Test (ICT) [1] procedure was applied. Figure 1 a) and 1 b) show an optical profiler 3D image and cross section profile, respectively, to demonstrate how the values of the uncut shoulder were measured, showing the ductile region (W_d) which will be used as the raw measurement of the critical thickness of cut (t_c).Table 2 describes the experimental conditions used in the cutting tests. Only one feed rate was choosen since it was the maximum feed rate determined in terms of economical viability for ductile material removal. The diamond turning was carried out using a lubricant and coolant fluid, synthetic water soluble oil.

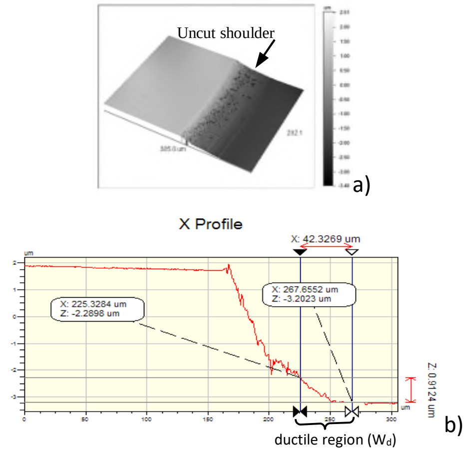

Figure 1. Optical profile results to show how the the values of the critical thickness of cut (t_c) were estimated. a) Uncut shoulder and, b) cross section profile, respectively.

The estimation of the critical thickness of cut, at which the ductile to brittle transition occurs, was then made using the following equation (Blackley and Scattergood ,1991):

$$t_c = \frac{(W_d \cdot f)}{R_p} \qquad (1)$$

where f (µm/rev) is the feed rate per revolution, R_p (µm) is the tool nose radius and W_d (µm) is the distance between the tool centre and the point of the transition measured from the cross section view of the shoulder region (Fig.1b).

Table 2 Cutting conditions used in the tests

Cutting test	**Parameters**	**Crystal**
Nose radius (mm) Rp= 0.76 and 1.52	f = 2,5 (µm/rev) ap = 5.0 ;10.0; 15.0 (µm)	(001) (111)
Rake angle γ = 0° and -25°	f = 2,5 (µm/rev) ap = 5.0 ;10.0; 15.0 (µm)	(111)

3. Results and Discussion

The results obtained for both nose radius and different crystallographic orientation are presented in Tables 3 and 4.

The tool nose radius seems to present a positive influence upon the ductile machining response in silicon. The increase in the tool nose radius changes the position of the brittle to ductile transition upward along the uncut shoulder. This is manifested by a factor of $(R_p)^{1/2}$. The results showed that the ductile width of cut (W_d) on the uncut shoulder increased with the increase in the tool nose radius, however, the critical thickness of the chip is still larger for the smaller tool nose radius. The increase of the tool nose radius and the decrease of the critical thickness of cut might be related to a variation in the contact pressure along the contact length. Smaller tool nose radius will have, for a certain depth of cut, smaller edge contact length. From this assumption it is possible to assert that critical thickness of cut should be variable as function of the tip radius and the inclination along the contact length [2].

Table 3. Monocrystalline Silicon (100) f = 2.5 µm/rev.

a_p	$W_d \pm \sigma$ (µm) (CO30LG)	$W_d \pm \sigma$ (µm) (CO60LG)	$t_c \pm \sigma$ (nm) (CO30LG)	$t_c \pm \sigma$ (nm) (CO60LG)
5	42.52 ± 0.46	72.54 ± 1.0	137.9 ± 1.5	119.3± 1.6
10	43.80 ± 0.86	70.09 ± 0.7	142.1± 2.8	115.3± 2.8
15	43.45± 0.86	72.72±1.5	140.9 ± 2.8	119.5 ± 2.,4

The difference in ductile response shown for different crystallographic orientation may be related to the slipping system. The crystallographic plane (111) has a preferential slipping direction [110], which is considered the likely direction of easiest to occur slipping of the crystallographic planes and, consequently, larger ductile response. Results shown by Shibata et al. [3] demonstrated that Si(111) plane presents a larger proportional surface area machined in the ductile mode than for the Si(100) plane. This may determine a relationship between the machinability presented by these two crystallographic orientations.

Table 4. Monocrystalline Silicon (111) Feedrate f = 2.5 µm/rev.

a_p	$W_d \pm \sigma$ µm) (CO30LG)	$W_d \pm \sigma$ (µm) (CO60LG)	$t_c \pm \sigma$ (nm) (CO30LG)	$t_c \pm \sigma$ (nm) (CO60LG)
5	51.37 ± 0,82	72.19 ±0.41	166.6 ± 2.6	118.7 ± 0.6
10	55.00 ± 1.62	72.48 ±0.75	178.4 ± 5.3	119.2 ± 1,2
15	52.36 ± 0.35	70.09 ±0.75	169. 8 ±1.1	115.3 ± 1.2

Table 5 present the results of critical thickness for the cutting tests with different tool rake angles. The crystallographic orientation chosen was (111) since it was the crystal orientation that presented the larger ductile response during machining. In this case the values of W_d and t_c presented a difference up to 100% or higher under the same cutting condiyions when a negative rake tool was applied! Negative rake angle hinders the propagation of microcracks as well as increase the compressive strain in the interface region between the cutting edge and the material. This implies in higher hydrostatic pressure along with higher shear stress which favors the phase transformation responsible for the ductile response in the machining of semiconductors crystals [2; 4-5].

Table 5. Monocrystalline Silicon (111), f = 2.5 µm/rev.

a_p	$W_d \pm \sigma$ (µm) (γ = 0°)	$W_d \pm \sigma$ (µm) (γ = -25)	$t_c \pm \sigma$ (nm) (γ = 0°)	$t_c \pm \sigma$ (nm) (γ = -25)
5	72.19±0.4	123.29± 0	118.7 ±0.6	201.45 ± 0
10	72.48± 0.7	142.66±0.9	119.2 ±1.2	233.10±1.6
15	70.09±0.7	160.20±1.2	115.3 ±1.2	266.76 ± 2

It is possible to assert that the critical thickness of cut does not have an exact value but it would present ranges of values as function of the cutting condition, crystallographic plane and tool geometry. The estimation of the critical thickness of cut value or the maximum ductility achieved in silicon crystal machining depends upon the combinations of tool nose radius, rake angle, feedrate and depth of cut in order to reach an optimized cutting condition. The values estimated for the critical thickness of cut t_c varied within the range between 100 - 266 nm. Information available in the literature, related to the critical thickness of cut reported for Si, shows that the values of critical thickness of cut obtained in these works are found in the range from 50 nm up to 290 nm [1-7]. Nevertheless, the ductility of silicon seems to rely on the depth or the extension of the layer that undergoes phase transformation induced by pressure/stress that different cutting condition/tool geometry impose in the uncut shoulder [2;5]. When this limit is overcome the formation of microcracks takes place instead of ductile material removal.

5. Final Considerations

This paper reported the effect of cutting parameter and tool geometry on the ductile response of single crystal silicon machined with diamond tools. The surface crystal orientation presented influence on the ductile response during machining. The value of maximum critical thickness of cut, estimated for two crystallographic orientations and for two different tool nose radii (0.76 mm and 1.52mm), ranges conversely, showing that the largest value of chip thickness was obtained with smaller tool nose radius with surface crystallographic orientation (111) Si (t_c = 178 nm). The ductile response on the (111) orientation is larger than for (100). When negative rake angle was used the value of the critical thickness of cut is the double the value for the tool with 0° rake angle. It was also observed that the critical thickness of cut also increased with depth of cut when negative rake tool was used.

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