INFLUENCES OF CUTTING CONDITIONS SCALING IN THE MACHINING OF SEMICONDUCTORS CRYSTALS WITH SINGLE POINT DIAMOND TOOL

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Abstract. *This article intends to discuss the ductile response of semiconductors crystals based on the quantitative dependence of brittle-to-ductile transition upon the transition pressure value in single point diamond turning. It is proposed that the transition pressure value can be considered as a useful information to predict whether the ductile or brittle regime will prevail during micromachining and consequently to determine the machinability of monocrystalline semiconductor crystals. It is well established that feedrates larger than 2.5 μm/revolution is not appropriate to machine silicon crystal. In this paper, the generation of subsurface damage during machining will be discussed. Examples of large feeds (20micrometer/revol.) applied to silicon crystals generating ductile response are presented. The application of this concept to generate microstructures in soft and hard semiconductors is briefly discussed. The use of the phase transformation concept to machine semiconductors crystals with large feeds is proposed. Mirror like surfaces with nanometric roughness are obtained on single crystal silicon with tool feed up to some tens of micrometers. Ductile regime turning is realized at large tool feed up to some hundreds of micrometers on indium antimonide which presents lower transition pressure value. This is based on the fact that the ductility of semiconductors crystals during machining is inversely proportional to the transition pressure value. The use of this concept makes it easy to generate microstructures in semiconductor crystals with single point tools.*
Keywords: Semiconductors crystals, diamond turning, brittle-to-ductile response

1. INTRODUCTION

The machinability of a material is currently defined as a relative measure of how easily a material can be machined. The condition and physical properties of a work material may have a direct influence on its machinability. The anomalous plasticity presented by typically brittle materials is attributed to a structural transformation into a metallic state induced by hydrostatic pressure and stress. The amorphous state detected within the indentation impression as well as in the scratching groove observed in semiconductors crystals, enabled a new approach for analyzing the plastic behavior in single point diamond machining. Since the plastic response can be considered the main subject in the study of the machinability of normally brittle materials, mechanical properties are the first parameters used to predict the material's plastic behavior, correlating the experience with metal cutting theory. It is well established that the lower the material hardness the higher will be the ductile response. If this common sense is applied to semiconductor crystals, the material response will not directly correspond to expectation.

This article intends to discuss the ductile response of semiconductors crystals based on the quantitative dependence of brittle-to-ductile transition upon the transition pressure value in single point diamond turning. It is proposed that the transition pressure value can be considered as a useful information to predict whether the ductile or brittle regime will prevail during micromachining and consequently to determine the machinability of monocrystalline semiconductor crystals.

2.EXPERIMENTAL PROCEDURE

The microindentation and micro-cutting test were performed on 12 mm x 12 mm square, 0.5 mm thick samples of monocrystalline (001)-oriented InSb, Si and GaAs. Indentation tests were performed in a VMHT met Leica™ (Leica Mikrosysteme, Gmbh; A-1170, Vienna, Austria) microindentation apparatus using a Vickers pyramidal indenter. The indentation loads used in the tests were varied between the range of 5 g, 10 g, 15 g, 25 g, 50 g and 100g.

Samples were single point diamond turned using facing operation on a Rank-Pneumo ASG 2500 (Precitech, Inc., Keene, NH, USA) diamond turning machine. Facing cuts were performed and Interrupted Cutting Test (ICT) procedure was applied which is described elsewhere. Cutting fluid used was a synthetic water soluble oil with the intention of cooling. This fluid was continuously mist sprayed onto the workpiece during machining. Cutting conditions as well as cutting tool (Contour Fine Tooling, Hertfordshire, UK) geometry are presented in Table I.

Table I. Cutting conditions and tool geometry used in the machining tests.

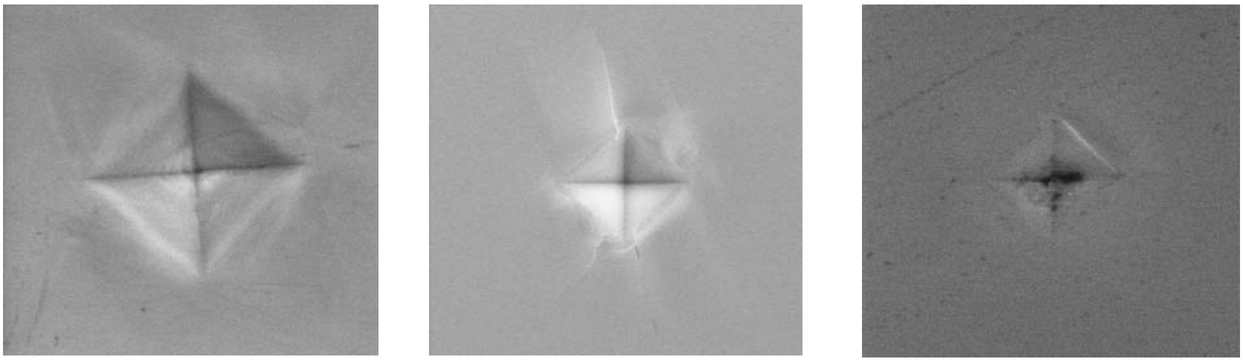
Cutting conditions and tool geometry	**Value**
Depth of cut (μm)	6
Feedrate (μm/rev)	1.25, 2.5. 5 ; 20
Tool nose radius (mm)	0.7708
Rake Angle	0°
Clearance angle	12°
Spindle speed	1000 rpm

3.RESULTS AND DISCUSSION

3.1. Indentation Experiments

Figure 1 (a), (b) and (c) shows SEM micrographs of InSb, GaAs and Si indented with the same load (5 g). As can be seen, the deformation volume is larger in the case of InSb (Fig. 1 a) which has the lower microhardness (~2.3 GPa). Consequently, InSb presents a larger plasticity than

GaAs and silicon. However, how to explain that gallium arsenide (~6.9 GPa) (Fig. 1b), which has a smaller microhardness when compared to silicon (11-12.5 GPa) (Fig. 1c), presented a more clear brittle response. This was attributed to the fact that GaAs (17-18 GPa) has a higher transition pressure value than silicon (11-12.5 GPa) and consequently as the indenter penetrates the material the border of the indentation do not reaches the pressure needed to trigger the phase transformation and microcracks propagate.



a) b) c)

Figure 1. Microindentation Vickers under small load (10g) of different semiconductors crystals; a) InSb (magnification 5000x); b) GaAs (magnification 5000x) and; c) Si (magnification 5000x)

3.2. Application of the Concept of Transition Pressure Value to the Machining Tests

Figure 2 a) and b) present scanning electron microscope image of the uncut shoulder of InSb and Silicon, respectively. The top image shown in Figure 2a) is the surface finish of the sample cut with 5.0 mm/rev where no sign of microcracks are observed, either in the uncut shoulder shown in the bottom image. Figure 2 b) shows the silicon sample cut under the same cutting condition as to InSb. In this case, the microfracture damage is evident in both, surface and uncut shoulder. In the case of GaAs, only with the smallest feed rate condition the uncut shoulder presented a very narrow ductile response. When the cutting conditions are feed rate of 1.25 mm/rev and 6 μm depth of cut the uncut shoulder of the GaAs present a large amount of microcracks. Furthermore, the microcracks formed along the uncut shoulder replicate below the plane of the machined surface. In this case cracking and "spalling" damage, which are characteristics to the brittle regime, predominated.

Table II summarizes the material removal mechanism involved during the cutting tests. Under the cutting conditions used to cut the semiconductors crystal it was observed that InSb presented the best results in terms of ductility, followed by silicon and at last GaAs.

Table II**.** Qualitative analysis of the material removal mechanism involved in the cutting tests.

Material	$H_{Vickers}$ GPa)	Pt (GPa)	Quality of the uncut shoulder x Cutting condition		
			f =1.25 μm/rev ap= 6 μm	f = 2.5 μm/rev ap= 6 μm	f = 7.5 μm/rev ap= 6 μm
InSb	2.3	2.3	**D**	**D**	**D**
Silicon	11.3-12.5	11.3-12.5	**D**	**D-F**	**F**
GaAs	6.8	~18	**D-F**	**F**	**F**

It is worth mentioning that under all cutting conditions InSb presented always the ductile response irrespective to the feed rate used. This gives support the concept that brittle-to-ductile transition during machining is inversely proportional to transition pressure value of the semiconductor crystal.

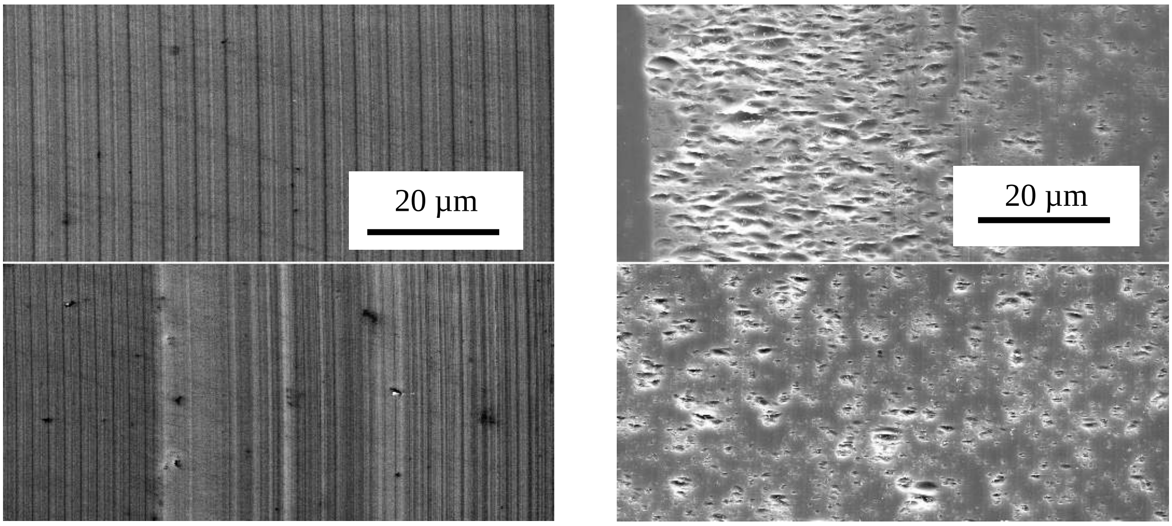


Figure 2. Photomicroraphs made by scanning electron microscope of the uncut shoulder and surface of a) InSb and b) Silicon.

3.3. Surface and Subsurface damage

It is commonly asserted that brittle materials can be diamond turned in a ductile mode since cutting conditions (depth of cut and feed rate) are kept below a critical value(1,2,3,4). However, it has been observed that the residual stress in ductile regime diamond turning of silicon decreases with the increase in depth of cut (2). The reason for this is related to the formation of subsurface cracks that release the energy introduced by the cutting tool. In the same work it was observed a negative stress strain on the InSb sample and positive stress strain for silicon. This difference in residual stress may be attributed to the fact that InSb has more capacity of sustain plastic deformation than silicon. Based upon this, a Transmission Electron Microscopy (TEM) analyses was carried out in order to find out if even when the surface finish presents no sign of damage caused by pits or microcracks, may present microcracks responsible for the release the energy introduced by the cutting tool in the subsurface. Figure 3 shows bright field image made by TEM of the cross section of the surface cut with 2.5 µm/rev and 5 µm depth of cut. It is possible to observe that the microcracks are aligned perpendicularly to the cutting direction, at a depth around 0.5 µm. These microcracks are formed within the cut groove resembling the median crack formed in scratching(5), as shown in Figure 4.

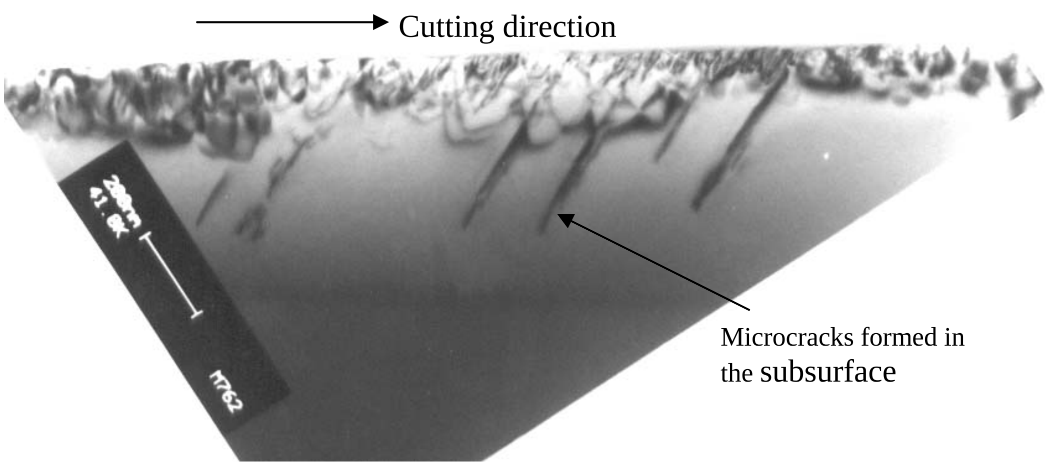


Figure 3. TEM image made of the silicon sample cut with ap= 5 µm f = 2.5 µm/rev showing subsurface microcracks aligned perpendicularly to the cutting direction.

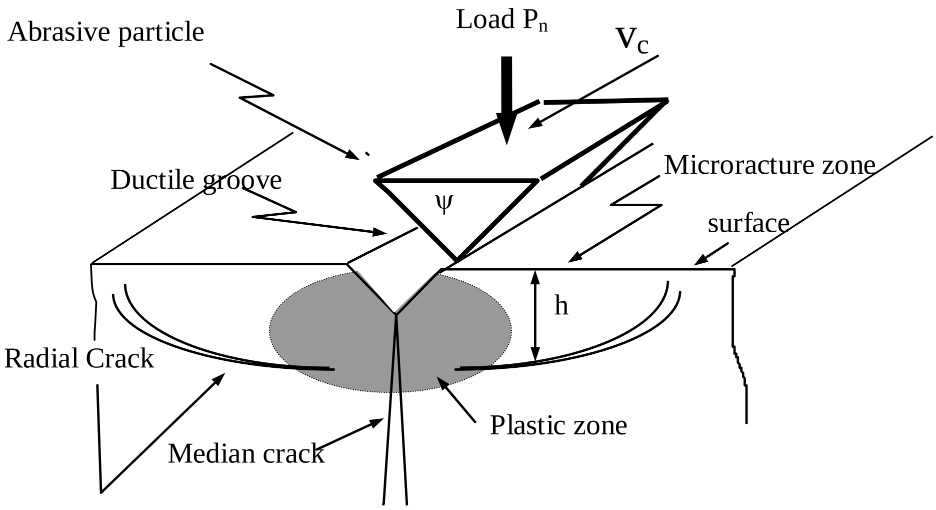


Figure 4. Schematic drawing of the crack system generated during scratching, according to Lawn and Evans[5].

This was used as a motivation to find out a new method of detection subsurface damage induced by the cutting tool. Fig.5 shows optical photomicrograph of a silicon sample cut with two different cutting depths (0.5 µm after a pass with depth of 5 µm) using the same feed rate (2.5 µm/rev). Figure 5 a) shows the uncut shoulder of the first machining condition, i.e., depth of cut 5 µm and feed rate of 2.5 µm/rev. It is possible to observe the brittle-to-ductile transition and the free damage surface. However, in the next pass the sample was cut under the same feed rate but with 0.5 µm depth of cut, as shown in Figure 5 b). The uncut shoulder do not present any sign of microfracture. On the other hand, small pits are observed within the cut surface. Figure 5 c) shows a scanning electron photomicrograph of a detailed view of the surface damage. The top image shows the surface cut with 5 µm depth of cut and the bottom image presents the surface machined with 0.5 µm cutting depth, showing the regular aligned microcracks within the cutting grooves. This damage resembles median cracks likely formed with previous pass. It is possible to observe that the microcracks are aligned perpendicularly to the cutting direction, at a depth around 0.5 µm.

This shows that despite the cutting is apparently made in the ductile regime the subsurface layer may present damage by brittle fracture. Minowa e Sumino[6] demonstrated in scratched silicon sample that even after a heat treatment of annealing the subsurface crack were not recovered.

3.4. Large feedrates during machining

The fact that the cutting condition has to be kept below a critical value does not mean that the feed rate can not be increased up to values higher than the conventional feed rate value used for silicon (around 2.5 micron /rev). For instance, after diamond machining (polishing, grinding and turning) of silicon the amorphous surface layer as well as the critical thickness of cut are both in the range 20 up to 250 nm[7,8,9]; why not try to cut the material with a cut condition within this range., i.e., combining with large feed rate and small depth of cut. The value proposed was f = 20 micron/rev and depth of 0.05 micron, cutting tool geometry was 0.77 mm nose radius and -25^{o} rake angle. Figure 6 a) shows an image of the section analysis made by Atomic Force Microscopy (AFM) of the uncut shoulder. The surface is ductile and its profile contains periodical peak-valley marks corresponding to the tool feeds. It has roughness of 4.633 nm R_a and 53.608 R_{max}, which approaches the theoretical values

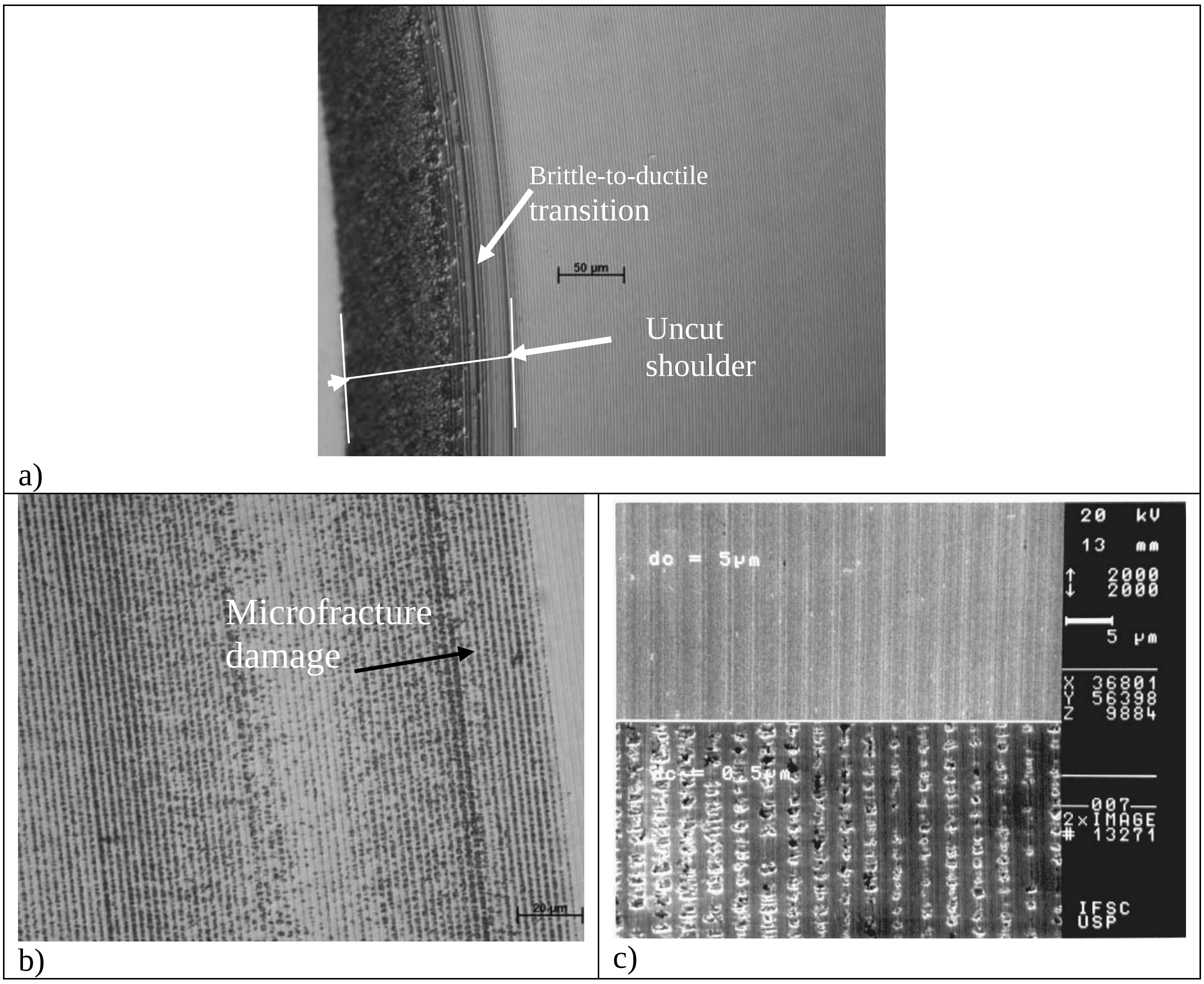
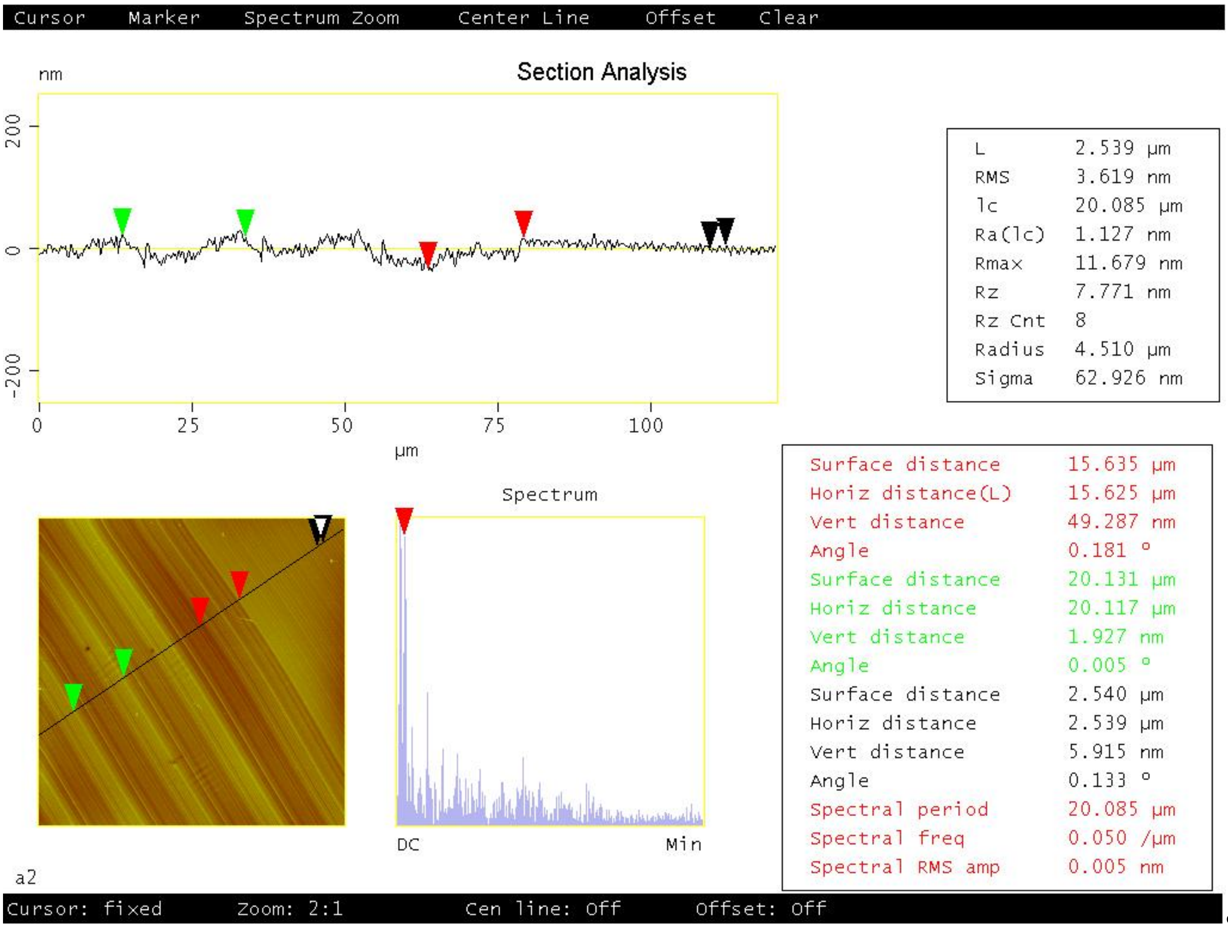


Figure 5. Image made by optical microscopy of the silicon machined sample with two subsequent cutting depths; a) f = 2.5 µm /rev ap= 5 µm; b) detail of the damage generated into the surface (f = 2.5 µm /rev ap= 0.5 µm); c) SEM detail image of the surface cut with ap= 5 µm (Top) and ap= 0.5 µm (Bottom).

3.5. Generation of structures in brittle materials

Based upon the concept that the plastic response of semiconductors crystals during machining is inversely proportional to its transition pressure value, InSb samples were machined under cutting conditions extremely large. Figure 6 Nomarski optical microscopy micrographs of the cutting grooves left by the tool. The cutting pass is very large when compared to conventional cutting condition used to machine brittle materials. As an enabling material, the possibility of using semiconductors crystals for the fabrication of micromolds are finding more and more applications in diverse fields from micro-optics to micro-fluidics.



a)

Figure 6. Diamond turned surface of monocrystalline silicon with large feed rate (f = 20 micron/rev), a) 3D AFM image of the uncut shoulder; the spectral period shows that one of the main frequencies is 20.085 micrometers which is in accordance to the feed rate.

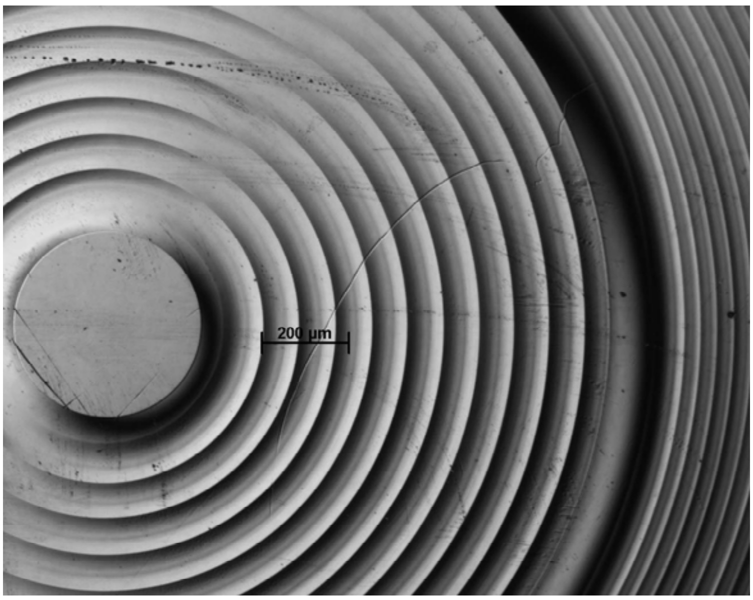


Figure 7. Generation of large feed rate in InSb.

4. CONCLUSIONS

Results reported here show that transition pressure value can be used as useful information to predict whether the ductile or brittle regime will prevail during diamond turning of semiconductor crystals. Mirror like surfaces with nanometric roughness are obtained on single crystal silicon with tool feed up to some tens of micrometers. Ductile regime turning is realized at large tool feed up to some hundreds of micrometers on indium antimonide which presents lower transition pressure value. This is based on the fact that the ductility of semiconductors crystals during machining is inversely proportional to the transition pressure value. The use of this concept makes it easy to generate microstructures in semiconductor crystals with single point tools.

5. ACKNOWLEDGEMENTS.

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6. REFERENCES

1) JASINEVICIUS, R.G., **Influência da Transição de Fase Sobre os Limites de Ductilidade Observados na Usinagem de Ultraprecisão de Silício Monocristalino.** 1998, 173p. Tese (Doutorado em Engenharia), , EESC - Universidade de São Paulo, São Carlos, 1998.
2) SILVA, H.A. T., **Monitoamento do Torneamento de Ultraprecisão de materiais Frágeis**, 2003, 170p., Tese (Doutorado em Engenharia, EESC - Universidade de São Paulo, São Carlos, 2003.
3) JASINEVICIUS, R.G.,. PIZANI, P.S., LANCIOTTI JR., F., DUDUCH, J.G, Diamond turning induced surface damage in silicon investigated by means of Raman spectroscopy and microscopy technique, In: 4^{th} International Conf. of the Europ. Soc. of Prec. Engg. And Nanotechnol., Proceddings., 2002, Eindhoven, Holanda, pp.671-674,.
4) JASINEVICIUS, R. G., PIZANI, P. S., DUDUCH, J. G., Brittle to ductile transition dependence upon the transition pressure value of semiconductors in micromachining - **Journal of Materials Research**, Vol. 15 (8):1688-1692, Aug.2000.
5) LAWN, B.R., EVANS, A.G., "A model for crack initiation in elastic/plastic indentation fields", **J. of Materials Science**, Vol. 12, p.2195-2199, 1977.
6) MINOWA, K., SUMINO, K., "Stress-Induced amorphization of a silicon crystal by mechanical scratching", Phys.Rev. Letters, Vol. 69, n.2, p. 320-322, July 1992.
7) PUTTICK, K.E., Whitmore, L. C., Gee, A.E., Chao, C.L., "Transmission electron microscopy of nanomachined of silicon crystals". **Phil. Mag. A**, Vol.69, p.91-103, 1994.
8) SHIBATA, T., FUJII, S., MAKINO, E., IKEDA, M., "Ductile-regime turning mechanism of single crystal Si", **Prec. Engg**., Vol.18, n. 2/3, p.129-137, April/May 1996.
9) JOHANSSON, S., SHWEITZ, J-A., "Contact damage in single crystal silicon investigated by cross sectional transmission electron microscopy", **J. Am. Ceram. Soc**., Vol.71, n.8, p.617-623, 1988.