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Influence 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. This was investigated by carrying out microindentation and single point diamond turning tests in three different [0 0 1]-oriented semiconductors, InSb, GaAs and Si single crystals. It is shown 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 proposed that the ductility of semiconductors crystals during machining is inversely proportional to the transition pressure value. The application of the phase transformation concept to machine semiconductors crystals with large feeds is demonstrated. The generation of microstructures with extreme cutting conditions in soft and hard semiconductors is discussed. Examples of large feeds with ductile response applied to silicon and indium antimonide single crystals are presented. The generation of subsurface brittle damage during ductile machining will be briefly discussed.

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 at room temperature presented by semiconductors crystals during microindentation and machining is attributed to a structural transformation into a metallic state induced by hydrostatic pressure and stress [1–3]. The amorphous state detected within the indentation mark as well as within the scratching groove in semiconductor crystals [2,4], enabled a new approach for analyzing the plastic behavior in single point diamond machining [3,5]. 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 tests were performed on 12 mm × 12 mm, 0.5 mm thick samples of monocrystalline (0 0 1)-oriented InSb, Si and GaAs. Indentation tests were performed in a VMHT met Leica^{TM} (Leica Mikrosysteme, Gmbh; A-1170, Vienna, Austria) microindentation apparatus using a Vickers pyramidal indenter. The indentation loads used in the tests were 5, 10, 15, 25, 50 and 100 g.

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 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

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Table 1
Cutting conditions and tool geometry used in the machining tests

Cutting conditions and tool geometry	Value
Depth of cut (μm)	0.5 and 5
Feed rate (μm/rev)	1.25, 2.5, 7.5 and 20
Tool nose radius (mm)	0.762
Rake angle	0°
Clearance angle	12°
Spindle speed	1000 rpm

Table 2
Qualitative analysis of brittle and ductile response in the microindentation tests

Material	Brittle and ductile response observed around microindentation mark					
	5 g	10 g	15 g	25 g	50 g	100 g
InSb	Ductile	Ductile	Ductile	Brittle	Brittle	Brittle
GaAs	Brittle	Brittle	Brittle	Brittle	Brittle	Brittle
Si	Ductile	Ductile	Brittle	Brittle	Brittle	Brittle

cutting tool (Contour Fine Tooling, Hertfordshire, UK) geometry are presented in Table 1.

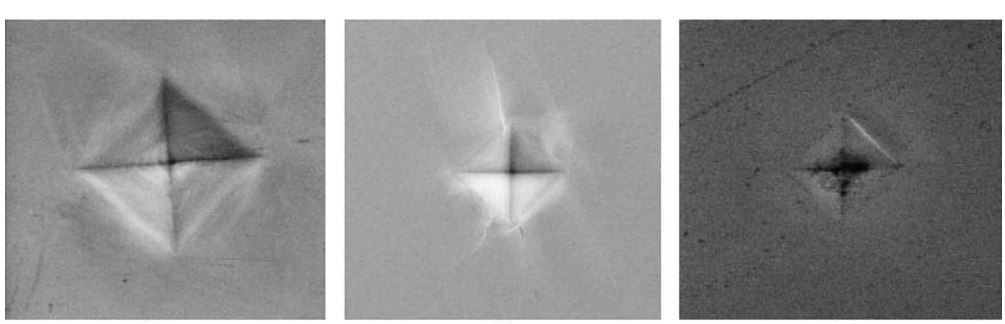
3. Results and discussion

3.1. Indentation experiments

Fig. 1(a–c) shows SEM micrographs of InSb, GaAs and Si indented with the same load (5 g). The indentation fingerprints presented plastic deformation replicating the Vickers pyramid indenter geometry. As can be seen, the deformation volume is larger in the case of InSb (Fig. 1(a) which has the lower microhardness ($H_V \sim 2.3$ GPa). Consequently, InSb presents a larger plasticity than GaAs ($H_V \sim 6.9$ GPa) and silicon ($H_V \sim 11$–12.5 GPa). Another interesting aspect observed in these experiments was the relationship between load and the onset of brittle failure, i.e., brittle cracking generated by the indentation process. Table 2 summarizes the ductile and brittle response observed around microindentation marks after loading with different loads. It would be expected that the brittle damage around the indentation mark should appear first for the hardest material but this was not followed. Under low loads (5 and 10 g) no sign of lateral microcracks were probed in InSb and silicon (Fig. 1(a) and (c), respectively). However, under all loads GaAs presented microcracks around microindentation impression. Fig. 1(b) shows the indentation mark made in GaAs with loads of 5 g. Despite gallium arsenide present a smaller microhardness than silicon (demonstrated by the larger diagonal mark in the former), the fragile response observed in GaAs is manifested even for the smallest load used. Moreover, how to explain that gallium arsenide, which microhardness is smaller than silicon, presented a more clear brittle response revealed by small lateral microcracks? This brittle behavior could well be explained by means of the transition pressure value of these single crystals semiconductors. This can be attributed to the fact that GaAs (17–18 GPa) has a transition pressure value larger than either indium antimonide (2.3 GPa) as well as 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. The increase in load also increase the indented area and the pressure imposed at the vicinity of the indented area will decrease, promoting brittle response instead of plastic deformation.

3.2. Application of the concept of transition pressure value to the machining tests

Based upon the results obtained in microindentation, cutting tests were carried out in order to investigate this relationship into a dynamic process. Fig. 2(a)–(d) present scanning electron microscopy images of the surface generated in InSb, silicon and GaAs, respectively, under different cutting conditions. The SEM photmicrograph shown in Fig. 2(a) is the surface finish of the InSb sample cut with 7.5 μm/rev where no sign of microcracks are observed. Fig. 2(b) shows the silicon sample cut under the same cutting condition as the former. In this case cracking and "spalling" damage, which are characteristics to the brittle regime, predominated. However, Fig. 2(c) shows a photomicrograph made of the silicon sample cut with a lower feed rate (i.e., 2.5 μm/rev) which presents a damage free surface finish. In the case of GaAs, the ductile response was achieved only with the smallest feed rate condition of 1.25 μm/rev (Fig. 2(d)). Table 3 summarizes the qualitative evaluation of the material removal mechanism observed on the surfaces after the cutting tests. Under the cutting conditions used to machine all the semiconductor crystal samples it was observed that InSb presented



(a) (b) (c)

Fig. 1. Microindentation Vickers under small load (10 g) of different semiconductors crystals. (a) InSb, diagonal size: 9.3 μm (magnification 5000×); (b) GaAs, diagonal size: 5.5 μm (magnification 5000×); (c) silicon, diagonal size: 3.9 μm (magnification 5000×).