ULTRA-PRECISION CUTTING FOR GALLIUM ARSENIDE

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ABSTRACT Gallium Arsenide (GaAs) is widely used in semiconductor and optical industries because of its excellent performance, which is the most important of the III-V compound semiconductors today for fabricating high-speed field-effect and bipolar transistors, infrared-emitting diodes, solid-state lasers, and integrated circuits. With this material, there is an immense need to obtain nanometric surface finish owing to the advantage of improved performance of the components. Thus, the use of ultra-precision machining becomes critical for this case. However, the mere use of ultra-precision machining for this brittle material would not yield mirror surface finish. Therefore, experiments were conducted by using diamond cutting for machining GaAs. Based on the experimental work, a new strategy was proposed for obtaining nanometric surface finish and the cutting mechanism was studied in detail. Also, in this paper an alternative approach was recommended for the sharpness measurement of diamond cutters.

Keywords: Gallium arsenide, Brittle materials, Ultra-precision machining

INTRODUCTION

The gallium arsenide (GaAs) integrated circuit industry continues to mature and emerge from its position as an advanced laboratory activity. After several years of promoting the superiority of GaAs ICs over silicon ICs in speed, power, temperature range and radiation hardness, many people began to think of GaAs ICs as exotic devices in a world by themselves. Ironically, one of the principal goals of industries today is to minimize the differences between the two kinds of products. The unusual properties of GaAs are recognized by the users of high-speed digital and analog ICs although the higher cost and more limited availability of GaAs ICs must be considered in any plans to replace an existing silicon IC with a GaAs IC.

As a brittle material, it is hard to obtain the mirror surface finishing for GaAs because of its high hardness and low fracture toughness. Diamond turning as an ultra-precision machining technology is increasingly demanded in the area of the mirror surface finishing[1-4]. Its advantages are particularly recognized in the machining of spherical and aspheric surfaces. During the machining, the surface finishing is directly influenced by the cutting conditions and tool geometry. And also, the sharpness of cutting tools is very critical. In this paper, in addition to the above goal, a new approach for measuring the sharpness of cutting tools by using vertical scanning-interferometry is proposed. Subsequently, the mirror surface was obtained, and the integrity of the machined surface was analyzed by atomic force microscopy and scanning electron microscopy.

GALLIUM ARSENIDE

Gallium arsenide (see Table 1)[5,11] is the most important of the III-V compound semiconductors today for fabricating high-speed field-effect and bipolar transistors, infrared-emitting diodes, solid-state lasers, and integrated circuits.

Table 1: Material properties

Properties	GaAs	Si
Young's Modulus, GPa	83	168
Density, g/cm^3	5.37	2.34
Knoop Hardness, kg/mm^2	750	1020
Poisson's Ratio	0.31	0.27
Melting point, ^{0}C	1240	1420
Thermal Conductivity, w/cm/^{0}c	0.46	0.2

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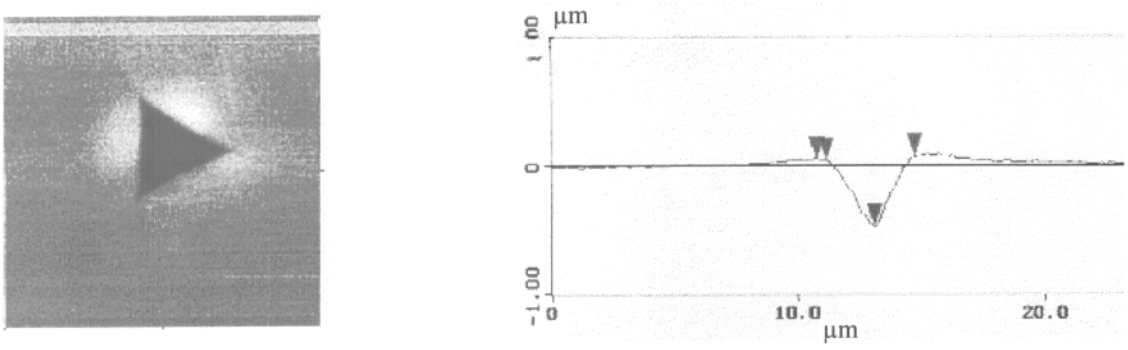
Like silicon, GaAs belongs to the cubic class of crystals. The crystal structure of GaAs consists of two interpenetrating face-centered cubic sublattices, which are called the zinc blend structure[5]. In GaAs, each sublattice contains atoms of only one element type. When both sublattices contain identical atoms as in the case of silicon, the lattice is called the diamond cubic lattice. The energy gap of GaAs is 1.43 eV at room temperature.

Semi-insulating optical GaAs provides an alternative to ZnSe in medium and high power CW CO_2 laser systems for lenses and rear mirrors. GaAs is particularly useful in applications where toughness and durability are important. Its hardness and strength make GaAs a good choice where dust or abrasive particles tend to build up on, or bombard, the optical surface.

DIAMOND CUTTING

Brittle materials, as mentioned above, exhibit properties which are needed for today's and future advance applications. However, hardness and brittleness often renders them difficult to finish-machine using conventional turning and grinding machines without causing substantial brittle fracture[6-9].



(a) Top view of nano-indentation

(b) Section analysis

Figure 1 Nano-indentation for the critical stress intensity of GaAs.

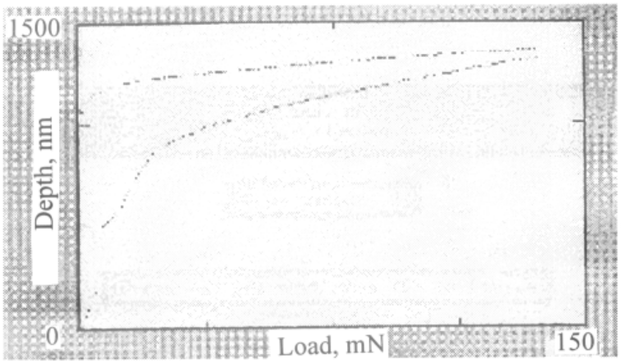


Figure 1 (c) Loading curve.

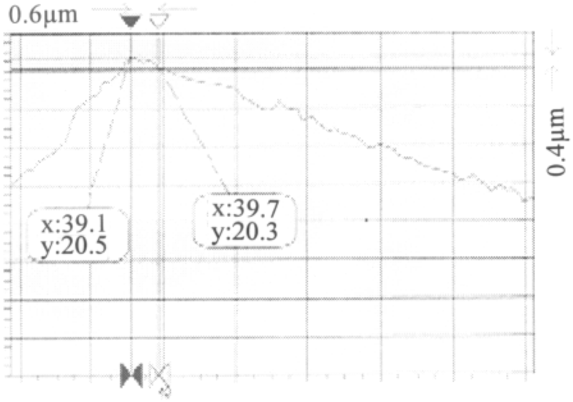


Figure 2 VSI for measuring the sharpness.

There is one hypothesis recently advanced involving "ductile" machining of brittle materials. According to this hypothesis, all materials, regardless of their hardness and brittleness, will undergo a transition from a brittle to a ductile machining region below a critical machining in feedrate. Below this threshold depth of cut, the energy required to propagate cracks is believed to be larger than the energy required for plastic deformation, so that plastic deformation is the predominant mechanism of material removal in machining these materials.

Ductile regime machining is necessary for obtaining mirror surfaces. In order to have a basic understanding of the ductile mode cutting, it is necessary to look into the indentation model which provides a criterion for the transition between the ductile and brittle regimes. An indentation fracture mechanics approach attempts to describe chip formation via crack propagation. Fig. 1 shows the nano-indentation with different loads. A load P pushes the indentor into the surface to a depth of d. This induced a plastic zone to form in the high stress zone under the indentor tip. When the indentor (or the cutting tool moves away), residual stress remains at the plastic zone boundary which, if large enough, will result in median and lateral cracks.

According to fracture mechanics theory[8-10, 12] , crack propagation occurs when the stress intensity K_I at the crack tip exceeds the critical stress intensity K_{IC} of the material.

$$K_I \le K_{IC} \tag{1}$$

Where $K_{IC} \propto \sigma_0 \sqrt{a}$ is critical stress intensity, 2a is crack length (as shown in Figure 1) and σ_0 is stress normal to the crack. Subsequently,

$$d_C = \beta \left(\frac{E}{H} \right) \left(\frac{K_{IC}}{H} \right)^2 \tag{2}$$

Where E and H are the elastic modulus and the hardness of the material respectively. β is a factor that will depend upon geometry and process conditions, such as rake angle and coolant etc. From the results of the Fig. 1, the critical stress intensity of 1.22 $\mathrm{MNm}^{-3/2}$ can be calculated.

After understanding the critical depth of cut dc, we can control the cutting in ductile regime.

TOOL SHARPNESS MEASUREMENT

Measurement of diamond tool edge geometry is essential for quantitative study of the ultra-precision machining process. Recently reported work has shown significantly differences in the surface finishing which results when machining with different tool sharpness of single diamond tools. In the present study, the tool sharpness was quantitatively measured by vertical scanning- interferometry, atomic force microscopy, and scanning electron microscopy.

(1) Vertical Scanning-Interferometry

Vertical scanning-interferometry (VSI) is a new technique for measuring surface profile. In principle, a white light beam passes through a microscope objective to the sample surface. A beam splitter reflects half of the incident beam to the reference surface. The beams reflected from the sample and the reference surface recombine at the beam splitter to form interference fringes. The system measures the degree of fringe modulation, or coherence, instead of the phase of the interference fringes unlike phase shifting-interferometry (PSI). That's why it is able to measure a wide range of surfaces. Figure 2 shows the sectional analysis of the diamond tool edge by using this technique. The edge sharpness measured for the cutter in the Fig. 2 is 400 nm.

(2) Atomic Force Microscopy

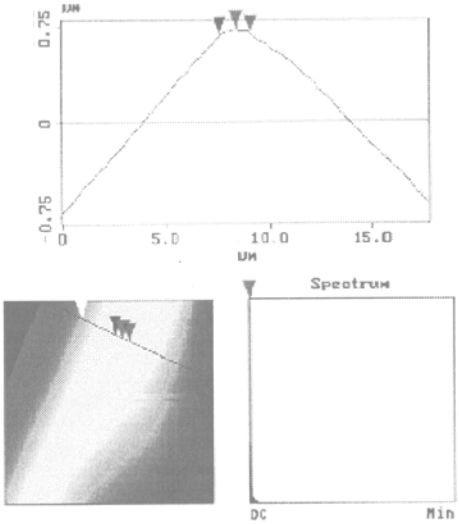


Figure 3 AFM for measuring the sharpness.

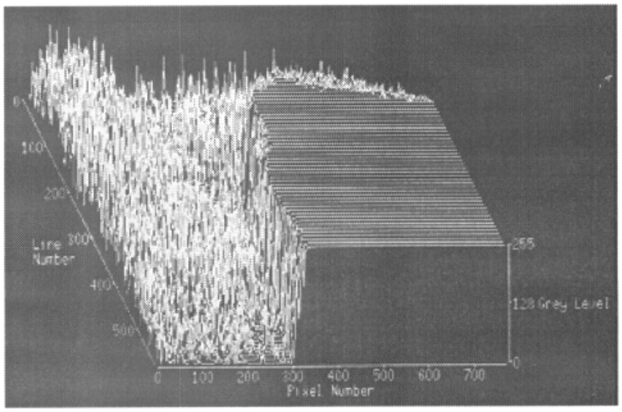


Figure 4 SEM for measuring the sharpness.

Scanning probe microscopy (SPM) offers researchers and technologists the capability to make images of many surfaces at near-atomic and even atomic resolution. The field of SPM has expanded enormously because of the subsequent proliferation of many types of high resolution imaging mechanisms. In many types of probe-based techniques used successfully in research on microscopic surface phenomena, the most important technique is the atomic force microscope (AFM), which measures surface topography in a straightforward way.

The use of atomic force microscopy, whereby a diamond tool is positioned directly under the scanning cantilever tip has also shown promise for characterization of single crystal diamond tools. Suppliers of commercially available Si_3N_4 cantilevers estimate tip radii to be in the range of 20-40 nm[4]. As a result, when using the force microscope to measure the edge of a diamond tool, there will be a convolution of cantilever tip and tool edge geometry which will become important when the tool edge radius is of the order of the cantilever tip radius (Figure 3). A number of cutters have been measured during the experiments. Figure 3 shows that the value calculated for the cutter edge sharpness is 210 nm.

(3) Scanning Electron Microscopy

The scanning electron microscope (SEM) is popular because it uniquely combines some of the simplicity and ease of specimen preparation of the optical microscope with much of the performance capability and flexibility of the more expensive and complex transmission electron microscope. By means of scanning electron microscopy, a graphical representation of the grey levels with the image of the cutter (Figure 4) can be obtained. According to the figure, the edge of the diamond tool can be analyzed. The sharpness value of the cutter is about 400 nm.

MIRROR SURFACE FINISHING

Diamond cutting experiments were performed on a diamond turning machine using single crystal diamond tool with a rake angle of 0 degree with a radius of 0.50 mm (waviness controlled, 0.25 µm). For turned gallium arsenide, mirror surfaces of 1.0 nm roughness are achieved, where a depth of cut of 1.0 µm, width of cut (feed rate) of 0.6 µm/rev, and a cutting speed of 90 m/min are used. It can be seen clearly that the ideal ductile cutting is substantiated through 3-D analysis and section analysis by using an atomic force microscope (Digital Instruments Inc.) as shown in Figure 5. The roughness values of the turned mirror surfaces are Ra=1.0 nm, Rmax=10.0 nm and Rms=1.3 nm in the area of 10 x 10 μm^2.

Originally, it was hypothesized that the maximum chip thickness, t_m, would be the dominant parameter in determining whether the surface suffered pitting damage or not. But the understanding of pitting along the tool shoulder eliminates that hypothesis. The pits created at the point of maximum chip thickness are not very deep (0.1-0.3 µm, compared to a depth of cut of 2-200 µm). Their creation would have little to do with the final surface.

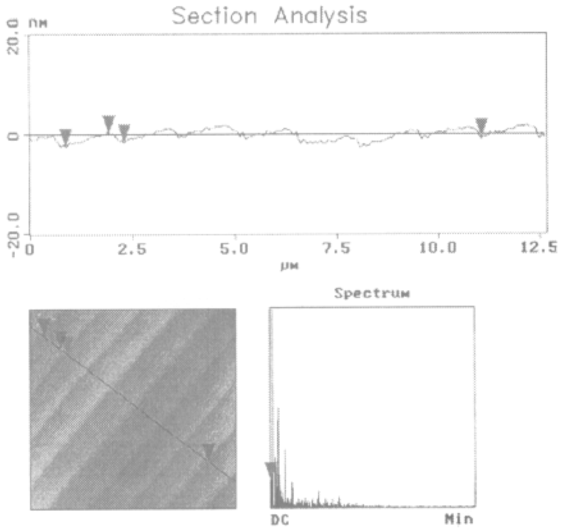


Figure 5 Mirror surface analysis.

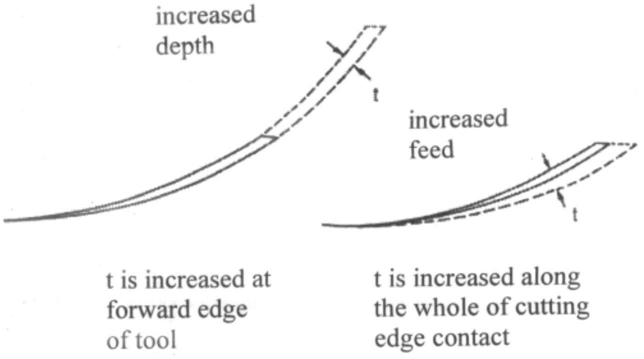


Figure 6 The effects on the undeformed chip cross-section of increased depth and increased feed.

More significant would be the chip thickness at the point along the tool shoulder where pits ceased to be created. It can be seen that the feed per revolution will have a dominant effect on the chip thickness. Figure 6 illustrates the effect of increasing depth of cut on the cross-sectional shape of the chip, and the effect of increased feed. Increased depth increases t_m, but merely by making the chip wider, leaving the relationship between chip thickness and distance along the chip width unchanged. However, increasing the feed increases the chip thickness along its whole width[8,10].

CONCLUSIONS

Gallium arsenide material is widely used in semiconductor and optical industries today. Its excellent electronic and optical performance makes itself obtain more and more attention. For the ultra-precision machining of gallium arsenide, the sharpness of diamond tools affects heavily the surface finishing. Different approaches were investigated in the experiments, and atomic force microscopy is alternatively selected to measure the edge of the tools since it has a high resolution and is easy to obtain the accurate coordinate values of the edge. As a kind of brittle material, gallium arsenide's mirror surface finishing was realized in ductile mode, and surface roughness of Ra=1.0 nm was achieved successfully. The surface integrity was analyzed by scanning electron microscopy and atomic force microscopy. It appears that a truly ductile cutting response can be achieved only when the effective cutting depth, or chip thickness, is less than a critical value. Factors such as tool rake angle are significant in that they will affect the actual value of the critical depth of cut for transition from brittle to ductile response.

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