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MICROGRAPHIC FRACTURE CHARACTERIZATION OF GALLIUM ARSENIDE WAFERS

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Abstract

Single crystal gallium arsenide (GaAs) specimens were loaded to failure. Scanning electron microscope examination of fracture surfaces showed that GaAs fails in a brittle manner on {110} planes. Features on these fracture surfaces were used to identify preexisting (critical) flaws that potentially initiated fracture when loaded by tensile stresses. Critical flaws in each specimen were identified by comparison to an intentionally damaged control. The size and shape of critical defects were consistent with existing failure models.

Key Words: Gallium arsenide (GaAs), brittle fracture, cleavage, flaw identification, single crystal, wafer, critical crack, semiconductor, fracture surface, scanning electron microscopy.

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Introduction

Gallium arsenide (GaAs) is used as a semiconductor in applications where conventional materials, such as silicon (Si), may not be adequate. A major problem with GaAs is the combination of its low mechanical strength and extreme brittleness, which is responsible for significant breakage during the production process and in service. A better understanding of GaAs fracture mechanisms is therefore necessary to help predict failure under typical loading conditions.

It is well understood that failures in brittle materials are due to the presence of small, naturally occurring flaws or defects inherent to the material. When a body is loaded, these defects magnify the stresses in their vicinity and initiate fracture. Failure of brittle materials, and of GaAs in particular, can be formulated in terms of the mechanical stresses and the geometry of the flaws present in the body [1, 3, 6]. Gallium arsenide tends to fracture on {110} planes, which extend from edge to edge of a wafer because wafers are single crystals [2]. Since fracture occurs most readily on the {110} planes, the flaws leading to failure on these planes were analyzed theoretically and {110} fracture surfaces were examined with a scanning electron microscope (SEM). The goal of this project was to perform an SEM analysis of the fractured surfaces of failed GaAs specimens and to gain a better understanding of the fracture characteristics of GaAs. Hopefully this knowledge can eventually be used in the design of processing and handling techniques to minimize the inherent weaknesses of GaAs.

Materials and Methods

Rectangular prismatic specimens 57.15 mm x 6.35 mm (2.25 in. x 0.25 in.) were cut from 76.2 mm (3 in.) diameter, 0.635 mm (0.025 in.) thick, (001) partially processed GaAs wafers with a diamond saw at different orientations (angles $\alpha = 0°$, 22.5°, 30°, 45°, 53°, 60°, 67.5°, 80°, and 90°) relative to the {110} planes (Fig. 1). Sixteen to forty-five specimens were tested for each orientation. These specimens were placed in a fourpoint bending apparatus where the bending moment was slowly increased until failure occurred. Loading specimens, cut at different angles, placed a combination of normal and shear stresses on the expected {110} failure planes. It was assumed (and verified) that failure would always occur on planes in the {110} family, and thus only stresses and flaws on these planes were considered. The normal and shear stresses at failure (on the {110} planes) for each orientation angle were obtained by standard stress transformations applied to the bending stress. These experimental data conformed to the theoretically predicted failure criterion [1]. Seven randomly selected GaAs specimens were also pedestal mounted, cleaned with acetone, and examined with a JSM-35CF JEOL (Peabody, MA) scanning electron microscope (SEM) operated at accelerating voltages of 20-25 kV.

Results and Discussion

The specimens were quasi-statically loaded to failure (the term "quasi-static" is commonly used in mechanical testing to refer to a situation where the loading rate is slow enough to consider the specimen in static equilibrium during the test; any inertial or dynamic effects, and transient effects, can be ignored). Fracture was instantaneous, typical to cleavage in brittle materials. All of the specimens tested failed along the {110} family of planes, regardless of the loading direction α. The fracture surfaces were generally flat and smooth, indicative of brittle failure. Infrequent surface patterns and irregularities were characteristic of the initial phase of crack growth. Figures 2 and 3 show fracture surfaces that are typical of those observed. The curved lines present on the fracture surface in Figure 2 are called Wallner lines [4]. These lines are caused by the interaction between stress waves reflecting off the specimen boundaries and the propagating crack, and their position and orientation can suggest the initiation site of the fracture.

To better identify the initiation site, three randomly selected control specimens were intentionally damaged with a pointed scalpel and then placed in bending such that fracture initiated at the damage site. Figure 4 shows the fracture surface of the control specimen, with steps that occurred in a vertical band. A surface flaw intersects many {110} failure planes, and thus the crack initiates on several {110} planes. As the crack "seeks" its ultimate propagating plane, it creates the observed steps. On either side of this band, the fracture surface was flat until Wallner lines appear (Figs. 5 and 6). The region without Wallner lines was most likely the distance that the crack traveled before the stress waves reached the specimen boundary and reflected back to interact with the propagating crack. The Wallner lines are symmetric about the flaw (Fig. 4), suggesting that this flaw initiated fracture. These control specimens were only used to analyze the far field characteristics (Wallner lines, etc.) and for comparison to typical brittle failure characteristic behavior. They were not used for the local and specific analysis of the initiation site.

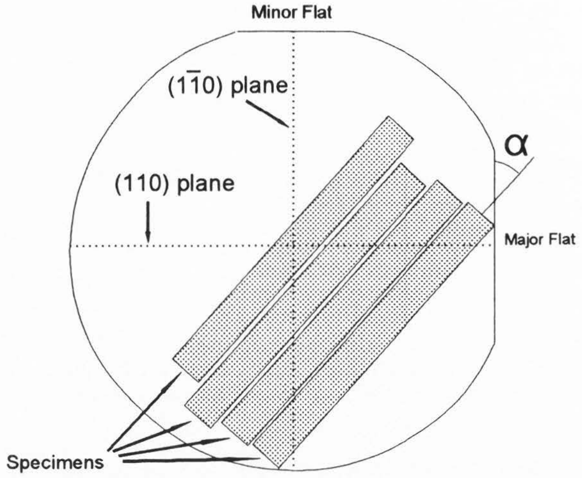
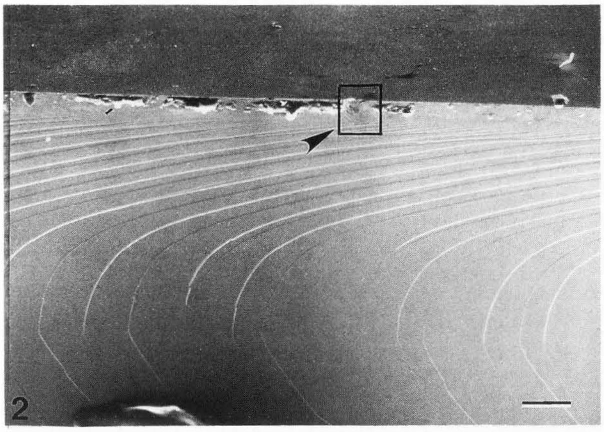


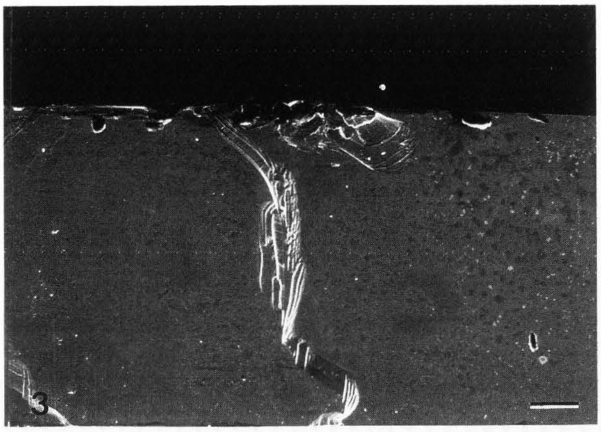
Figure 1. Test specimen orientation relative to GaAs wafer.

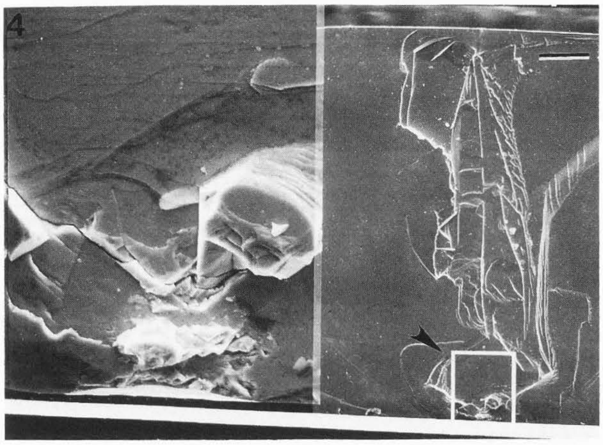
Figure 3 shows a naturally occurring initiation site, which was identified by the vertical band of steps, as above. The center of the micrograph shows this band, emanating from the flaw at the top center, is similar to that in the control specimen. Again, there was a flat region on either side of the vertical band of steps, followed by Wallner lines that were symmetric about the flaw (left side shown in Fig. 2).

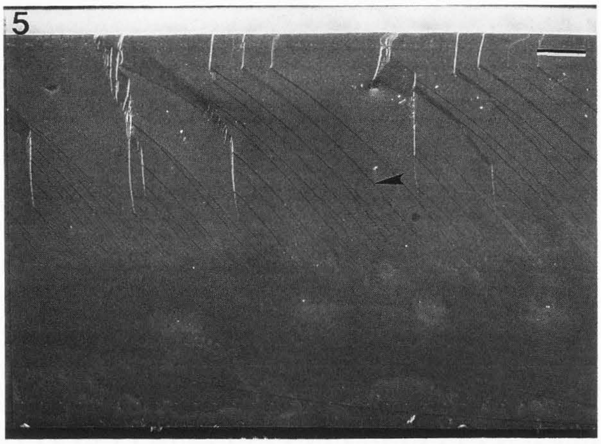
In general, many flaws exist in any material, but only one becomes critical under load and leads to failure. It is important to note that although it was clear that the cracks initiated at existing defects along the edges of the specimens, the cause of this initiation site cannot be determined and was not within the scope of this study. In many cases, there were other flaws present on the tensile side of the fracture surface. Figure 7 shows an enlargement of a defect on the fracture surface circled in Figure 2. There was no band of vertical steps emanating from this flaw and the Wallner lines seem unaffected by its presence, indicating that this flaw did **not** initiate fracture.

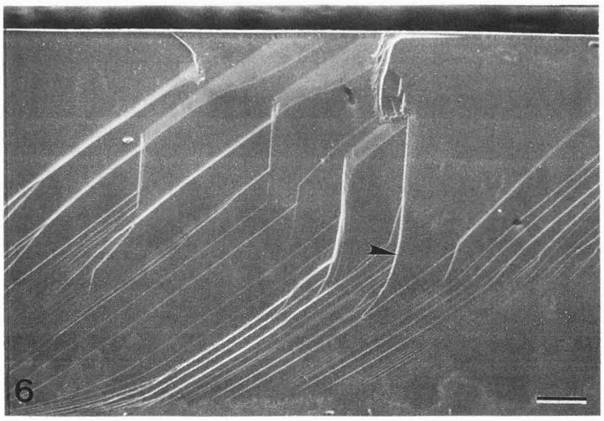
Experiments have shown that a crack propagating in a brittle material tends to reorient itself to be perpendicular to the maximum tensile stress [3]. However, a crack in GaAs will not propagate on an arbitrary plane, but prefers to propagate on a {110} plane. Evidence of both phenomena was observed. A typical example is shown in Figure 8, which displays the failure plane of a











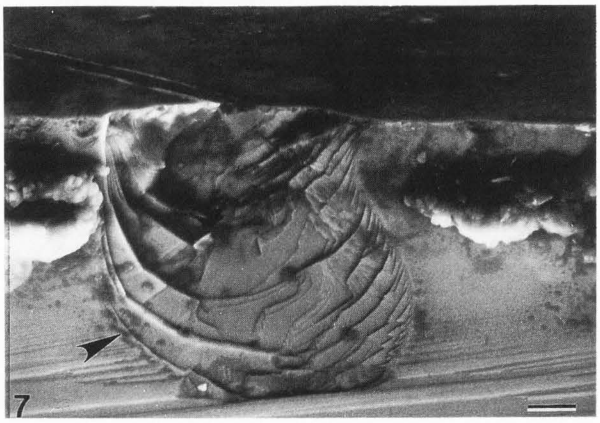


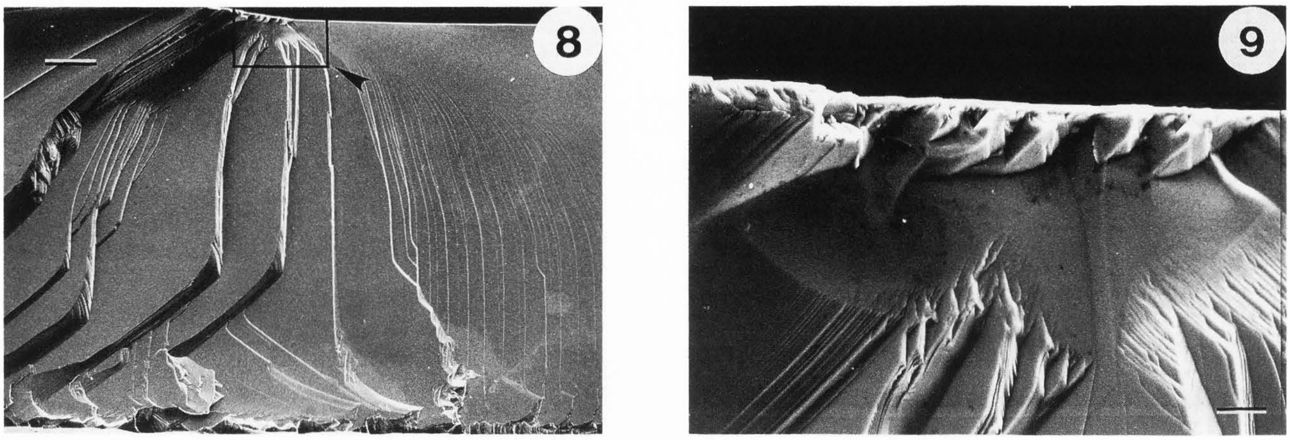
Figure 2. Fracture surface showing Wallner lines on an otherwise flat surface. Surface flaw (boxed) is on the tension side of the specimen. The area indicated by the arrow is shown enlarged in Figure 7. Bar = 100 μm.

Figure 3. Another area of the same fracture surface of Figure 2. The vertical band of steps originating from the flaw at the top (tension side) of the specimen, indicating that this was the initiation site. Bar = 100 μm.

Figure 4. A control specimen, intentionally damaged to help recognize fracture initiation sites. The vertical band of steps originated from the flaw is shown ten times enlarged on the left side of the micrograph. Bar = 100 μm.

Figures 5 and 6. Areas to the left (**Fig. 5**) and right (**Fig. 6**) of the initiation site (Fig. 4), showing Wallner lines in opposite directions. Bars = 100 μm.

Figure 7. Enlargement of flaw indicated by arrow in Figure 2. The Wallner lines seem unaffected by the presence of this flaw. Bar = 10 μm.



Figures 8 and 9. Initiation site identified by steps emanating from area outlined. The boxed area of Figure 8 is enlarged in Figure 9. Bars = 100 μm (Fig. 8) and 10 μm (Fig. 9).

specimen loaded by a combined tensile and shear stresses. The steps emanating from the initiation site (enlarged in Fig. 9), were not in a clear vertical band. This was probably due to the shear loading on the failure plane, which caused the maximum tensile stress to occur on a plane oriented at 30° to the (110) failure plane. The stresses within the specimen prevented the crack from settling on a {110} plane as rapidly as in the tension-only cases of the previous specimens. The Wallner lines were again symmetric about the initiation site.

After identifying the flaws that initiated fracture, the size of the initial flaw was measured in randomly selected specimens and compared to the theoretical model and previously published values for the fracture strength of GaAs [1]. As an example, the flaw in Figure 9 was modeled as a semi-elliptical surface crack in a thin elastic plate subjected to bending using the model of Newman and Raju [5]. The details of this calculation are presented elsewhere [1], but the results predict a flaw size of approximately 32 μm deep and 91 μm wide to cause failure at the measured bending stress of this specimen. The flaw geometry in Figure 9 is consistent with this prediction, which indicates that the theoretical model not only fits the experimental data, but also incorporates the observed physical phenomenon that causes fracture in GaAs.

Conclusions

Analysis of the scanning electron micrographs revealed several important aspects of GaAs fracture: (1) the micrographs showed that the fracture surfaces are along {110} planes and are flat except for Wallner lines, which indicates that GaAs fractures in a brittle manner; (2) characteristic steps were found on the fracture surfaces that emanated from, and thus identified, the fracture initiation sites; (3) all of the fracture surfaces examined were found to contain defects originating from the surface and in all cases, the flaws that appeared to have initiated fracture were on the tensile side; and (4) the flaws that initiated fracture were found to be consistent in size and shape with those predicted by the fracture model and published values of the fracture strength of GaAs. These observations also showed that the fracture model effectively captures the physical phenomenon of GaAs fracture.

Acknowledgment

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References

[1] Belsinger HE Jr, Wilner B, Tasch U, Topoleski LDT (1994) A fracture criterion for gallium arsenide wafers. Eng Fract Mech **48**(2): 199-205.

[2] Blakemore JS (1982) Semiconducting and other major properties of gallium arsenide. J Appl Phys **53**(10): R123-R128.

[3] Erdogan F, Sih GC (1963) On the crack extension in plates under plane loading and transverse shear. Trans ASME, J Basic Eng **85**: 519-527.

[4] Metals Handbook, Vol. 8. 9th Edition (1985). American Society for Metals, Metals Park, Ohio. p. 15.

[5] Newman JC Jr, Raju IS (1981) An empirical stress-intensity factor equation for the surface crack. Eng Fract Mech **15**: 185-192.

[6] Yasutake K, Konishi Y, Adachi K, Yoshii K, Umeno M, Kawabe H (1988) Fracture of GaAs wafers. Jap J Appl Phys **27**: 2238-2246.

Discussion with Reviewers

D.H. Kohn: A motivating factor for conducting this research is fracture of GaAs during production. How might the results of this study lead to the changes in production that reduce fracture?

Authors: The theory of fracture of GaAs has not yet been fully developed to the point of practical application. Although much more information is needed to completely understand the mechanics of brittle fracture in GaAs, the information obtained in this paper and the previous one [1] has been used to identify the best way to position GaAs wafers in processing units to minimize the critical stresses along the failure planes.

D.H. Kohn: Are all such GaAs wafers single crystal? If not, how might the results change if GaAs wafers were polycrystalline?

Authors: GaAs wafers used in electronic packaging are all single crystals, which gives them their unique electrical properties. Extra care is given to the manufacturing of these single crystals, in order to be as pure as possible (i.e., with minimum defects and dislocations). Obviously, a polycrystalline material will have different fracture characteristics, in particular, it will not have the specific fracture planes, and the unique fracture envelope discussed previously [1].

D.H. Kohn: The fractography indicates that failure initiated at the edges of the samples. Were any of the defects not inherent defects, but due to machining? Can machining defects be differentiated from inherent defects in the wafers?

Authors: GaAs wafers are made to be as pure and defect-free as possible (99% or higher). The wafers are carefully inspected prior to their processing as well. Defects are introduced to the GaAs wafers during the implantation processes and handling. This study focused on identifying critical crack geometries [1] and propagation characteristics. Various processing operations will alter the surface and create potential defects. Understanding the defects is critical; however, the source of the initiation site was not considered to be within the scope of this study, and is left to future investigations.

D.H. Kohn: What were the specific effects of orientation on fracture mechanisms? Did all failure initiate as shear and then reorient into mode-I damage?

Authors: The specific effects of orientation of the fracture failure enveloped has been discussed elsewhere [1]. It is important to note that in contrast to brittle fracture of polycrystalline isotropic materials, the cracks in the GaAs specimens did not propagate in mode-I, but remained in a combined mode-I/mode-II (tension/shear) along the preferred $\{110\}$ plane.

D.H. Kohn: You state that fracture steps around a flaw that do not interact with Wallner lines (e.g., Fig. 7) imply that the flaw does not initiate failure. Is it possible that the flaw was a site of crack initiation, but the Wallner lines blunted the crack?

Authors: Since the Wallner lines are created by the propagating crack interacting with stress waves reflected off the specimen boundaries, these lines typically become visible at a distance from the crack initiation site. The data presented in this study is consistent with this fracture characteristic. The defect shown in Figure 7 does not interact with the Wallner lines, and hence with the propagating crack, therefore, it cannot be the initiation site. Also, the Wallner lines cannot be attributed to crack blunting since brittle materials exhibit little to no blunting (blunting is characteristic to ductile fracture).

D.H. Kohn: Can you estimate the stress intensity factor for damage initiation at the critical defect or for the scalpel induced damage? How reproducible was the scalpel damage?

Authors: The critical stress intensity factor for GaAs was calculated in a previous paper and by other researchers as well; an approximate K_{1C} value for GaAs was found to be 0.44-0.46 Mpa $m^{1/2}$ for the $\{110\}$ family of planes [1]. Reproducibility of the scalpel-initiated damage was not studied, since these control specimens were only used to examine the far field fracture morphology. It will be appropriate to further investigate surface defects in future studies of crack initiation.

W.W. Predebon: The statement (in **Materials and Methods**) "It was assumed (and verified) that failure would always occur on planes in the $\{110\}$ family, and thus only stresses and flaws on these planes were considered" raises questions concerning the general validity of your conclusions. Please comment about the probability of failure on other planes and whether it has been observed experimentally in the literature.

X.-J. Zhang: Is there a table or graph showing that most of the specimens failed on the $\{110\}$ planes regardless of specimen orientation?

Authors: As stated in **Results and Discussion**: "All of the specimens tested failed along the $\{110\}$ family of planes, regardless of the loading direction α." This observation has been made by other researchers as well [2, 6].

S. Radin: The authors state: "The fracture surfaces were generally flat and smooth, indicative of brittle failure." It is also worth mentioning that, in addition to being indicative of brittle failure, "flat and smooth" surfaces could also be indicative of a very slow crack propagation.

Authors: Brittle fracture in single crystals, in contrast to ductile failure and fatigue, is characterized by rapid crack growth. The smooth and flat surface is, therefore, an indication of such a fracture mechanism in brittle materials.