JOURNAL OF MATERIALS SCIENCE 6 (1971) 390–394

The Maximum Fracture Velocity of Silicon

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A "Wallner Line" effect on the fracture surface of silicon is described and is used to determine a maximum fracture velocity of (3800 ± 400) m/s or (0.75 ± 0.07) v_t. The mirror energy of silicon is also measured. The values are compared with those for glass and other materials and are shown to be consistent with a solid whose crack branching angle is restricted to 70°.

1. Introduction

Single crystals of germanium can be made to fracture at different bending stresses by varying the surface treatment [1]. Stresses of order 1000 MN/m^2 can be reached after careful electropolishing and at these stresses the fracture surface lies mostly on $\{111\}$. When the surface is etched, areas of damage are revealed. They consist of very small side cracks formed on the neighbouring $\{111\}$ planes by a crack branching mechanism, and their occurrence depends on the direction of crack propagation with a three-fold symmetry as explained in fig. 1.

In the course of other work [2], similar damage has been observed in silicon. It was noticed that in silicon the etched damage, particularly at the edge of the damaged area, tends to be distributed along distinct lines. These lines always lie at an angle between 35 and 55° to the radial cleavage steps, are often curved, and do not correspond to any particular crystallographic direction. There are usually a number of short lines parallel to one another and occasionally two sets of lines cross. As can be seen from fig. 2, near the specimen edge the lines have the definite appearance of Wallner lines.

Wallner lines in glass consist of small disturbances of the fracture surface produced by the interation of a shear wave with the crack front [3]. Their formation is shown in fig. 3. A crack spreads out radially from C with speed v_b. At S it meets with a disturbance which produces a shear wave front velocity v_t. Interference between shear wave and crack front causes a disturbance of the fracture surface along their line of intersection. This is called the Wallner line. If the crack front and the source of the

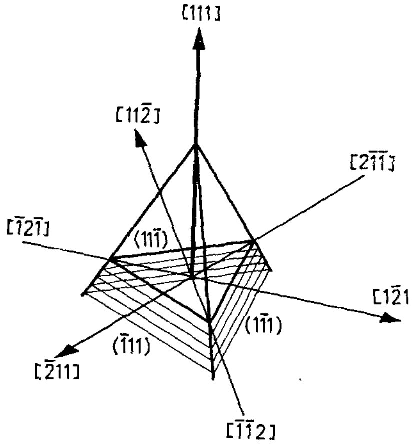

Figure 1 Formation of damage by crack branching in silicon and germanium at high speeds. If (111) is the fracture plane, with [111] the upward normal and $[\bar{2}11]$ the direction of crack propagation, then the $(\bar{1}11)$ plane lies below the lower surface at 70° to the propagation direction and is thus favourable for crack branching. Above the upper surface however, the same plane lies at the corresponding angle of 110° which is less favourable. Secondary cracks form therefore more readily on the lower surface than on the upper. If the crack propagation direction is $[\bar{1}\bar{1}2]$ secondary cracks form on the $(11\bar{1})$ plane on the upper surface. This pattern repeats itself every 120° and leads to the characteristic threefold symmetry of the damage distribution.

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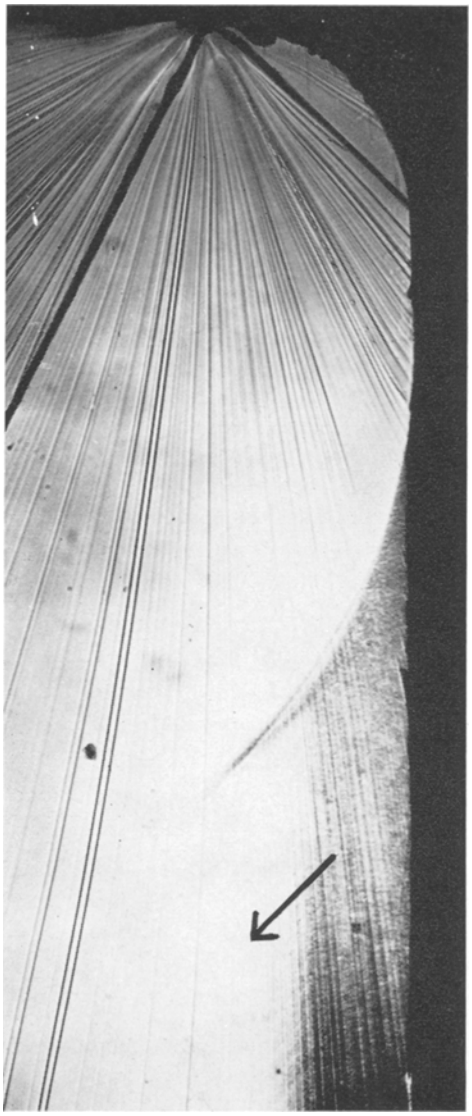

Figure 2 Distribution of secondary cracks at the edge of the fracture surface in silicon after etching. The lines in the direction arrowed appear similar to Wallner lines. With the exception of the large initial line, the sources cannot be identified, although they might be expected to lie at the specimen edge. $\sigma = 106$ MN/m^2 ($\times$ 70).

Wallner line are known, the ratio v_b/v_t at P, which is equal to $\cos\phi/\cos\theta$, can be deduced using the geometrical construction shown.

It is assumed that the lines in silicon are formed by a similar mechanism as Wallner lines, that is, that the crack branching process itself, rather than the orientation of the surface, is disturbed by the arrival of a shear wave. With certain limitations described below it is then

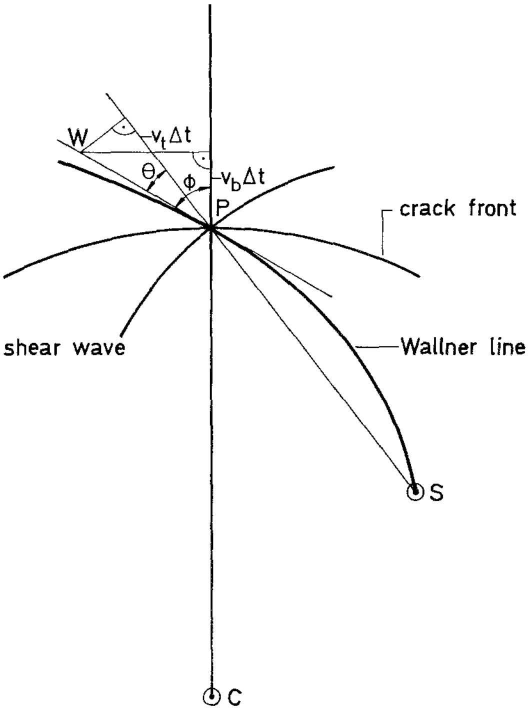

Figure 3 Geometrical construction required to deduce the ratio v_b/v_t at the point P. C is the crack origin, S the source of the Wallner line.

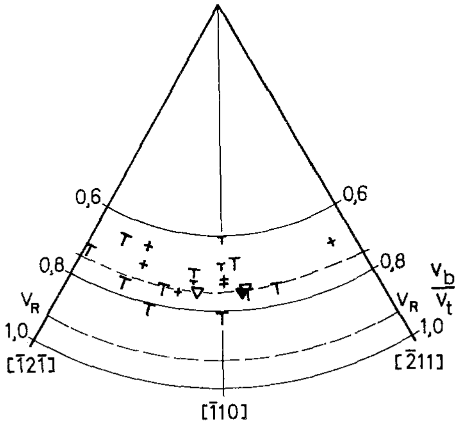

Figure 4 Measurements of crack velocity in the damaged region in silicon plotted as ratios of v_t with respect to crystallographic orientation. The different signs are explained in the text. The results are superimposed upon the 60° sector between [$1\bar{2}1$] and [$\bar{2}11$], which can be mirrored about either of these directions and the resulting 120° sector repeated three times on the cleavage surface. It must be remembered that the sector between [$\bar{1}2\bar{1}$] and [$\bar{1}10$] faces a sector crystallographically equivalent to that between [$\bar{2}11$] and [$\bar{1}10$], so that any dependence of velocity on crystallographic orientation must also be symmetric about [$\bar{1}10$]. The dashed line represents $v_b/v_t = 0.75$.

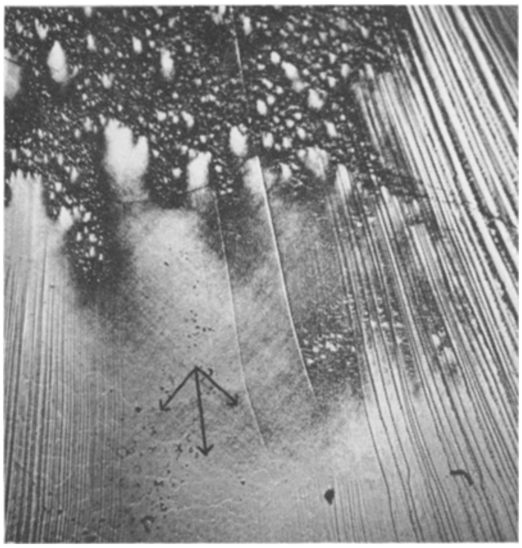

Figure 5 Etched lines on the fracture surface of silicon (× 100). The directions of the "Wallner lines" are arrowed and the direction of crack propagation between them. $v_b/v_t = 0.75$.

possible to estimate the crack speed. The appearance, curvature and distribution of the lines, the narrow range of crack speeds measured and their agreement with a rough check based on the longitudinal waves reflected from the back specimen as well as a theoretical estimate are taken to support this assumption.

2. Experimental

Chemically polished silicon specimens were fractured in bending and the fracture surfaces etched with a solution of 10 g CrO_3 + 30 cc HF + 50 cc H_2O for 5 min [4]. Germanium specimens tested for comparison were etched with a solution of 8 g $K_3Fe(CN)_6$ + 12 g KOH + 100 cc H_2O for 6 min [5]. The bending stresses lay between 150 and 1000 MN/m^2. As in [1], the tests were carried out in a viscous oil which absorbed some of the reflected waves and prevented complete fragmentation of the specimens. The oil would not be expected to affect the maximum fracture velocity as its viscosity would prevent it from being present at the crack tip.

3. Results

3.1. The Maximum Velocity

The results of this analysis, taken from twenty-two measurements on fifteen different specimens, are plotted in fig. 4 according to the direction of crack propagation.

The measurements made were subject to the following limitations:

(1) The crack was assumed to have run perpendicular to the cleavage steps. When two sets of lines crossed, this assumption was not necessary and such measurements are marked as triangles in fig. 4. In the cases in which it could be checked, the maximum error introduced by this assumption was 7%.

(2) The sources of the "Wallner lines" could not always be identified. In certain cases the lines could, as in glass, be traced back to the crack surface. In cases such as that shown in fig. 5 (marked in fig. 4 as a filled triangle) the "Wallner lines" apparently start near large side cracks. These side cracks, which represent unsuccessful attempts at branching, lie on facets of {1 1 1} planes [1] and are frequently followed by blank unetched patches. Unsuccessful branching could well be the source of a shear wave, but it is not possible in fig. 5 to attribute a particular "Wallner line" to any individual side crack. Where the source could not be identified a minimum value of crack velocity could be determined by setting $\cos\theta = 1$. Such points are shown as "T" in fig. 4. Other points are shown as crosses. In the cases in which it could be measured, however, $\cos\theta$ was never greater than 5%.

(3) In order to detect any deviation, measurements made near the specimen edge are shown smaller in fig. 4.

The values of v_b/v_t shown in fig. 4 all lie between 0.6 and 0.8. It appears that velocities measured near the specimen edge are lower than average, which may indicate either that damage can occur there at lower velocities, or that the "Wallner lines" there are more intense. Dragging of the crack front at the edge would produce artificially high measurements of the velocity, but if the crack were to accelerate when it met the surface at an acute angle, therefore producing increased roughness, the curvature of the crack would indeed give rise to artificially low measurements of the velocity. There was no dependence on crystallographic orientation, and further checks were made to show that there was no identifiable dependence on where the measurement was made, either with respect to the bending axis or to the position of the etched area [2]. The maximum velocity is taken to be

$$v_b = (0.75 \pm 0.07)v_t$$
$$= (3800 \pm 400)\text{m/s}.$$

By measuring the distance travelled by the crack before it meets the longitudinal wave reflected from the bulk of the specimen, Johnson and Gibbs [1] were able to estimate a value for the maximum fracture velocity of germanium of 0.8 v_t. A similar analysis applied to five specimens of silicon gave a value of $(0.71 \pm 0.10)v_t$ which is in agreement with the value deduced above from the "Wallner lines".

The "Wallner lines" were not observed in germanium. Out of fifteen specimens tested one result was obtained, from a line which formed the initial boundary of a damaged region. This gave a speed of 0.53 v_t or 1600 m/s. Higher speeds have been measured by a different method [2].

3.2. Other Effects

Two further effects were observed in silicon at high speeds. Firstly, it was found that radial cleavage steps in the six $\langle\bar{2}11\rangle$ directions developed into narrow wedge-shaped strips. Secondly, when the surface was etched, the initial region had a characteristic shape. Assuming that the expanding crack was semicircular, damage first occurred in the favourable $[\bar{2}11]$, $[1\bar{2}1]$ and $[11\bar{2}]$ directions at a radius of l_1, the wedge-shaped strips at a higher radius l_2 and the damage in the least favourable $[2\bar{1}\bar{1}]$, $[\bar{1}2\bar{1}]$ and $[\bar{1}\bar{1}2]$ directions at a radius l_3. The ratio $l_1:l_2:l_3$ was found to be independent of stress and for seven specimens equal to

$$l_1 + l_2:l_3 = 1:(1.6 \pm 0.2):(2.2 \pm 0.7)$$

The values of l_3 were subject to considerable scatter.

The size of the initial region can be compared with that in glass. In glass there is an undamaged, semicircular "mirror" region whose radius can be used to give a "mirror energy", G_m, by means of the formula for a penny-shaped crack,

$$G_m = \frac{4\sigma^2 r(1 - \nu^2)}{\pi E}$$

where r is the radius of the region, σ the local tensile stress, E Young's modulus and ν Poisson's ratio. For glass $G_m = 74$ J/m² which, with critical fracture energy $G_{IC} \sim 10$ J/m², gives $G_m/G_{IC} \sim 7$ [6, 7]. The crack branching angle in glass is approximately ± 15°, and the best comparison with silicon would therefore appear to be the damage which occurs by forward crack branching, that is at radius l_1. For the same seven specimens used above

$$\sigma\sqrt{l_1} = (5.8 \pm 0.6) \times 10^6 \text{ MN/m}^{3/2}$$

giving

$$G_m \sim 200 \text{ J/m}^2 \sim 80\, G_{IC} \qquad [8]$$

An estimate of the corresponding value for germanium obtained from five specimens with σ between 120 and 250 MN/m² gave $l_1:l_2 = 1:3$ and

$$G_m \sim (70 \pm 30) \text{ J/m}^2 \sim 35\, G_{IC}\,.$$

The narrow wedge-shaped strips do not occur in germanium.

4. Discussion

The values of mirror energy and maximum fracture velocity in silicon are interesting for the following reason. In glass, crack branching occurs at angles of approximately ± 15° about the direction of crack propagation. In silicon this angle is fixed at 70°. Crack branching is correspondingly more difficult, and therefore occurs at a higher relative value of the mirror energy. In the same way the maximum fracture velocity lies between that for glass ($\sim$ 0.5 v_t) and those for cubic crystalline materials in which no crack branching is observed, such as tungsten at 20°K (0.82 v_t) [9] or MgO (0.79 v_t) [10]. According to present quasistatic calculations, the velocity at which the tensile stress on a plane inclined at 70° to the fracture direction exceeds that on the forward fracture plane lies indeed between 0.7 and 0.8 v_t [11]. For complete forking to occur, however, the side crack, once nucleated, must be capable of keeping up with the main crack. At an angle of 70° this would require a considerable difference in speeds or, since the main crack is already travelling at the maximum velocity, a large deceleration on its part. It may be significant that in this work no case of total crack branching was observed.

Acknowledgement

I am grateful to Professor F. Kerkhof for his encouragement, to Dr W. Theis of the A.E.G. Forschungszentrum, Frankfurt am Main, for the provision of material, to Dr E. Sommer for valuable discussion and the Royal Society for a fellowship under their European Programme.

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Received 17 November 1970 and accepted 20 March 1971.