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ALLOWABLE SILICON WAFER THICKNESS VS DIAMETER FOR INGOT-ROTATION ID WAFERING

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ABSTRACT

In order to meet Low-Cost Solar Project goals, thinner silicon wafers are needed. Inner diameter (ID) wafering of ingot rotation has been investigated as a means of reducing the ID saw blade diameter. The blade thickness could then be reduced, resulting in minimal kerf loss. However, significant breakage of wafers was found to occur during ingot-rotation wafering as the wafer thickness decreased. Fracture mechanics concepts were used to develop an equation relating wafer thickness, diameter and fracture behavior at the point of fracture by using a model of a wafer, supported by a center column and subjected to a cantilever force. The analytical model indicated that the minimum allowable wafer thickness would not increase appreciably with increasing wafer diameter; it was found to be approximately 500 μm for the conventional sizes of ingot-rotation ID wafering. Fracture through the thickness rather than through the center-supporting column was found to limit the minimum allowable wafer thickness. This model suggested that the minimum allowable wafer thickness can be reduced by using a vacuum chuck on the wafer surface to enhance cleavage fracture of the center core and by using <111> ingots.

INTRODUCTION

Crystal growers have made efforts to grow larger-diameter Czochralski silicon ingots, because increased diameter results in lower wafer cost per square meter. However, greater wafer thickness was expected to be necessary to withstand the greater stresses during wafering, cell processing and handling. Most cell manufacturers determine their minimum silicon wafer thickness for unconventional sizes by trial and error. Semiconductor Equipment & Materials Institute (SEMI) standards for these dimensional requirements for semiconductor industries are neither cost-effective nor practical for solar cell industries.

In order to meet Low-Cost Solar Array Project goals, thinner silicon wafers are needed. Ingot-rotation ID wafering has been investigated as a means of reducing the ID saw-blade diameter. The blade thickness could thereby be reduced, resulting in minimal kerf loss. However, significant breakage of wafers was found during ingot-rotation wafering as the wafer thickness decreased. The breakage usually took the form of circular cracking, often to the extent that the entire center of the wafer was broken out. The equations developed here provide guidelines for the fabrication of wafers of unconventional sizes by ingot-rotation slicing.

In Reference 1, fracture mechanics analysis was used to develop an equation describing the stress conditions of a wafer during conventional ID wafering. This equation predicted the minimum wafer thickness as a function of diameter for ID sawing. The required wafer thickness increased with increasing wafer diameter and was appreciably smaller than the existing SEMI standard.

In this paper, fracture mechanics concepts were extended to analyze the loading conditions of a wafer during ingot-rotation ID wafering. It is expected that this analytical model can be used for estimating the allowable wafer thickness vs diameter for ingot-rotation ID wafering in terms of fracture mechanics parameters.

FRACTURE MECHANICS MODEL

Ingot wafering is one of the most critical processes in controlling cell production yield. A wafer with center support subjected to a cantilever force can be considered to represent the stressed condition of a wafer during ingot-rotation ID wafering (Figure 1). The diameter of the rigid center support, d, can be considered to be the diameter of the center core (uncut area) during ingot-rotation wafering. The applied cantilever force, P, on the wafer may be due to saw-blade vibration and surface tension, and increases with cutting rate (Reference 1). The force on a wafer during slicing could be either a distributed loading or a cantilever force. In either case, an equivalent concentrated force P (Figure 1) can be used to describe the force conditions affecting a wafer during ingot-rotation ID slicing. The dragging force parallel to the wafer surface was found to be insignificant compared with the stress level within the wafer or in the center core, as the height of the center core is very small (i.e., 300 μm). Only the cantilever force perpendicular to the wafer surface was found to be significant during slicing.

Fracture of materials is the result of the extension of a pre-existing flaw under stress. Fracture mechanics defines the flaw size required for the onset of rapid propagation and fracture (for a given stress level) as the critical flaw size (a_c). This critical size in turn depends upon the values of the critical stress intensity factor (K_{IC}) for the material. Therefore, the fracture strength of material is controlled by a_c and K_{IC} of the material. For a small semicircular flaw, the relationship equation of fracture stress as a function of a_c and K_{IC} was derived (Reference 1) and can be expressed approximately as:

$$\sigma = \frac{K_{IC}}{\pi a_c} \qquad (1)$$

Thus, to determine the failure in any direction, it is necessary to know σ, K_{IC} and a_c. K_{IC} is a material constant, although directional, and a_c is a function of wafering technology. The surface damage to a wafer controls a_c.

Application of a force P at the edge of the wafer results in a stress both in the wafer and in the center support. These stresses can result in failure by propagation of microcracks in directions A and B, respectively. The propagation through the wafer thickness (direction A) destroys the wafer; propagation through the central core (direction B) reduces total wafering time. Considering first the stress in the wafer (failure in direction A), the maximum stress in the wafer was found to occur at the edge of the center support and can be expressed analytically (Reference 2) in an equation:

$$\sigma_A = \frac{P}{t^2}\beta \qquad (2)$$

where:

σ_A = stress in the wafer at the edge of the center support

P = applied cantilever force

t = wafer thickness

$= \frac{3}{\pi}\sum_{0}^{\infty} e_n$

and $\sum_{0}^{\infty} e_n$ is a Fourier series in which e_n is a function of:

ν = Poisson's ratio

d = diameter of center support

D = wafer diameter

n = , 1, 2, . . .∞

Substituting Equation (1) into Equation (2), the wafer thickness, t, can be written as:

$$t^2 = \frac{\sqrt{\pi a_{cA}}}{K_{IC}} P_A\beta \qquad (3)$$

where

a_A = critical flaw size for propagation in direction A

P_A = allowable force to cause crack propagation in direction A

A computer calculation of β as a function of d/D for n up to 30 and $\nu = 0.22$ for silicon (Reference 3) is shown in Figure 2. Thus Equation (3) expresses the relationship between the required wafer thickness and diameter of a solar cell. Next, considering the tendency of the stress in the center support to cause crack propagation in direction B, the fiber stress, $_B$ can be expressed from structure analysis (Reference 4) as follows:

$$\sigma_B = \frac{16P_B D}{\pi d^3} \qquad (4)$$

Substituting Equation (1) into Equation (4), the allowable applied force (P_B) of the center-support column, in terms of wafer diameter and fracture mechanics parameters, can be written in a form:

$$P_B = \sqrt{\frac{\pi}{16}} \frac{K_{IC}}{\sqrt{a_{cB}}} \frac{d^3}{D} \qquad (5)$$

In this equation, P_B and a_{cB} are allowable force and critical flaw size, respectively, for the center support column. They may be of a different value from P_A and a_{cA} for wafers in some cases, as will be discussed below. It should be noted that P_B does not depend on wafer thickness.

APPLICATION OF ANALYTICAL MODEL

Application of the model to ID wafering of rotated silicon ingots is straightforward. The fracture mechanics studies (Reference 5) on single-crystal silicon found that the critical stress intensity factor K_{IC} in several crystalline planes is as follows:

$$\begin{aligned} K_{IC} &= 0.82\ \mathrm{MNm}^{-3/2} \quad \text{in} \quad \{111\} \\ K_{IC} &= 0.90\ \mathrm{MNm}^{-3/2} \quad \text{in} \quad \{110\} \\ K_{IC} &= 0.95\ \mathrm{MNm}^{-3/2} \quad \text{in} \quad \{100\} \end{aligned} \qquad (6)$$

The typical wafer surface damage from ID sawing was measured (Reference 6) and found to be approximately 50 μm or:

$$a_c = 50 \times 10^{-6}\ \mathrm{m}$$

Substituting these values of K_{IC} and a_c into Equation (3), the allowable applied force, P, for wafer failure at several wafer thicknesses for slicing 100-mm ingots is shown in Figure 3. It is noted that, from Equation (3), P_A decreases with increasing a_{cA}. An example of the effect of changes in a_{cA} is shown by error bars on the $t = 300\ \mu$m curve. Points to the left are for $a_{cA} = 60\ \mu$m and to the right for $a_{cA} = 40\ \mu$m.

As shown in Figure 3, the minimum required wafer thickness without cracking at very small values of d (e.g., 2 mm) is very sensitive to the force P. Therefore, decreasing the cutting rate near the small d region is important for ingot-rotation wafering in order to maintain minimal wafer thickness. Deflection of the wafer is directly proportional to the applied force P. Controlling wafer deflection can be a means of controlling the bending stress in the wafer, so that a minimal usable wafer thickness can be achieved.

Again, Figure 3 shows the effect of the center-core diameter on the allowable applied force P of the wafer fracture. Observations from Figure 3 can be summarized as follows:

(1) At each wafering thickness, the allowable force on the wafer decreases with decreasing center core diameter. In other words, the probability of cracking a wafer during ingot-rotation wafering increases with increasing depth of cutting.

(2) The allowable applied force P for a wafer decreases rapidly as the center core diameter is reduced to a small value (e.g., 5 mm). Therefore, cracks in the wafer are usually found near the center of the wafer from ingot-rotation wafering (Figure 4).

(3) In typical conventional ID slicing at a cutting rate of 51 mm/min, a P force was estimated (1) to be 0.5 newton. Using $p = 0.5$ N, for example, to evaluate ingot-rotation a 200-μm-thick wafer is very likely to be cracked at $d = 50$ mm, while a 300-μm-thick wafer would be cracked at $d \approx 14$ mm. However, successful ingot-rotation wafering occurs when a wafer is broken off from the ingot at the center core without generating cracks in the wafer. A typical wafer surface from ingot-rotation slicing is shown in Figure 5. The diameter of the center core is ≈ 1.5 (0.06 in.).

From Equation (5), the fracture force for the center supporting core as a function of core diameter is plotted in Figure 3 by using $a_{cB} = 50\ \mu$m and $K_{IC} = 0.82$ MNm$^{-3/2}$. If an applied force P_B is 0.5 N (a typical value for ID sawing, as discussed above), the fracture of the wafer center supporting core for a 100-mm-dia wafer can occur, in Figure 3, at $d = 1.6$ mm. This calculated d value has the same magnitude as the observed value of d in Figure 5.

It has been pointed out that the fracture force P_B vs the core diameter d in Figure 3 is independent of the wafer thickness. It is found that 700-μm-thick wafers can be sliced at regular cutting speed for $P = 0.5$ N and the center core will fracture at ≈ 1.7 mm. A 600-μm-thick wafer can be sliced by reducing cutting force (0.5 N) from near $d = 2.5$ mm at a rate following its P vs d curve to $d = 1.5$ mm, where fracture of the center core occurs at $P = 0.34$ N. Figure 3 suggests that 500-μm-thick wafers require force reduction to less than 0.2 N and 400-μm-thick wafering appears to be impossible with ingot-rotation slicing. This limit is generally consistent with the present state of the art of ingot-rotation slicing.

TECHNOLOGY IMPLICATIONS

This analysis has implications for potential improvements in ingot-rotation slicing. These include control of a_c, K_{IC} and directional stress, σ_B. Thus, to enhance fracture in the B direction, a_{cB} and σ_B should be maximized, while K_{IC} should be minimized.

At present, ingot-rotation wafering is done mostly in <100> ingots. Because the fracture strength of the material is directly proportional to K_{IC}, as shown in Equation (1), the allowable fracture force for the center core in <100> can be greater than that in <111> axis, because K_{IC} on {100} is greater than K_{IC} on {111} as shown in Equation 6. Thus, if <111> ingots were used, easier fracture in the central core would occur. However, the difference is small (Figure 3). In addition, the fracture surface of silicon in {111} was found (Reference 5) to be a clean cleaved fracture; the fracture surface in other crystalline planes reveals rough crack branching.

It is also possible to control fracture by means of stress. If σ_B can be made greater by means of some additional force other than (P), then fracture in the B direction is favored. This can be accomplished by means of a uniform force on the wafer (e.g., by a vacuum chuck).

The application of a vacuum chuck to ingot-rotation wafering can be shown schematically. As shown in Figure 6, the total vacuum force on a wafer can be calculated:

$$F = p \frac{\pi D^2}{4} \tag{7}$$

where p = vacuum pressure, max p is 1 atm ≈ 0.1 MNm^{-2}.

The relationship of D and d can be expressed:

$$\frac{D}{d} = \sqrt{\frac{\sigma_n}{P}} \tag{8}$$

where σ_n = nominal stress in the center core.

Because of the existence of stress concentration in a deep groove, Equation (8) can be rewritten:

$$\frac{D}{d} = \sqrt{\frac{\sigma_c}{k_t p}} \tag{9}$$

where:

k_t = stress concentration factor in the bottom of the groove

σ_c = stress on the flaw

The stress concentration factor, k_t, for a grooved bar in tension is given (Reference 7) in Figure 7, in terms of the ratio of groove root radius, r and d. For ingot-rotation ID slicing, the typical value of r/d is very small (e.g., <0.02), and D/d is very large (e.g., 20); k_t value can be very large (Figure 7). Assume that:

$D = 100$ mm

$k_t = 15$

$K_{IC} = 0.82\ MNm^{-3/2}$

$a_{cB} = 50 \times 10^{-6} m$

Substituting these values into Equations (1) and (9), the calculations indicate that the fracture of the center core occurs at D/d = 6.6 or d = 15 mm, as indicated by the line in Figure 3. In this case, if P = 0.5 N, from Figure 3, the minimum allowable wafer thickness can be reduced to approximately 300 μm, compared with 700 m without the auxiliary force. It is important to use <111> ingot to maintain clean cleaved fracture in direction B, as mentioned above.

The most indefinite parameter in this calculation is the value of the stress concentration factor (k_t). This factor in a machine notch of brittle ceramic can be a very large value, because microcracks are usually found in the bottom of the notch. The microcrack is of the order of 10^{-9} m; the value of r/d can be extremely small. The data in the large k_t region are not available in Figure 7. Experimental determination of k_t value in this region is necessary. Thus, the exact location of the fracture curve in Figure 3 using the vacuum chuck is imprecise; however, there will be a large enhancement of direction B fracturing as a result of this additional force.

CONCLUSIONS

(1) An analytical model of a thin circular wafer, supported by a center core and subjected to a cantilever force at the wafer edge, was used to describe the loading condition of a wafer during ingot-rotation ID wafering.

(2) A fracture-mechanics concept was found to be useful in developing a relationship equation for the allowable wafer thickness vs diameter as:

$$t^2 = \frac{\sqrt{\pi a_{cA}}}{K_{IC}} P\beta$$

where β is a factor relating to the ratio of D and d and Poisson's ratio ν.

(3) The allowable thickness is dependent upon the depth of surface damage (flaw size a_c) of the wafer.

(4) It is important to reduce applied force P by minimizing saw vibration and cutting rate in order to maintain minimal wafer thickness, especially at small center-core diameters.

(5) At the present state of the art of ingot-rotation ID wafering, a limit of minimum wafer thickness was found to be ≈500 μm for the conventional wafer diameters (e.g., 100 mm).

(6) Fracture in the center core at large diameters was found to be important in controlling the minimum allowable wafer thickness during wafering. Use of the vacuum chuck to enhance cleavage fracture of the center core of <111> ingot in ingot-rotation wafering was shown to have great potential to maintain useful wafer thickness at a minimum.

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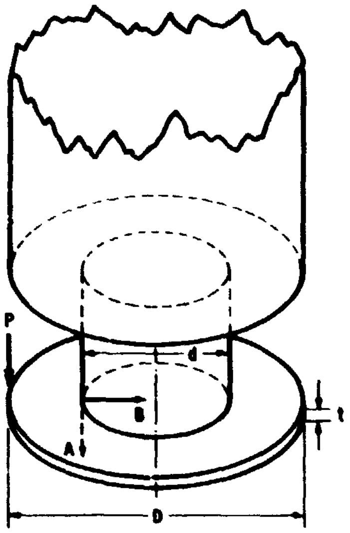

Fig. 1. Thin Wafer, Center-Supported, Subjected to a Cantilever Force

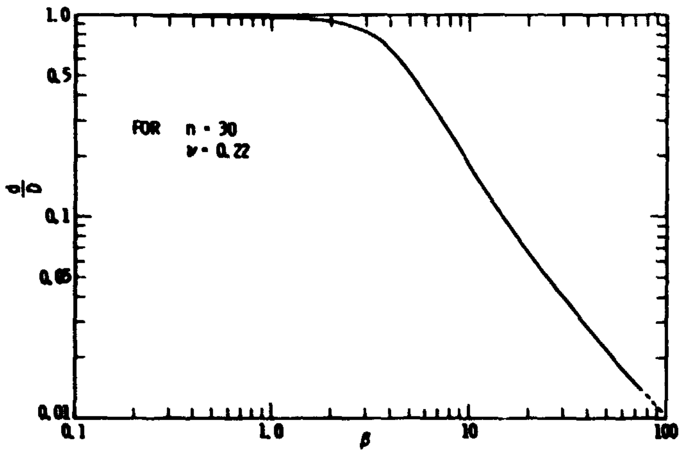

Fig. 2. Factor β as a Function of d/D

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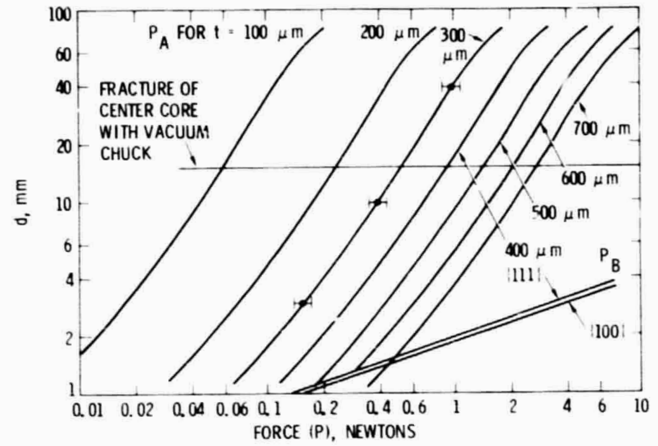

Fig. 3. Failure Force (P) vs Core Diameter for Ingot-Rotation Wafering of 100-mm Wafers (Flaw Size 50 μm, Except for Error Bars, Which Are 40 to 60 μm; P_A Based on K_{IC} for <111> Plane)

Fig. 4. Cracks Found Usually Near the Center of Wafer in Ingot-Rotation Wafering (Arrows)

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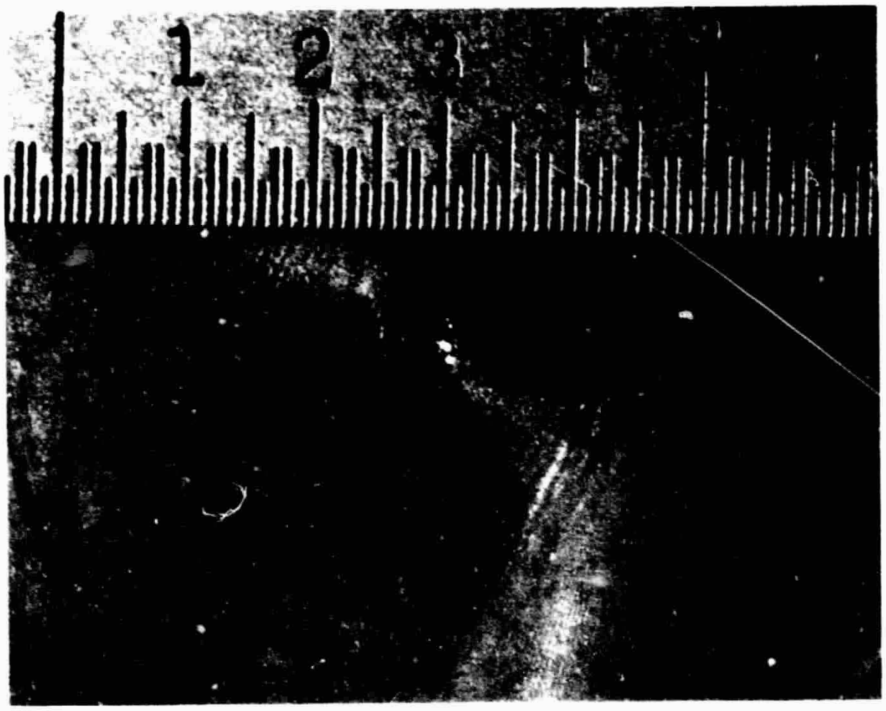

Fig. 5. Typical Surface Condition of Product of Ingot-Rotation Wafering

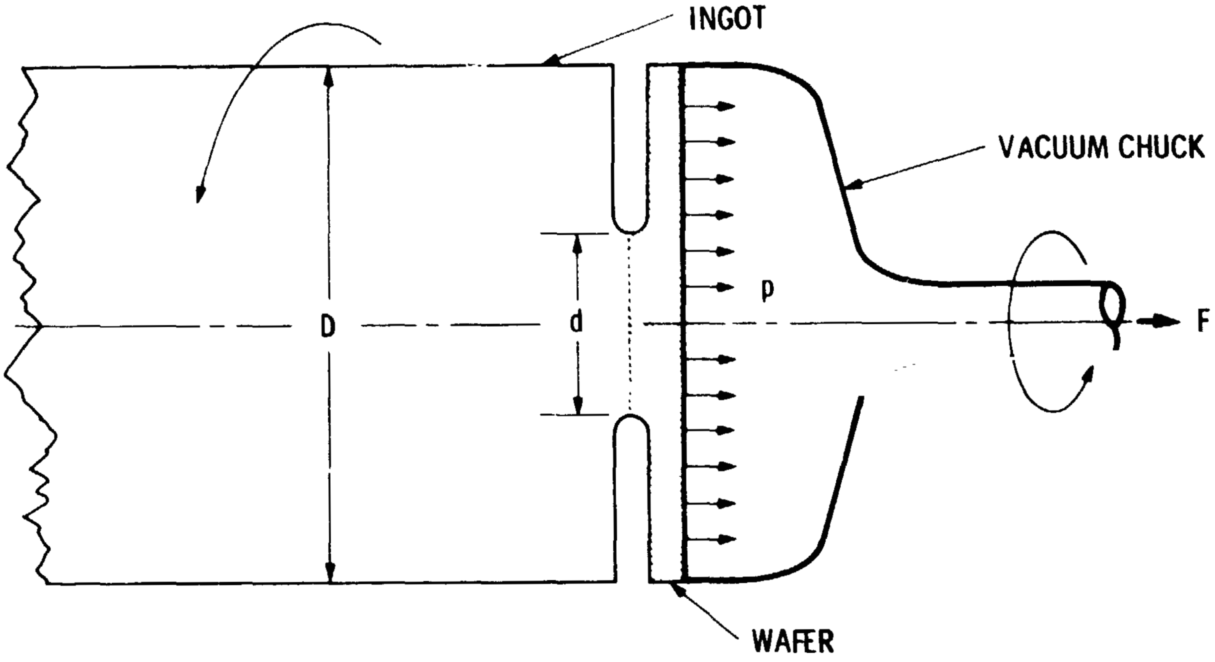

Fig. 6. Use of Vacuum Chuck in Ingot-Rotation Wafering

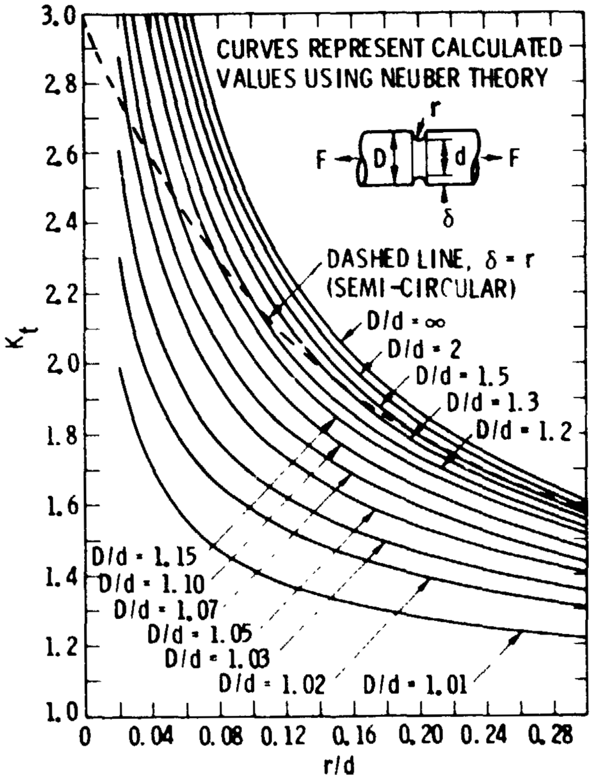

Fig. 7. Stress Concentration Factor K_t for a Grooved Bar in Tension (Reference 7)

DISCUSSION:

SCHWUTTKE: It looks to me that your model applies to the crystal lying horizontally. If you do ingot rotation wouldn't it be more favorable to have the crystal vertical?

CHEN: Some people claim horizontal is better than the vertical and some claim that vertical is better than horizontal. My model doesn't suggest either.

SCHWUTTKE: You assume that there is no advantage or disadvantage.

CHEN: This question relates to your paper and to the preceding one. Several times the subject came up that it is more favorable to use (111) orientation, in your case because you induce cleavage readily, and in the former paper because the cutting rate would be larger. Now silicon is an anisotropic material in terms of hardness. That means if you use a (111) plane for cutting the crystal you may go faster because the (111) is the softest plane. On the other side, the saw damage you incur will be much larger. So you have to remove more crystal material and these things have to be taken into consideration if you want to be cost-effective.

DYER: Dr. Schwuttke, a number of years ago, showed that for the saws that he evaluated, the horizontally held blade gave worse results than the vertical blade as far as the depth of damage is concerned. How do you think that gravity would be as a force in this? How about the weight of the slice pulling away? Does that put tension on those cracks that you are talking about?

CHEN: If you are talking about 500 microns and what kind of mass would contribute to the breakage in the center core, I would think it very small. But you could have other reasons for slicing in a vertical direction.

DYER: It has been shown in the literature, I believe it was in Meek and Huffstutler's paper in 1969, that if you have too much lubricating fluid carried into the kerf slot, it increases the hydraulic pressure in that slot and that might be another thing contributing to that force P. I realize that your analysis doesn't apply to that.

CHEN: That is right, so I've got to generate another model to describe that.

YERKES: I notice that some of the speakers call this lubricating fluid and Peter Aharonyan called it coolant. I presume that it is there for both purposes but it would seem to me that it is a damping material or it could cause a hydraulic pressure. Has the whole dynamics of this interface been studied? It seems to me that your model is simplistic compared to what is really going on where the diamonds touch the silicon and where all of this fluid is. It seems to me that is a rather complex thing that is happening millions of times during a cut. Statistically and otherwise, it would seem to me it is something that is the real root of the problem.

DYER: What do you think about, instead of concentrating on reducing the force P or doing these other things, just back up the slice with something rigid and if it has to rotate, make a device to make it rotate, e.g., instead of just letting the slice be free floating as you cut it, back up the slice with a thick rigid piece of steel, for example, just barely in contact and not pull on it and not push on it, have it rotate synchronously with the crystal?

CHEN: If you have a rigid backing on the wafer, essentially you can reduce the P force resulting from the blade vibration. That would help to reduce the P force and would cause smaller stress in the A direction. On the other hand, you reduce the stress in the B direction. If you have a rigid vacuum chuck technique that can control the deflection of the wafer in the A direction or you can increase the stress in B direction, this will be more favorable for rotation ingot wafering.