N82 23674

EXIT CHIPPING IN I.D. SAWING OF SILICON CRYSTALS

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INTRODUCTION

This study is part of a general effort to understand the sawing process for silicon, in particular the internal diameter diamond sawing process (1). Fig. 1 illustrates the geometry schematically. An idealized process may be described as follows: a rotating annulus with diamond particles coating its inner rim is caused to move through the crystal in a perfect planar motion. The contact stresses and scraping action from the diamond particles causes multiple intersecting cracks and comminution of the silicon to be kerfed out.

In practice there are many deviations from the ideal process which cause defects in the slices. The present approach was to select one defect that was known to be caused by sawing and about which there existed some shop knowledge, then to try to understand that defect so that preventive action could be taken. The chosen defect occurs where the saw exits the crystal after cutting a slice and is therefore termed an "exit chip". Figure 2 shows a typical exit chip.

Exit chipping decreases the fraction of salable slices; if such slices are passed to a semiconductor slice processing facility, they generate fear of increased particle generation in handling. In addition, exit chipping may be accompanied by deeper-than-usual damage in the slice itself. Since slices with exit chips may be screened out, and surface removal procedures may be adopted to remove the extra damage depth, the phenomenon of exit chipping is merely a nuisance in the semiconductor industry.

To another industry -- low cost solar cells -- the exit chip may be very important indeed under another name: a "saw fracture". In this case the "exit chip" is more extensive, starting much farther back into the crystal because of the thinner slices and high cutting rates required for low cost. Table I shows a comparison of specifications for semiconductor slices and for low cost solar cell slices.

TABLE I. COMPARISON OF SLICE CUTTING SPECIFICATIONS

SPECIFICATION	CONVENTIONAL	LOW COST SOLAR CELL GOALS
DIAMETER	75-100MM	125MM
SLICE THICKNESS	25-30 MILS	10-11 MILS
KERF	11-16 MILS	5-6 MILS
CUTTING RATE	1-2 IN/MIN	3-4 IN/MIN
YIELD	HIGH	95%
BLADE LIFE	2000	4000
CORE	5 MILS	1-2 MILS

In the following discussion it should be evident that "exit chipping" or saw fracturing is a major problem to be overcome if these low cost solar cell goals are to be met.

DISCUSSION

Historically exit chipping is seen mostly in the (100) orientation. Unfortunately, this is the most desirable orientation for solar cells because of the added benefits of pyramidizing the surface (2). Positive blade deviation (bow) and excess hydraulic pressure are known to be deleterious influences. Backing by sacrificial silicon strips and using vacuum slice retrieval have helped reduce the problem at times. The middle slices in a group of 8 or 10 are sometimes more likely to show exit chipping. Other knowledge that bears on the subject is 1) that surface damage is predominantly microcracks oriented parallel to the abrasive path (1), and 2) that the inside (crystal side) of the wafer has the deeper damage (3).

Figure 3 shows an example of the fracture surface. The fracture surface consists of a collection of subfractures that originate in the kerf and move substantially as a single crack after starting at either edge. The fracture is roughly parallel to saw marks and lies approximately at the same angle from the slice as does the preferred cleavage plane (111). Even if the direction of cut is toward another azimuth than the standard ⟨110⟩ direction, the fracture parallels the saw marks and is composed approximately of {111} surfaces. Figure 4 shows a fracture surface near an edge of the slice, where there may be more or less connected sub-fractures paralleling the exit chip, but which did not develop into a full fracture. Figure 5 shows "sparkle", a reflection parallel to the exit chip that often accompanies it and implies deeper-than-usual damage to the area of the slice on which it occurs. The opposite side of the slice and the 90°-and 180° rotated slice show much less pronounced reflections. Figure 6 shows clustering of slices from surface tension when a slice retrieval unit is not used. If a saw is producing exit chipping, a series of slices decreasing in thickness will show increasing width of the exit chip.

An interpretation of the foregoing observations will now be given in terms of crack propagation as acted upon by the sawing stresses. Figure 7 shows a scale cross section of the I.D. saw kerf slot during the last part of the cut. The direction of crack travel and possible locations of exit chips are shown. Note that if the crystal orientation were ⟨111⟩, contact fractures from the diamond edge can readily form on planes parallel to the kerf slot (plane 1-6) and would be removed by the advancing blade. This explains why only (100) exit chipping is seen. Since the exit chips are roughly parallel to saw marks, the general locus of the crack must be determined by contact stresses although the exact locus depends on already existing subfractures located in the kerf region which are caused by more than one abrasive particle. The crack starts at either edge since these are weak areas in flexure. In the more extensive "saw fracture", the fracture plane often changes part-way across the slice to be other than parallel to the saw mark because the speed of the crack accelerates beyond the speed of the blade travel; i.e., outstrips the advance of the contact stress field.

With this picture of crack origin and propagation in mind, the influence of various external factors on the opening of the crack can be seen. These factors can be conveniently divided into two types: factors that wedge the crack apart and those that bend the slice away from the crystal.

Factors of the first type are: dull blade (abrasive particles not sufficiently exposed), excessive feed rates, blade eccentricity, and in-plane vibration. Figure 8 shows what happens if any of these factors rises above reasonable limits: the material to be removed builds up; contact stresses increase greatly, and microcracks lengthen accordingly. Since some of the cracks extend beyond the kerf slot into the silicon, the general damage to the slice is greater than is necessary. Such damage is directional: microcracks on one of the two sets of {111} planes whose intersection is parallel to the blade travel propagate away from the slice as they progress, while the other set of microcracks propagate into the slice.

Factors of the second type are: lateral blade vibration, (1) excess hydraulic pressure (1), surface tension toward adjacent slices (4), bow (5), and flexure of the mounting strip (4). All of these factors can be seen through Figure 7 to be capable of contributing to the bending of the slice away from the crystal. Positive bow would apply a greater lever arm to a bending force than would negative bow, and would therefore be more deleterious. Even the weight of the slice would add to bending in the case of horizontal blades, which perhaps explains deeper damage in the case of horizontal saw (5). Lateral vibration of the saw blade is a main contributor to bending force and to dynamic stress pulses (6). If the major out-of-plane deflections occur at ν = 500-1000 times/sec (1), there would be sufficient time for cracks to move through the slice with only 5% of the time under tension: Crack penetration = $v/\nu \times 0.05 = 20\times10^3/1000 \times 0.05$ = 1mm, where v = crack velocity. (Crack velocity in abraded silicon accelerates from 20-40 to 1000 m/sec within approximately 0.05mm (7). A major contribution to inplane & lateral vibrations is the imbalance in the cutting head (8). Another is loss of blade tension. Factors of the bending type also introduce a further directionality to the damage: when the blade is far from the last part of the cut, the slice flexure away from the crystal favors crack propagation which damages the inside of the slice rather than the outside.

The foregoing considerations indicate how a conventional saw can be operated to minimize exit chipping; they also indicate design factors for a new generation of saws for cutting low cost solar cell slices. These factors are listed in Table II.

Another practical benefit of this study of exit chipping to present saw practice is that the depth or width of the exit chip may be used as a simple and convenient measure for studying the effects of various parameters on slice damage by the saw.

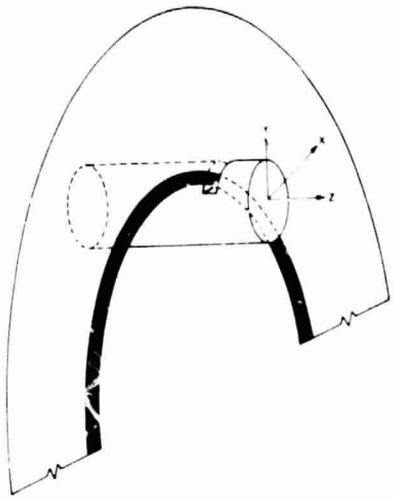

Fig. 1. I.D. saw geometry.

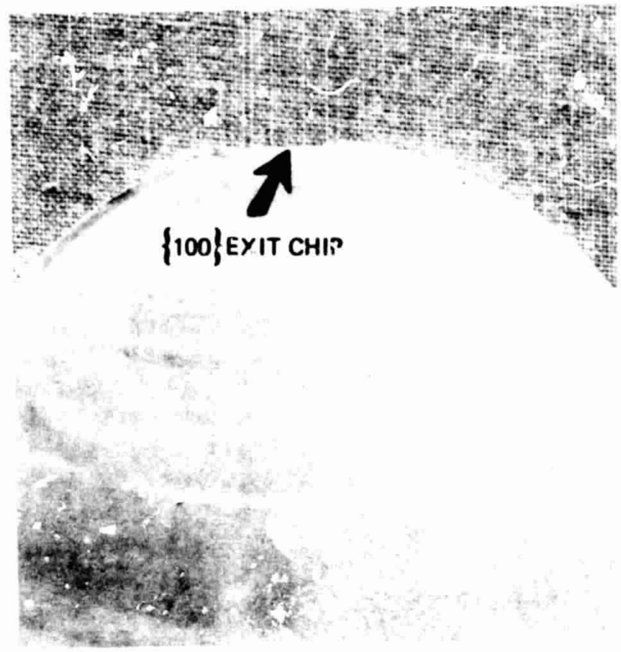

Fig. 2. {100} exit chip. Direction of blade travel toward chip.

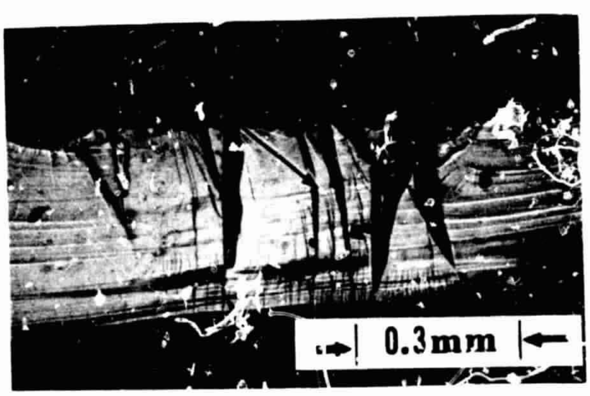

Fig. 3. Fracture surface of {100} exit chip. Direction of blade travel toward bottom of page.

Fig. 4. Subfractures in slice surface paralleling exit chip.

Fig. 5. "Sparkle" : Reflection from slice surface parallel to exit chip.

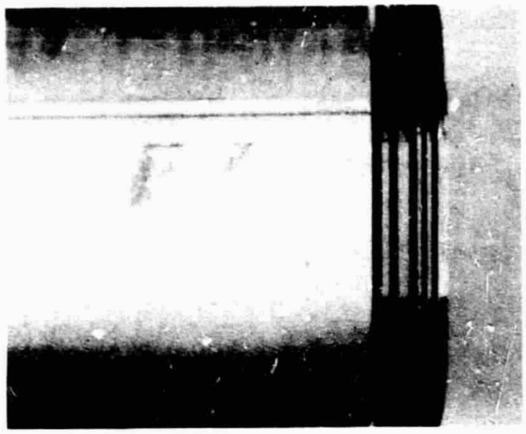

Fig. 6. Clustering of slices from surface tension.

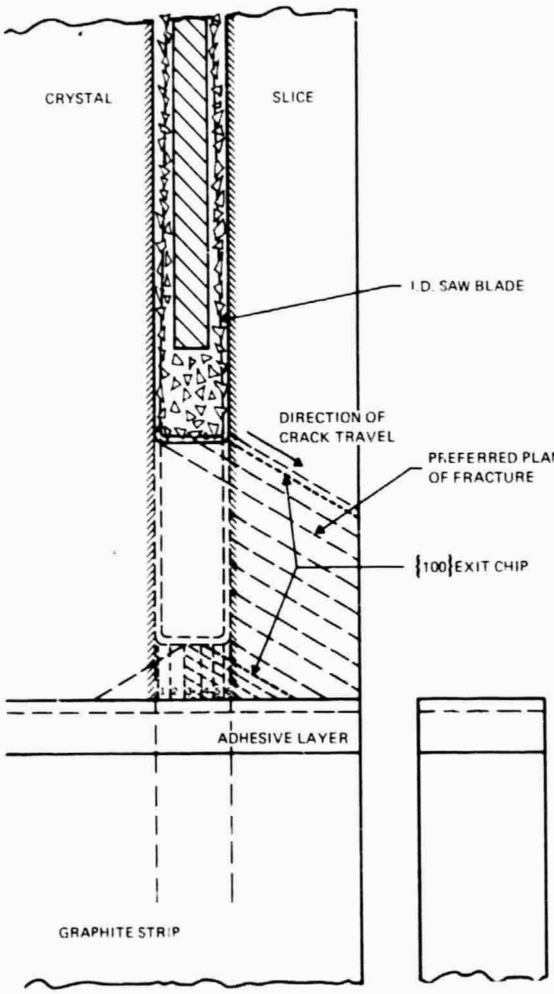

Fig. 7. Scale cross section of I.D. saw kerf slot.

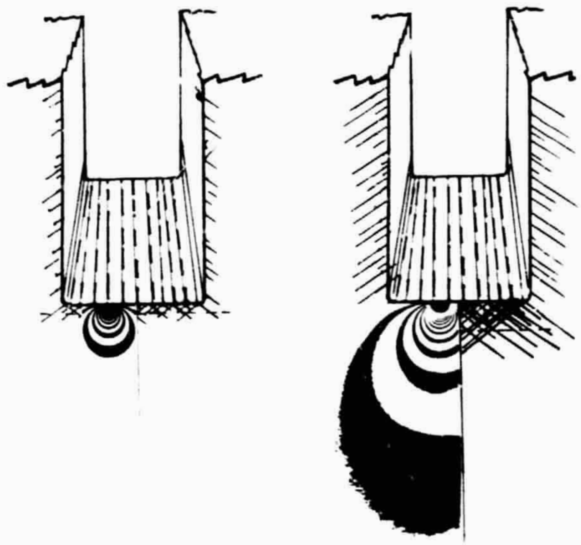

Fig. 8. Schematic diagram of stress fields caused by a single particle contact in kerf slot in the case of continuous (concentric) cutting (left), and intermittent (eccentric) cutting (right).

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CONCLUSIONS

This study has:

- o Given a better understanding of exit-chip or saw-fracture formation, and of the I.D. sawing process for silicon.
- o Shown how to minimize the exit chip as a nuisance defect and obtain shallower damage as a bonus.
- o Indicated a serious problem in cutting low cost solar cell slices by present I.D. saws.
- o Pointed out desirable design features for new saws for ultra-thin slices.
- o Found a simple way to measure harshness of the sawing condition - measuring the size of the exit chip.
- o Explained why the crystal side of a raw slice has deeper damage then the outside.

TABLE II DESIRABLE CONDITIONS FOR MINIMIZING EXIT CHIPPING AND DAMAGE IN PRESENT SAWS AND A NEW GENERATION OF SAWS

PRESENT SAWS		NEW SAWS	
CONTACT FACTORS	BENDING FACTORS	CONTACT STRESS FACTORS	BENDING FACTORS
CONCENTRIC BLADE	BALANCED HEAD	MIN. SPRUNG WEIGHT & HEAD	SLICE BACKING
MIN FEED RATE (TRADE-OFF)	LOW HYDRAULIC PRESSURE	FORCE SENSITIVE FEED	BLADE DAMPENING (1)
AUTO SHARPENING	SLICE RETRIEVAL		
TENSION CHECKING AND CONTROL	SLICE TRACKING (BOW)		

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DISCUSSION:

CHEN: Your paper is extremely interesting. I have a paper published in the Proceedings of the Electrochemical Society, an analytical model, which shows the edge chip due to the same P force, either wedging force or bending force from the blade. That model indicated the exit chip can be prevented by sufficient support because if your submounting strip under the ingot is not large enough when the force is great, the bending force would break up the wafer. A sufficient supporting of the wafer would prevent this exit chip. There is a relationship between the forces and thickness as a function of the width of the submounting.

DYER: People told me before that when they support the crystal all around with some sort of coating or something, that problem is helped. In our industry they want to get by with as little as possible. They wouldn't pay for a very big thing under there.

WOLF: It seems that without a sacrificial submount no wafer could come out without exit chips. If your feed force is pushing down, there will be a stress concentration on the corner. Just at the end; where this is weak enough it ultimately should snap off. There's no way of preventing it unless we have something underneath, which stiffens it, and prevents it from being bent down at the end.

DYER: Of course, we do have a fairly thick support under the thing. But you see all of these things have elasticity and the mounting medium, the glue that you put it on with, is not perfectly rigid.

If you look closely under a microscope at the edges of the slices, you'll see some degree of exit chipping on the (100) in almost all circumstances.

If it's only a tenth of the way through the slice, it's not important either to solar cells or to the industry because we grind away the edge for other reasons.

WOLF: I didn't quite understand this "clustering of the middle wafer" in a cluster of wafers ... how was this obtained, and what's the problem?

DYER: It was an interesting thing that they had noted. In sequence, first you cut a slice without a slice retrieval unit and leave it standing there. Then you cut the next slice and if there's sufficient liquid around, it is attracted to the first wafer and it moves over half the size of the kerf slot. Then the next slice moves over another half of a kerf slot. Eventually you reach a point at which the stress is high enough to help make this exit chip. Then you reach a point that the restoring force is so great that you can't make the surface tension connection with the next slice. So then it's free-standing again, and the next one attaches to it, and so on. They cluster in groups of anywhere from two to six or eight. Generally, four or five. With a slice retrieval unit, you get rid of that entirely.

REIMANN: I'd like to know the thickness of the wafers and what adhesive you used to mount the crystal?

DYER: The drawing I showed is as if the slices were 20 mils thick. That was 3-inch slices. Typically, people in the industry cut them a little thicker than that. The substrate and mounting strip can be any number of things. I know that we have used a bakelite-type plastic and graphite.

REIMANN: Which did you find better?

DYER: That depends. Better is not the case here. Which is cheaper? They both work.

KUAN: Did you find this exit chipping phenomenon occurs more often when you were slicing the end of the ingot or in the middle of the ingot?

DYER: There didn't seem to be any difference where you were in the ingot. Of course, you don't leave all those slices on at a time. You just take them off every once in a while. It's better to take them off one at a time. The various saw manufacturers have slice retrieval systems, if your operators will take the trouble to keep them working and if it means anything to them, which it apparently doesn't, because they don't work half the time.

MORRISON: Do you notice a difference in depth of damage from the top of a wafer to the bottom of a wafer? Admittedly, when you get to the bottom your whole lever forces are greater, but when you're at the bottom, you do have damping in the slot that might reduce the depth of damage. Have you measured depth of damage from top to bottom of a wafer?

DYER: I've seen both, actually. This is more complex than I've shown here. There are times when, for some reason, the vibrational situation seems to all of a sudden hurt the bottom part of the slice more than the top, and I've seen it where it's worse at the top also.