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WIRE-BLADE DEVELOPMENT FOR FIXED ABRASIVE SLICING TECHNIQUE (FAST) SLICING*

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ABSTRACT

A low-cost, effective slicing method is essential to make ingot technology viable for photovoltaics in terrestrial applications. The Fixed Abrasive Slicing Technique (FAST) is a new slicing process which combines the advantages of the three commercially developed techniques. In its development stage FAST has demonstrated cutting effectiveness of 10 cm and 15 cm diameter workpieces by slicing 25 and 19 wafers/cm respectively. Even though significant progress has been made in the area of wire-blade development it is still the critical element for commercialization of FAST technology. Both impregnated and electroplated wire blades have been developed; techniques have been developed to fix diamonds only in the cutting edge of the wire. Electroplated wires show the most near-term promise; hence the emphasis has been placed on this approach. With plated wires it has been possible to control the size and shape of the electroplating--this feature is expected to reduce kerf and prolong the life of the wirepack.

INTRODUCTION

The Fixed Abrasive Slicing Technique (FAST) makes most ingot technologies viable for photovoltaic applications. Compared with current wafering methods --Internal Diameter (ID), Multiple Blade Slurry (MBS) and Multiple Wire Slurry (MWS) processes--the FAST approach offers the potential of lowest add-on cost (1). FAST uses diamond fixed on wires in a multiple-wire pack configuration for slicing silicon. This new technique was made feasible by developing a method for making bladepacks with equal wire spacing and tension and a higher speed reciprocating slicer. The development of FAST is being discussed in another paper at this conference (2). At the present time a preprototype slicer designed for FAST slicing is being optimized. Significant progress has been made in the area of wire blade development but it is still the critical element for commercialization of FAST technology.

For any ingot technology to be cost effective for photovoltaic applications, it has to be combined with a low-cost slicing method. Kerf loss and ingot utilization (kerf plus slice) are major considerations in silicon sheet cost. An economic analysis (3) of silicon slicing has indicated that the ingot utilization considerations limit the cost reduction potential of the ID technology. This analysis also showed that the expendable materials costs, slurry and blades, dominate the wafering costs of MBS. Demonstration tests (4) of MWS method has shown that lowest kerf widths are obtained with wire slicing. However, the cost of the wire is even more than the slurry costs, thereby increasing the expendable materials costs of MWS even more than the MBS process.

In FAST a pretensioned, fixed-diamond, multiple-wire pack is reciprocated similar to the MBS process to slice through the workpiece. The multi-wire FAST approach combines the economic advantages of ID, MBS and MWS techniques. Expendable materials costs are low as in ID slicing, capital equipment and labor costs are low as in MBS slicing, and material utilization is high as in MWS wafering.

ADVANTAGES AND REQUIREMENTS OF FAST WIREPACKS

Aside from the economic advantages, there are technical advantages of using multi-wire FAST approach:

(1) Due to the symmetry, wires do not torque the wafers after slicing as in the case of flat blades; this allows for less clearance and, therefore, reduced kerf width.

(2) In case of wire breakage only two wafers contacting that wire are lost.

(3) The diamonds fixed on the wire prevent wire wear, hence wire and abrasive cost is minimized.

(4) No fatigue problems occur because wire is not wrapped around rollers.

(5) Wires are cheap to fabricate to a higher dimensional accuracy and uniformity.

(6) No corrosion problems occur since the wires are nickel or copper plated.

(7) Wires can be pretensioned to higher stresses.

(8) Wires do not buckle under high feed forces.

(9) Slicing is carried out under low feed forces resulting in low surface damage.

(10) Wafers produced show no edge chipping problems.

The essential requirements of wirepacks used for FAST slicing are:

(1) The wires must be clamped to prevent slippage and must be with equal tension and spacing in the bladepack.

(2) Wire core must have high yield strength and modulus for minimum deflection.

(3) Diamonds must be fixed on wire with high, uniform concentration.

(4) Prevent erosion of the matrix holding the diamonds.

(5) Diamonds must exhibit long life and high cutting rates.

(6) Wire diameter must be minimum to reduce kerf.

(7) Minimized wander for accurate slicing.

(8) Prevent corrosion between the matrix holding the diamonds and the core material.

In the above tabulation the first requirement is related to fabrication

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of wirepack and the rest relate to properties of wire, matrix and procedures for fixing diamonds onto wires. Simple fabrication procedures have been developed which give the wires equal spacing and tension with no problems of cumulative errors. After evaluation of various core materials (5) a selection was made to use high strength steel, stainless steel and tungsten. High strength steel and stainless steel wires were selected based on high yield strength and tungsten on the basis of its high modulus. Most of the work was carried out with a 5 mil (0.125 mm) tungsten wire because of its high modulus and corrosion resistance.

Two approaches were pursued in fixing diamonds, *viz.* impregnated wires and electroplated wires. In the former case diamonds were impregnated into a soft copper sheath on the core wire, whereas in the latter case diamonds were fixed by electroplating.

IMPREGNATED WIRES

Commercially available impregnated wire (6) was 5 mil (0.125 mm) stainless steel core with a 1.5 mil (37.5 μm) copper sheath impregnated with 45 μm natural diamonds. Slicing with this wire showed that cutting effectiveness was lost within approximately 0.25 inch depth of cut. Examination of the wires showed considerable diamond pull-out. Electroless nickel plating of these wires reduced the diamond pull-out considerably. It was found that nickel plating thickness of 0.3 mil (7.5 μm) produced best results; a nickel layer of 12.5 μm was sufficient to bury the diamonds. A wafering experiment of a 10 cm diameter silicon workpiece with 114 parallel wires spaced at 19/cm with these wires showed an average slicing rate of 2.33 mils/min (0.059 mm/min) and produced a 96.5% yield.

Impregnation techniques developed within Crystal Systems showed that it was possible to impregnate diamonds in the cutting edge of the wires only in an area less than the bottom half circumference of the wires. Figure 1 shows a cross section of such a wire. Natural diamonds of 45 μm size were impregnated into a 1.5 mil (37.5 μm) copper sheath on a 5 mil (0.125 mm) stainless steel core wire. A 0.3 mil (7.5 μm) electroless nickel layer was plated after impregnation. Slicing tests using wirepacks with diamonds impregnated in the cutting edge only improved the average slicing rate to about 3 mils/min (0.075 mm/min) and reduced the kerf. This approach also allowed use of 60 μm diamonds without significantly adding to kerf. The advantages of diamonds in the cutting edge only are:

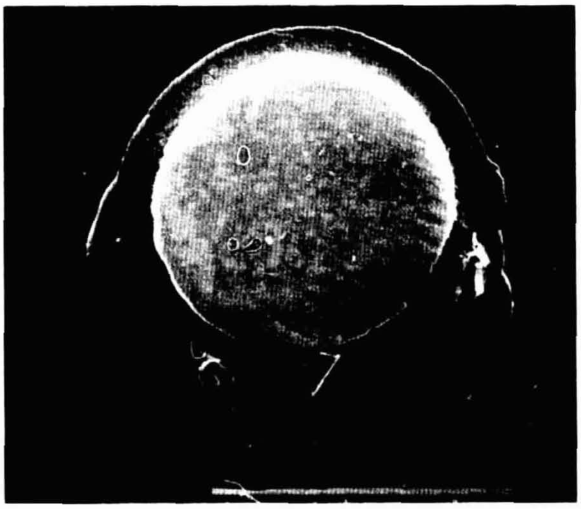

Fig. 1. Cross-section of wire with diamonds impregnated in cutting edge only

(1) Lower kerf.

(2) Use larger diamonds.

(3) Ability to add more than one layer with marginal increase in kerf.

(4) Minimize degradation of guide rollers in the FAST slicer.

(5) Better seating of the wires in the grooved guide rollers.

(6) Improved accuracy of slicing because of absence of diamonds on the sides of the wires.

(7) Minimize wire wander when diamonds in the cutting edge are somewhat "du: led".

Even though significant progress has been made with impregnated wires considerable effort has to be devoted towards achieving high concentration of diamonds with good uniformity and preventing diamond pull-out during slicing.

ELECTROPLATED WIRES

At the start of this program electroplated wires were not commercially available. Initial work was carried out in cooperation with various plating vendors.

Choice of Core Wire

It was found that the core wire used as a substrate was very important to achieve plating with a good bond between the nickel matrix and the core substrate. Plating on steel caused embrittlement which resulted in considerable wire breakage during slicing. Difficulties in cleaning procedures prior to plating of tungsten necessitated the use of a thin nickel flash on the core wire prior to use as a substrate. Figure 2 shows the longitudinal and cross-section of electroplated wires using (A) a copper flash and (B) a nickel flash on tungsten core wires. It can be seen that the longitudinal sections show a high concentration of diamonds. Examination of the cross-sections shows corrosion problems in the copper flash layer which is not existent in the case of the nickel flash wire. No such problems were evidenced in plating directly onto a stainless steel substrate (Figure 3). Emphasis was placed on using nickel flash tungsten core 5 mil (0.125 mm) in diameter; recently procedures were developed in plating copper-flash, high-strength steel wires without embrittlement problems.

Choice of Diamonds

With fixed diamond it is very important to establish a speed-pressure relationship at the diamond tip for effective slicing. Rocking of the workpiece in FAST increases the pressure by decreasing the contact length; however, the diamond type and size needs to be optimized. Both natural and synthetic variety are available. In the synthetic type the choice is blocky, explosively formed, EDC, Man-Made (7), etc. The various varieties also include tough and friable; while the former stand up to slicing conditions without breakdown, the latter breaks down and exposes new surfaces for higher cutting rates. Under similar conditions of slicing to date the natural diamonds gave better results than the blocky type. An SEM of the two varieties is shown in Figure 4.

Besides the diamond type a choice has also to be made for diamond size. The larger particles are desirable for long life and higher cutting rates;

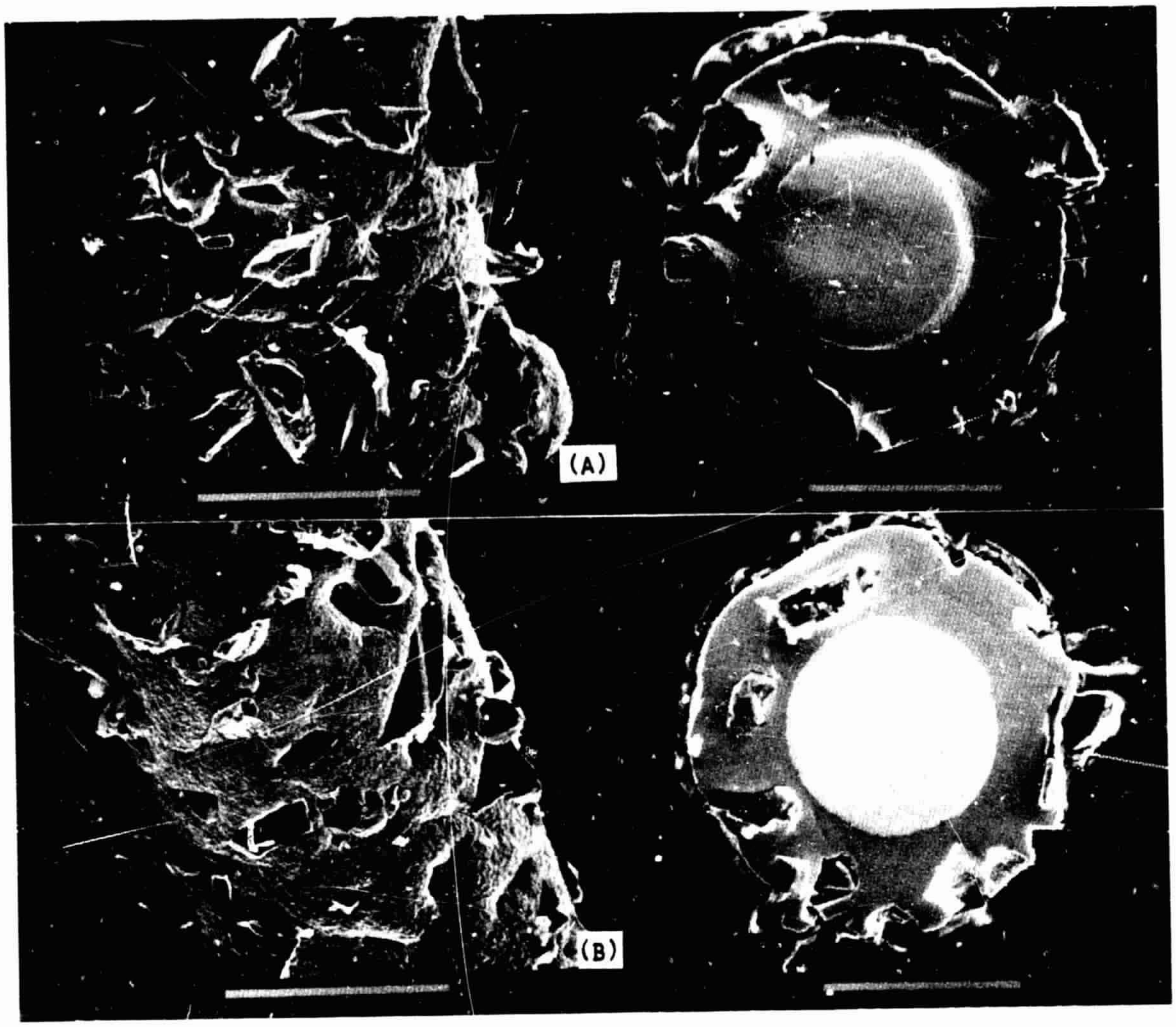

Fig. 2. Longitudinal and cross-section of electroplated wires using tungsten core with (A) copper flash and (B) nickel flash

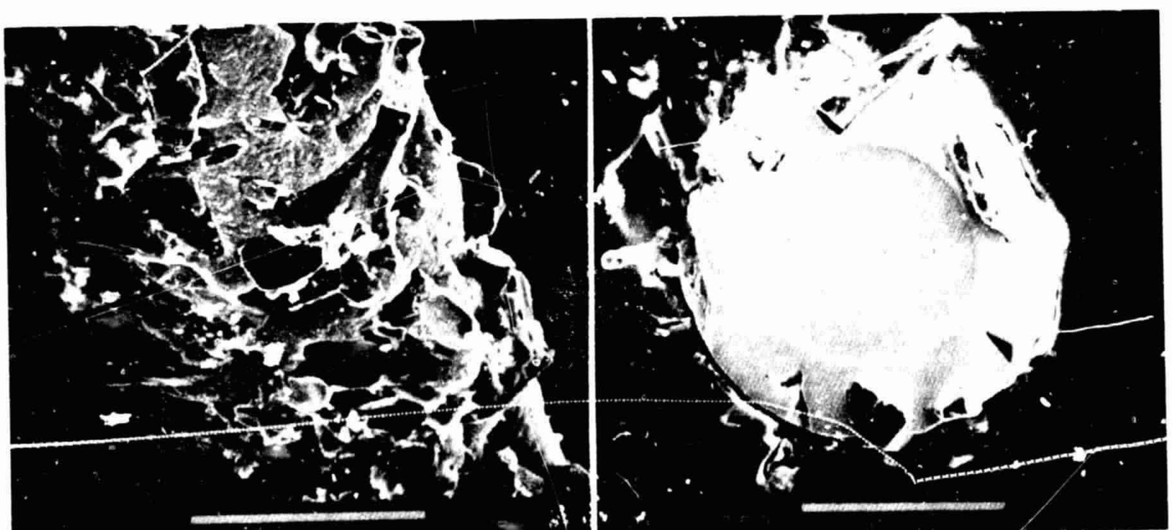

Fig. 3. Longitudinal and cross-section of an electroplated wire using stainless steel core

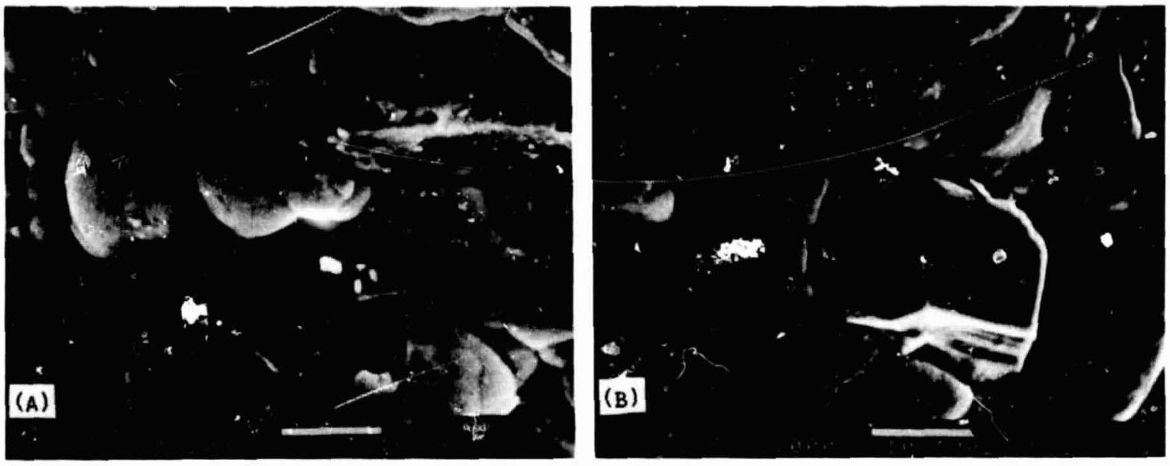

Fig. 4. SEM examination of electroplated wires with (A) natural diamonds showing sharp edges and (B) synthetic diamond showing blocky characteristic

however, they have larger kerf. The choice in particle size is, therefore, limited to the 22 μm to 60 μm range. Effective slicing has been demonstrated for the entire range with diamonds electroplated over the entire circumference. The lowest kerf of 6.2 mils (0.157 mm) was achieved with 22 μm diamonds. Best material utilization by slicing 25 wafers/cm on 10 cm diameter silicon was demonstrated by using 30 μm diamonds. The longest life wafering three 10 cm diameter ingots with the same wirepack has been with 45 μm size. Very limited experiments have been conducted with 60 μm diamonds plated over the entire circumference because the large kerf makes it impractical to slice 19 and 25 wafers per cm of silicon length with a 10 cm diameter workpiece.

With larger diamond particles or when low concentration is achieved by electroplating, the swarf generated during slicing tends to erode the matrix thereby pulling off diamonds from the wires. The concentration of diamonds to prevent erosion has to be such that the inter-particle distance is less than the size of the particle. Electroplating of wirepacks with 45 μm diamonds and small amounts of 30 μm and 15 μm diamonds has shown improved slicing effectiveness. The larger diamonds tend to slice and the smaller ones act as fillers to prevent erosion of matrix. This condition can be achieved by using screened rather than micronized diamonds. Examination of the swarf has shown the mean particle size to be about 0.5 μm and is not dependent on the size of diamonds in the range studied.

ELECTROFORMING

In order to effectively slice silicon for photovoltaic applications the wirepack fabricated should combine (i) low kerf, (ii) high density of spacing of wires, (iii) high slicing rate, (iv) long life of the wirepack and (v) high yields during slicing. The first two criteria are possible by using small diamonds; however, for the next two criteria larger diamonds may be desirable. For example, where 45 μm diamonds were plated all over the circumference of the wire, the minimum kerf achieved was about 8 mils (0.2 mm), whereas it was 6.2 mils (0.157 mm) with 22 μm size In impregnated wires where diamonds were impregnated only in the cutting edge of the wires a compromise was arrived at where larger diamonds could be used without significant increase in kerf. Techniques were developed where diamonds were electroplated in the cutting edge only and, therefore, benefits could be derived by using larger diamonds and maintaining a low kerf.

Masking of the wires during electroplating produced a flat top surface of the wires which did not seat in the guide rollers and, therefore, caused wire wander. Techniques were developed at Crystal Systems to electroplate diamonds and nickel in a form of desired shape and size, *i.e.*, electroform the plating. Figure 5 is three views of a wire rotated 120^{o} where diamonds are electroplated by the electroforming technique. Figure 6 is a cross-section of a wire which was electroplated preferentially in a 60^{o} V-groove. Under these conditions larger size diamonds can, therefore, be electroformed in any desired shape and size. If smaller diamonds are used plating only on the cutting edge allows more than a single layer of diamonds to be plated and the kerf width can still be controlled to the desired size.

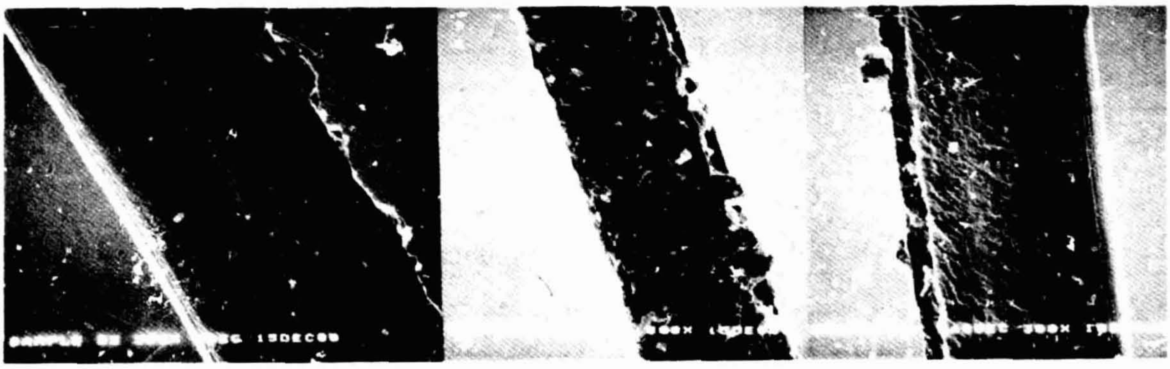

Fig. 5. Three views of an electroformed wire showing preferential plating on cutting edge only

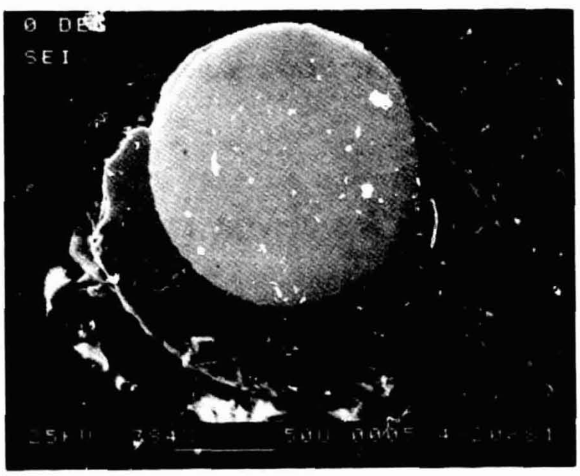

Fig. 6. Cross-section of an electroformed wire with plating in desired shape and form

RESULTS

The feasibility of using FAST for photovoltaic applications has been demonstrated. Wire-blade development has been found to be critical to commercialization of FAST. Control of the diamond plating on wires has shown effective slicing of 10 cm diameter silicon ingots at 25 wafers/cm with 224 wires in a wirepack at an average slicing rate of 3.03 mils/min (0.077 mm/min), and over 99% yield (2). It has been shown that the slicing rate is a strong function of the reciprocating speed of the bladehead; average cutting rates of 5.7 mils/min (0.145 mm/min) have been demonstrated. Wirepack life of wafering three 10 cm diameter silicon ingots has been shown. Effective slicing of 10 cm x 10 cm and 15 cm diameter cross-section ingots has also been carried out.

Electroforming techniques have been demonstrated on individual wires. Tooling for performing these tests on wirepacks has recently been received in-house; it is expected that this approach will increase the life of the wirepack considerably as well as optimize other slicing parameters.

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7. EDC and Man-Made are trademarks of DeBeers and General Electric Company, respectively.

DISCUSSION:

GALLAGHER: I have a question for IBM. I'm intrigued with the fact that you did get the results you did by applying the potential to the workpiece itself. Do you think it would be possible in real time to measure the out-of-plane vibration, and instead of using the dc potential as a function of time, using a rectified and variable ac potential wherein you could either vary the frequency, and/or vary the potential?

KUAN: I think the point of applying a dc potential is to enhance the absorption of ion species and if you apply the dc potential I don't think you would observe any effects. I agree that it would be nice if we could observe directly the amplitude of blade vibration, but it is very difficult to do so. So that is why we observed instead the surface morphology and the kerf size, which sort of indirectly gauge the vibration amplitude.

GALLAGHER: Do you do this (notice the kerf difference) in real time as you are cutting, or do you do it after the fact?

KUAN: After--but those are the features that were created during sawing.

DYER: It seems to me that if there is a potential, that is between the crystal and the blade, and if the slice is the most flexible thing in the whole business, there would be an opportunity for the slice to be either attracted to or repelled from the slot and this might be, in fact, just as large an effect as we're considering the Zeta potentials, etc. In other words, it would be a mechanical effect related to the one that was mentioned earlier today by Dr. Chen, on the flexure away from the crystal. I would suggest that you consider that as a possibility in your explanations. Also, you were saying that it was generally agreed (and I know this was stated by Meek & Huffstutler) that the out-of-plane blade vibration was the main damage mechanism. I certainly agree that there are times in the life of a saw in which this is the case, but he also stated that since the contact forces were the greatest at the bottom of the slot, then it is not consistent that the main damage mechanism is the out-of-plane contributions to the contact stresses. It would be, more than anything, the increases in the contact stresses in the cutting direction. I offer that for your consideration.

KUAN: For your first comment, I think that there is an attraction of the saw blade if you apply a dc potential. We do observe that the scratches on one side are larger and deeper than on the other side of the blade when you apply the potential and we got a negative effect if you applied a negative potential. For your second comment, I think that in our case it is the out-of-plane vibration because we got a good correlation between the depth of damage and the surface scratches. Of course, the non-circularity of the hole also contributes.

BOUJIKIAN: In some of the discussion we had here today and also Prof. Danyluk's presentation, we saw several evidences that there was plastic deformation in the cut in the silicon itself. This also was discussed by Prof. Werner, about the existence of very high temperature at the point of cut. I know for a fact, there have been several papers, by many companies, on thermal damage. It is i aic that General Electric people brought up thermal damage in the cut, w h, in my opinion, is much more severe than the vibration damage. I have been in the abrasive diamond-blade-business for 20 to 22 years. I would like to make a statement that General Electric really saved this diamond-abrasive industry by developing the industrial diamond. It was one of the real discoveries of the century if not the only one as far as the diamond-blade industry is concerned. However, there have been several studies (including General Electric, at their facilities over in Auburn years ago, through the direction of Tuzio and Ernie Raderman, etc.) that without any question there is a definite breakdown at high temperature with synthetic diamond compared to the natural diamond. In your speech, you referred to heat-treating it at 1100°C. You used the word "controlled." If you take your diamond and put it in even 1100°C in open air for half an hour you will end up with a bunch of black junk. I don't want to make the assumption that the GE diamond is actually, in terms of toughness, hardness and structure, superior to natural diamond. The only main factor is in ID slicing because temperature is more of a factor than anything else in that particular application. You did not address anywhere in your speech a comparison with the natural diamond in ID slicing. I would like to know why.

FALLON: To clarify a number of the points that were brought up: 1100°C is a test that we conduct to determine the thermal toughness index. It's one that we have been doing for years and we don't seem to reduce our diamonds to little black stubs by doing it to 1100°C. As regards the temperature breakdown, all I can do is again go back to the fact, mentioned earlier today, that bonding systems break down at 700°C, so if you have a diamond that can withstand 5000°C it doesn't really matter, if your bond is going to go at 700° anyway. We made no comparison, or try not to refer to any comparison with mined diamonds because depending upon test conditions, mined diamonds will be better than man-made diamonds, or man-made will be better than mined; they will be equivalent. The important point is the fact that man-made diamond is consistent. You will get the same diamond today that you get two years from now. This is not true with mined diamonds.

WERNER: First, I think you are absolutely right that the big advantage of man-made diamonds is that the characteristics and the properties are much more consistent. On the other side, especially in ID sawing, so far the natural diamond is preferred to the synthetic one. I would like you to comment a little more on what General Electric is doing at the moment to lift the synthetic material to the same performance level as the natural one. Second, a comment: the heat flows through the tip of the diamond and then is distributed in the much greater volume of the diamond. Therefore, the transition temperature from the diamond into the bond is several hundred degrees lower and the nickel layer never gets a temperature up to 700°. The maximum temperature that I would expect to occur in the nickel layer is maybe 150-200°, so your argument that the nickel fails before the diamond fails is completely wrong. Another misconception is the air cushion you referred to in the circumferential vicinity of the wheel. That cushion does not really exist. There are a few atoms going around with the wheel but the mass of this layer of air is much too small to prevent a fluid from getting into contact with the wheel. The real effect is that where a drop of oil or water gets into contact with the fast-spinning wheel it is vaporized. It all of a sudden is distributed in millions of little particles and therefore you have to apply a tangential stream onto the surface. You can only achieve that if you get the liquid out under high pressure and have matching velocities between the spinning wheel and stream of the coolant. In order to overcome the so-called air cushion layer it was recommended to increase the pressure to go through it. What really happened was that you sped up the velocity of the liquid to match the velocity of the grinding wheel. All the derivations, all the conclusions from this air-cushion model with regard to increasing pressure are right, but in designing special spouts and nozzles there has been a lot of misconceptions, and the wrong things have been recommended due to that. In ID sawing, the main setback is that the liquid does not automatically flow into the contact zone even if you apply it with higher pressure.

FALLON: Concerning the fact that right now the industry seems to be leaning more toward natural diamond, especially on the ID saw blades, I think this is a holdover from the fact that electroplating in general used to have natural diamond as the preferred source. Within the last year and a half we have perfected our electroplating product, EBG, standing for Electro Bonding Grinding. We have perfected our electroplated product to the point where it is, in the worst cases, comparable to the natural diamond. We are seeing more and more activity in this product line. I think it is indicative of the type of success that we have had in finally perfecting a diamond that can be used for electroplated applications.

WERNER: One further comment, you see that even where you have a resin-bond system where the maximum temperature is 350 to 400 surface degrees, and with diamond as an abrasive, if you would exceed that temperature it would just fall apart. But we know it stands pretty well if you have the right coolant conditions. With a metal matrix of nickel, you can expect basically lower temperatures because the nickel as a metal leads away the thermal energy faster than resin does. There are bond systems where you have a metal and resin at the same time. The Norton Aztec wheel is an example of that. Here they say it works that well because there are metal particles that contact each other so the temperature has a way to flow out of the contact zone and the measured temperatures in those cases are never higher than 300°, so I have reason to assume that they will not be higher in an ID saw either.

LIU: I have heard a lot about the cutting edge, plating of diamonds onto the cutting edge, etc. For the illumination of those of us who are less familiar with the process, could we hear more details about this process?

SCHMID: There is no question that plating plays a very important role in cutting effectiveness. The plating hardness can be adjusted. Certain types of plating give you a very hard bond. What is good for us is not necessarily good for ID. For example, our wire does have some flex to it, and so if you have a very hard bond you can initiate cracks in it that can propagate into the core wire itself. That is a condition that you really would not want. You would want a softer plating that would not do that. The other thing I didn't talk about to any extent is whether you are using screened diamonds or micronized diamonds. Micronized diamonds will give you a much narrower spread of particle size, but it may not protect the bond. By using screened diamond, you can protect the bond. There will be certain diamonds that will be exposed; others will be not exposed but will protect the bond itself. There has to be compatibility with the diamond and the plating. One of the big developments is the man-made diamond that will now allow for effective plating of the diamond itself. The natural diamond for some reason has been a good one to plate and the man-made one was impossible until they worked out procedures to do that. It is important that the bond is resistant to erosion (which you can help by selection of the diamond particles), to corrosion, and that sort of thing.

BOUJIKIAN: Nickel electroplating is relatively simple. You can control it any way you want in hardness, softness. When you talk about hardness in nickel it is not a chemical hardness, it is stress hardness. The more impurities you get or some electrolytes will cause more internal stress than others.

LIU: Do you think that development of this actual cutting-edge technology is pretty much in hand, or are further developments necessary?

BOUJIKIAN: The proof of that is that the ID diamond blade almost never wears, and anybody in here who uses it can testify on that: on 95% of all diamond blades that are discarded from the machine, the diamond is still on. At least a large percentage, if not over 50%, is still on. TI has one hanging on the wall that says 84,000 cuts came out of it. The life of the blade is built into it, but all other factors involved in extracting or using it have to be accomplished. One is the core material. If we can find a core material that is chemically hardened instead of plastic-deformation-hardened, then that will solve many problems connected with it. But it is not available. I saw a gentleman from Uddeholm this morning over here and I have been keeping in contact with him for the last 15 years. They make hardened or chemically hardened rolled steel up to 6 inches wide, and that is it. If we can get a breakthrough in that area where you can get a core material that would stand the tensioning stresses we will have a big breakthrough.

(To T. S. Kuan): I want to know why the thermal damage was not addressed, only vibration damage or mechanical damage was addressed.

KUAN: These cracks usually range from 10 microns, 20 microns up to 100 microns, in front of the blade edge, so at that position I believe that the temperature is rather low. I think that the small effect probably is not important in terms of propagation of cracks, that is, what we describe as the saw-damage mechanism. I said that the plastic deformation is not important because I did not observe any dislocations in the damaged structure. Probably it is because the temperature never reaches 600°, at the contact point.

SCHWUTTKE: You have to look at the situation of how the wafer user judges the wafer quality. Once the wafer has been sliced, the damage is removed by using different polishing techniques, so a semiconductor engineer is using a wafer that contains residual mechanical damage, a crack tip. Polishing produces a flat wafer, so if you have damage, the polishing would remove this anyhow. We are much more concerned that a wafer contains residual damage. This is what is killing the semiconductor wafer.

KOLIWAD: My question is to Drs. Danyluk and Kuan, on the Zeta potential variations with respect to using different chemical environments. The Zeta potential variation and the softening observed in cutting has actually been documented for ceramic cutting--aluminum oxide, for example, where there is beautiful work. When you are cutting, the wafer surfaces are really not virgin silicon any more. I don't have any knowledge of any studies done on Zeta potential on real silicon surfaces. I wonder whether you are influencing the potential of oxide formation and softening the oxide instead, if in fact there is an oxide, and you are affecting the absorption of ionic species on an oxide, or whether it would be better if you add some oxidizing agents to your solution in addition to whatever lubricants or temperature environments you are using?

DANYLUK: First, I would like to say I don't believe the Zeta potential measurements have much to do with the mechanisms that we are talking about. Most of the Zeta potential measurements are done on crushed silicon. My opinion is that the crushing process itself affects the Zeta potential measurement that is used in a description of the space charges. These space charges, which are essentially what Dr. Kuan is talking about and which I am implying exist at surfaces, essentially exist at surfaces that start out being electrically charged. For example, dislocation cores are electrically charged but the overall surface is electrically neutral. The problem then comes in as to what the space-charge region has to do with the cutting phenomena. I believe that it has got to do with the Debye-Huckle length of the space-charge region. If it is big, then it has one affect and if it is small, it has another affect.

KUAN: There are basically two theories to interpret the lubricant effects. One is the Rebinder effect and one is the Westwood mechanism. I personally believe tnat the Westwood mechanism is more important in our case because all of these propagations of dislocation occur several microns underneath the surface, whereas the Rebinder effect talks about the event occurring exactly at the surface plane, which is not directly related to our case. I would like also to comment about the formation of oxide. Under such high cutting rates, I think that the formation of oxide probably is not important, although the formation of oxide does occur in certain cases where the metal is being cut under some kind of lubricant.

DANYLUK: When you expose virgin surface of silicon, that is precisely what the absorption problem is. Absorption is the initiation of the oxidation. I think that essentially we are talking about the same mechanism, the very early stages of oxide formation.