Slicing of Silicon Ingots with Reduced Kerf

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1.0 INTRODUCTION

Slicing expensive material with wire is very attractive since the kerf width can be reduced; hence, the least material waste can be achieved with wire. In addition, wire lends itself better than blades to multi-wafer slicing. Wire can be used either with loose abrasive or with abrasive fixed on the wire. Loose abrasive slicing involves abrasive tumbling between the wire and the workpiece causing material removal by an indentation process. This is often referred to as a 3-body abrasion because it involves the abrasive, wire and workpiece. With fixed abrasive slicing, the fixed abrasive particles are forced into the workpiece to plow out the material. This is referred to as 2-body abrasion. With fixed abrasive slicing the abrasive only needs to be attached to the cutting edge of the wire. Crystal Systems has patented a method¹ of electroplating on the cutting edge of wire to further reduce the kerf width. The company has reduced the kerf width even more by forming a tear-drop shaped wire⁴. With loose abrasive slicing, wire wear and degradation of the abrasive occur as the wire becomes contaminated with the kerf and the abrasive breaks down. This results in high expendable costs for the wire and abrasive.

For fixed abrasive slicing, high forces are required to force the diamond into the work, but wire is not as stiff as a blade making it difficult to achieve this condition. Crystal Systems has developed several patented approaches to minimize the contact length by rocking the workpiece^{2,3} and by using the shaped wire⁴ which reduces the kerf width and increases vertical stiffness. The main drawback to the Fixed Abrasive Slicing Technique (FAST) approach is the low relative speed between the wire and work surface since the bladehead can only be reciprocated at 100 to 120 cycles per minute. Therefore, the relative speed between the abrasive wire and workpiece is about 1 meter per second, which is relatively slow and results in lower cutting rates than those for loose abrasive wire slicing. The Preston equation⁵, $R = KVP$, shows that the material removal rate, R , is equal to a proportional constant dependent on a combination of material properties, Young's modulus, fracture toughness and hardness times the pressure, P (force applied per unit area perpendicular to the surface), times V , the relative velocity between the abrasive and the surface.

A new approach was developed to increase the speed while maintaining the short contact length by rotating the workpiece at high rotation speed in the range of 2,500 to 5,000 rpm. At 2,500 rpm the surface speed is 13 m/sec, and 26 m/sec at 5,000 rpm for a 4-inch diameter workpiece. This has resulted in cutting rates that exceed rates for FAST slicing with rocking by 50 times, and exceed multiwire slurry slicing rates by at least 10 times. Good wafer accuracy was achieved with low surface damage using this approach. The depth of penetration and chip size was controlled by the rotation rate and infeed rate. When the infeed rate was held constant and the rotation rate was increased, the depth of penetration and chip size per revolution were decreased. The chip size determines the surface finish and depth of damage.

High rotation rate of the workpiece has resulted in a breakthrough for slicing expensive materials. Based on the slicing improvement achieved with a high speed rotary feed system, a prototype production machine was built (see Figure 1) and the experimental machine (see Figure 2) was further modified to achieve a rotary speed of 10,000 rpm. The R&D machine has the unique ability to control the infeed with either a constant force or constant feed rate. The constant force capability allows for determining the best combination of parameters, such as rotation rate, diamond size, etc., for different crystal rotation rates and materials.

Figure 1. Doubleheaded production FAST slicer with high speed rotation.

Figure 2. Singleheaded experimental slicer with high speed rotation.

2.0 PURPOSE OF RESEARCH

The photovoltaic industry is expanding rapidly. Fossil fuels are a non-renewable resource that will forever be harder to find and emissions cause environmental problems. Moreover, demand for photovoltaic modules as a viable energy option will rise as photovoltaic devices become more cost competitive. The most popular and efficient material for producing photovoltaic modules is crystalline silicon, but material costs are high. Recent advances in alternative materials and thin film silicon have yet to be fully tested. The potential for these new approaches is a reduction in material cost; however, at present the approaches suffer from low throughput, steep learning curves and marginal efficiencies⁶. Material losses and subsurface damage caused by slicing are recognized as problems associated with production of crystalline silicon wafers. Reduction of kerf width and damage is key to increasing material utilization to make crystalline silicon much more cost effective.

3.0 BACKGROUND

Fixed Abrasive Slicing Technique (FAST), the approach to slicing that Crystal Systems has developed²⁻⁶, possesses the desirable features of both ID and MWS techniques. Slicing with FAST is accomplished by reciprocating wires fixed with diamonds across the workpiece. Diamonds are plated only on the cutting edge of the wire and water is used as a coolant. An important feature of FAST is the patented rocking mechanism developed to reduce the area contact and enable the wires to cut more effectively.

A schematic diagram of the R&D FAST slicing setup is shown in Figure 3. The diamonds cut the silicon workpiece and protect the wire from the wear of cutting. Because no oil slurry is used, the swarf contains only silicon and water and can be recycled for other processes.

Figure 3. Schematic diagram of the R&D FAST slicer.

This rocking system was effective in reducing contact length, but the speed of the diamond abrasive against the workpiece was slow, resulting in low cutting rates. During SBIR Phase II Crystal Systems developed a feed system that rotates the workpiece at 2,500 rpm or greater, to increase the speed of the abrasive relative to the workpiece while maintaining a short contact length.

Development of FAST required both machine development and development of the cutting tool, which is diamond plated wire. Diamond plated wire was not available on a reliable basis, and a method for making bladepacks was developed.

An electroforming technique¹ was developed to nickel plate diamonds only on the cutting edge. Optimizing diamond density, diamond size and nickel deposition is essential for efficient slicing, accounting for slicing rate, life of the bladepack, and to a large degree, wafer quality. Therefore, minimization of expendable costs can largely be accomplished in house by improving the bladepacks.

In 1992 Crystal Systems⁴ presented the concept of using shaped wire with FAST to reduce kerf loss (Figure 4). The shaped wire reduced kerf width from 300 μm to 175 μm . The cross sectional area of shaped wire is over 50% greater than round core wire with the same kerf width. Structural advantages of shaped wire (increased cross sectional area and high aspect shape) are realized as an increase in productivity and wafer quality. Because of its increased strength, shaped wire can cut faster and more efficiently, increasing blade life and decreasing expendable costs.

Figure 4. Schematic diagram of shaped wire.

4.0 FAST DEVELOPMENT

Slicing tests were performed to determine how the FAST machine could be modified and how diamond wire bladepack fabrication could be changed to improve slicing performance. Slicing performance is characterized by slicing rate, wafer accuracy, kerf width and bladepack life.

4.1 New Fixed-Rate Infeed Rocking System

The new fixed-feed FAST machine was produced and tested. The reliability of the machine was successfully tested with an overnight, unsupervised run. All systems performed well.

Some problems associated with wafer accuracies appear to be caused by the feed mechanism. The workpiece in the older fixed force machine is supported on both sides, whereas the workpiece holder in the new machine is cantilevered from one side. During slicing there is some extra vibration in the system which was not seen in the earlier machine. It was anticipated that the fixed infeed system would result in improved cutting rates and wafer accuracy.

4.2 Test Results

The slicing tests showed that the slicing rates could not be substantially increased and wafer accuracy was not improved. On the basis of these results, it was decided that the relative speed between the abrasive and cutting surface had to be substantially increased. The R&D machine was therefore modified by installing a servo motor to rotate the workpiece at high rpm to increase the relative speed between the diamond abrasive and the workpiece. The guide rollers were also changed from brass to urethane to minimize roller wear, thereby increasing roller life and wafer accuracy.

Wire bladepack development involved shaped wire development, development of tooling for shaped wire and electroplating varying the diamond type size and concentration.

5.0 BLADEPACK DEVELOPMENT

5.1 Bladepack Manufacturing

Bladepack is the generic term used to describe the finished "wire packs" that are used as the cutting tool in the FAST saw. Bladepack manufacturing is a two-step process consisting of wrapping and plating. Minor modifications to wrapping equipment have increased throughput significantly. A new epoxy has all but eliminated rejects; however, the coefficient of thermal expansion is higher than the older formula causing a 0.0001" reduction in wire spacing. After-market fillers have been used to offset the thermal shrinkage.

Plating equipment is continuously evaluated for improvement, in part because this process represents the most time consuming and expensive step in the manufacturing operation. Early prototype designs of lightweight single bladepack mandrels and frames have been fabricated. Test runs have been successful and plans for further reducing weight with new structural material are going ahead.

6.0 SHAPED WIRE DEVELOPMENT

Shaped wire is an important component in the effort to reduce kerf width. Reduction of wire diameter below 0.007" in previous studies caused significant wire wander during slicing. Therefore, it is crucial to maintain or increase the cross sectional area of the wire. By using a preformed geometry (Figure 4) cross sectional area and wire height are increased, kerf is reduced and guidance is improved, all of which reduce the tendency of the wire to wander.

Early tests with shaped wire (Phase II, Period I) were unsuccessful as the plating did not adhere to the nickel flash, which is deposited by a vendor to increase the ease of plating. The nickel flash was deemed inappropriate for CSI's plating process and the vendor was removed from the source list. A known vendor prepared subsequent wire lots and shaped bladebacks were produced with adhesion success. The cross section (Figure 5) shows the plating and shaped wire with a 10° included angle. This wire is from an experimental bladeback produced with several layers of diamond to facilitate repeated dressing operations.

Figure 5. Shaped wire cross section showing several layers of diamond.

Figure 6 shows a round wire with a 10° included angle. The plating has produced flat sides on the round wire, and it holds the diamonds on the cutting edge of the wire.

Figure 6. 200-μm wire plated with 45 μm diamonds.

7.0 TOOLING

Tooling refers mainly to the process of making shaped grooves in the plating equipment (mandrel) and the guide rollers. Exact groove geometries are necessary to maintain low kerf loss, straight cuts, and proper wire relief. Precise grooves are needed in rollers to guide the wire in mandrels during slicing and to constrain the plating to the wire's top surface only. The small size of the grooves and the exacting dimensions necessitate the use of new technologies; Crystal Systems, as outlined in the Period I report, focused on several technologies to produce the desired parts.

To date, mandrels have been fabricated using shaped-tooth milling cutters; a mandrel has now been fabricated using a single point diamond tool. For shaped wire, the grooves are superior to those produced by the shaped tooth milling cutter and a blade pack has been produced with nearly optimized geometry. As an offshoot of the diamond tool technique a master mold is being investigated to produce mandrels by stamping. The technique is analogous to making LP records, and involves negatives and electroforming operations.

In addition to the new techniques described above, a traditional shaped tooth milling cutter is still being used to machine grooves in plating mandrels. The technique works well for some materials; however, problems exist when grooving some chemically resilient engineering plastics and for making groove widths below 200 μm . Work to refine the grooving process continues, as does the search for new mandrel materials.

8.0 DIAMONDS

FAST uses diamond as the fixed abrasive particle. Many different diamond grain types are available, each with unique strengths and shapes. As the silicon industry has traditionally used natural and synthetic diamonds, Crystal Systems has chosen two types as baseline particles when testing other variables. The particle sizes have, in the past, ranged from 30 to 75 μm . A study has been renewed partly to measure the effects of particle size change on slicing efficiency and wafer accuracy with the new generation fixed feed FAST slicer. Three RVG diamonds were tested: 30, 45 and 60 μm .

In addition to the above study, tests of different grain types continue, using the baseline grain types as a point for comparison. Nickel-overplated diamonds (RVG 880) offered some mechanical holding advantage but created other problems, such as contaminating the plating bath. Until the contamination problem is solved the use of these diamonds is suspended.

9.0 PLATING

Nickel plating is used to secure diamonds to the cutting edge of the wires. Nickel is used by the industry because of its low stress, moderate hardness and good ductility. Plating wires with nickel and diamond is not a common operation and has been developed largely by Crystal Systems for the FAST technology.

Following the development of a first generation plating mask to create uniform nickel deposits during the first part of Phase II, two identical masks were fabricated to conform to the plating operation for use in the testing program. The programmed thicknesses are within $\pm 3/10,000$ of an inch over 90% of the blade pack, and more importantly over nearly the entire cutting portion of the blade pack.

10.0 MACHINE DEVELOPMENT

Based on testing with a fixed feed system that showed low cutting rates, and in consideration of Preston's equation for material removal, it was determined that higher speed would be required to increase the cutting rate. Modifications were made to a large double-headed production machine that was previously used to slice 125 mm x 125 mm silicon. The rocking feed system was replaced by a rotary system with a 5,000 rpm rotary speed capability. This system also has the capability of rocking to cut through the central uncut section of the workpiece. This was accomplished by stopping rotation and adhering a graphite support piece on the outer diameter to hold the workpiece and then cut through the small uncut section by rocking.

11.0 SILICON SLICING TESTS

Machine modifications were accomplished near the end of the SBIR program. Therefore, testing was limited. Initial slicing tests were conducted with a three-inch diameter silicon crystal. A 200 μm wire plated with 45 μm diamonds (Figure 6) was used for the test.

The 76 mm diameter workpiece was rotated at 3,000 rpm, and the infeed rate was 2.5 mm/min. Therefore, the diameter was reduced 5 mm/min. This cutting rate was 50 times greater than the cutting rate established for rocking. The yield of good wafers was 100%. A lapped surface is produced as a result of the rotation, and the thickness variation in the wafer was less than 50 μm . To make the technology more commercial, blade packs were made with commercially-available 180 μm wire core with 20 to 30 μm diamonds plated over the entire circumference. After some initial trial runs, a 75 mm diameter, 100 mm long workpiece was mounted and rotated at 5,000 rpm. The feed rate was 2.5 mm/min (0.1 inch/min). This run resulted in 87 wafers (100% yield). A second run was conducted using the same parameters and a 100% yield was achieved again. The resulting wafers were sent to an outside laboratory for characterization. The thickness variation was 20 μm , which is quite good. The wafers were examined for subsurface damage, and it was less than 10 μm as sliced, which is low.

To determine the utility of the process, hard materials such as sapphire and high density SiC, and soft materials such as GaAs, were sliced. The technique successfully sliced each of these materials with low kerf loss, low subsurface damage and good wafer accuracy.

12.0 COMMERCIALIZATION

These tests showed that rotation of the workpiece at high rpm significantly advanced the state of FAST technology. On the basis of the success achieved with FAST slicing of silicon and other materials such as sapphire and gallium arsenide, Crystal Systems is commercializing the technology. One prototype machine (Figure 1) is being operated to produce commercial wafers and optimize the technology. Crystal Systems is applying for a patent on this development and is working with two major companies to expedite the commercialization of FAST. Crystal Systems has one double headed prototype machine producing wafers for commercial sale and has a second generation double headed machine being built. In addition, a highly instrumented experimental FAST machine is being modified (Figure 2), with a rotary feed system with a capability for fixed feed or fixed force feed system to optimize a combination of parameters for various materials.

Considerable advancements were realized during Phase II in blade and machine development, and the goal of slicing thin wafers with less kerf loss was accomplished. Shaped wire bladepacks were tested against previous round wire bladepacks and yielded promising results. Kerf losses were decreased 20%, and wafer quality increased 35%. Progress in lowering bladepack expendable costs was also accomplished by adjusting plating procedures, diamond type and diamond concentration and adopting controlled dressing strategies. A high-speed rotary feed mechanism was installed on the FAST machine to increase the cutting rate by a factor of 50. The advancements during the Phase II program to reduce kerf width and subsurface damage and improve productivity and wafer accuracy make FAST the most effective technique for slicing expensive materials into wafers.

Crystal Systems is currently commercializing this technology. FAST machines with a high-speed rotary feed system will be optimized in a prototype production phase where various materials will be sliced for commercial sale. Based on this experiment in the prototype production phase, the production version of the machine will be designed, fabricated and licensed to the industry.

13.0 CONCLUSION

Higher speed between the workpiece and diamond abrasive was required to increase slicing efficiency. Higher speed and lower contact lengths were achieved by rotating the crystal at high velocity. The cutting effectiveness was enhanced by increasing the rotary speed in the range of 2,500 to 5,000 rpm, and the reciprocation in the range of 100 cycles/minute. Rotation of the workpiece, rapidly relative to the speed of the diamond abrasive, causes the diamond particles to stay in contact with the work for longer periods than if the diamonds are moving fast, as in OD slicing and the work is moving slowly. By rotating the work to achieve a higher relative speed, four favorable conditions are achieved: (1) short contact length to produce high force between the diamond and the work; (2) long duration of the diamond in the workpiece much like single point diamond cutting for effective material removal; (3) high relative speed between the work and the diamond combined with high force increases the material removal rate; and (4) high speed rotation of the workpiece causes the diamond on the edge of the wire to lap the workpiece to produce a lapped surface.

Rotation of a workpiece in a multiwafer operation was previously not practiced because toward the end of the cut the central diameter decreases until it breaks before the cut is completed. This difficulty was overcome by stopping the rotation of the workpiece before the central core is so small it breaks and adhering a graphite bar from the drive ends across the top of the wafers to hold the wafers together. The slicing machine was started after the graphite support was attached, but operated in a rocking mode as described in U.S. Patent #4,727,852 until the cut was completed. The wafers are attached to the graphite bar which is removed from the supports. The wafers were removed from the bar by soaking in solvent to dissolve the epoxy.

Significant improvements have been made to FAST technology to increase the cutting rate by a factor of 50 to produce multiple wafers with low kerf loss, low surface damage and high accuracy. This has advanced FAST to be the most cost effective multiwire slicing technology. Based on these developments, Crystal Systems is commercializing FAST for slicing a wide variety of hard and soft crystals.

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