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WAFERING INSIGHT PROVIDED BY THE ODE METHOD

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ABSTRACT

Orientation-dependent-etching (ODE) can be used to slice silicon. The method has several possible advantages including high slicing yield (m^2/kg), plane parallel, thin slices, ready for processing and the chance of high throughput and low costs. There are limitations in the need for simple crystals, and in restricted depth of slicing. Analysis of the overall properties of the ODE method has added insight into the requirements of a successful wafering method.

BACKGROUND

Orientation-dependent (OD) slicing uses preferential etching down narrow slots in a silicon slab on form slices. This method of slicing was investigated to see if its advantages could be used to form more slices from high quality silicon crystals than can be achieved by mechanical slicing methods. In particular, an attractive feature was the possibility of forming thin slices (~50um), ready for cell processing; present methods for etching thin slices from already sliced silicon involve large losses of silicon. OD slicing has some limitations, which restrict the cell designs available. Attempts to overcome these limitations have led to study of different methods for processing the slices into cells and arrays.

ORIENTATION-DEPENDENT SLICING

OD etching has been used to form solar cell structures, including vertical multijunction cells (1), etched groove cells (2), and polka-dot cells (3). However, OD slicing requires formation of considerably deeper grooves.

Figure 1 shows a typical slicing sequence. (110) orientated slabs are cut from <111> orientated crystals. The slab thickness determines the eventual slice width, but there is no requirement for extreme accuracy in cutting the slabs. The slabs are chemically polished, and coated with SiO_2 and/or Si_3N_4 which act as masking layers during the OD etching. Using a slot-pattern mask and optical photolithography, a close-spaced, fine slot pattern is opened in the masking layers. An OD etchant (typically 30M KOH at 85°C) is used to etch down the slots; slices are formed when the slots are etched through. Figure 2 shows partial slicing with widespread slots ~450um deep.

Previous work (4) showed that for slots in the 111 direction and (110) faces, etch ratios (downward to sideways) as high as 400:1 could be achieved, and some reports (4,5) have quoted values as high as 600:1. These high ratios, which form deep, narrow slots require very accurate alignment (0.1°) of the slot direction with the (111) planes which are perpendicular to the (110) planes. These etch ratios are far in excess of the difference in bond densities for the different crystallographic planes, and a tentative explanation (6) involves preferential oxidation of (111) planes in the OD etchants. Accurate alignment has been achieved by extension of the fan-etch method (4) and once the fan-etch has shown the correct <111> directions of a typical slab from one ingot, subsequent slabs can be aligned with the slot-mask using precise mechanical adjustment.

The area yield, i.e. the slice area per starting mass of silicon, can be high if high etch ratios ($\geq$200:1) can be maintained. Figure 3 shows the m^2/kg obtainable for two slicing depths. Also, on this figure are indicated the range of m^2/kg available from present or projected mechanical slicing methods (multiple wires or saws) and sheet growth. Figure 4 shows how the etch ratio increases as the misalignment angle decreases. The etch rate down the slots (in the <110> direction) is fairly slow (~1um/min.), but despite this slow rate, a large number of slots can be formed simultaneously by etching several slabs at once. Using 10um wide slots, spaced 60um apart, 160 slices ~50um thick are obtained for each centimeter of slab width. Thus the areal output (cm^2/min) can be high. To form slices ~1mm thick requires etching for ~1000 minutes. This places severe requirements on quality of the masking layers.

Because the mechanical forces on the slices are small (none in slicing, mainly from the etchant motion or hydrogen pressure) it is possible to form very thin slices. Slices 50um thick have been the target, but thinner slices (down to 1um) have been formed. Typical slot widths are 10um, and for 200:1 etch ratio, a slice 1mm wide will involve a kerf loss ~20um. The slice faces are restricted to be (111) planes, giving chance of good parallelism for all slices formed. We had expected the slice faces to be very flat and they are flat and parallel. However, the prolonged exposure to the etchants forms etch figures on the slice faces (see Figure 5), probably arising from inherent bulk imperfections in the starting single crystal.

The OD slices are formed in silicon which has never experienced any mechanical processing. This is of interest, because it is believed that even after excessive etching to remove mechanical work damage, the effects of this damage can never be completely erased.

We have successfully OD sliced silicon and have found suitable combinations of slab preparation, masking layers, aligned slot formation and etchant conditions. However, we have also identified some practical limitations and they are discussed next.

Limitations in OD Slicing

There are several intrinsic limitations, including the need for starting single crystals, suitably oriented, the formation of very accurately aligned slots, and limited slice width (limitation on slot depth obtainable). We have also found some practical limitations as follows.

The thin slices formed must be supported during slicing to prevent breakage as slicing proceeds, and to prevent the need to handle many thin slices separately. Some support can be provided by masking the back surface of the slab, although it is difficult for this thin masking membrane to act as sole support. Several other methods have been used to give additional support. These methods include use of a heavily doped P+ layer, a few micrometers thick formed at the back surface to supplement the masking layers. These P+ layers (for concentrations $>6\times10^{19}cm^{-3}$) are attacked very slowly by the etchants, so that they act as a self-stopping membrane at the bottom of the slots. Such a stopping layer can also help to allow complete slot etching when the etch rate may differ in different slots. We have also studied the use of top surface support methods. By mask design, support struts can be left at intervals across the slot pattern. It is also possible to change the mask design to provide many mask bridges across each slot. There is some conflict involved in the need for slice support during formation, and the need for easy removal later in the process, and this will be discussed in the next section.

The slot width, slice thickness, and slot depth (slice width) values used were ~10um, ~50um, and ~1000um, respectively. We found several factors which gave variable etching in the deep slots. Because of capillary effects, it was observed that the etchant near the bottom of the slots could become depleted, thus slowing the etching rate. This etch depletion could also affect the oxidation rate of the (111) surfaces; if the slot faces are not protected, sideways etching can proceed by ledge exposure. In addition stresses at the top surface mask-silicon interface, or severe crystallographic defects on the etching slot faces, could also lead to sidways erosion. We did not find clear-cut connection between edge dislocations on the top slab surface or on the slice faces, and the occurence of excessive slot wall etching. No matter what the reason, this enhanced sideways etching formed very thin slices on parts of the slab, and often while the slots were etching deep, the slot pattern was "washed-out". Compounding these sideways etching problems was the formation of limiting surfaces near the bottom of the slots. These limiting surfaces were the family of (111) faces which are not at right angles to the (110) surface. (Figures 5,6.) These limiting surfaces slowed the etch rate, either requiring very long etch times to complete the slots, with greater chance of sideways etching, or they hindered methods developed to separate the completed slices.

We did form many slices ~1000-1250um thick, but the slicing was incomplete across the slab. These etching problems have slowed development of the slicing method. To avoid processing of many separate thin slices, we considered use of "matrix processing" wherein complete cells could be formed on the supported slices, before separation and use with spectral concentration (7).

COMMENTS ON ODE SLICING

It is instructive to use the experience of the ODE slicing method, to add insight into the wafering requirements needed to meet the cost goals of the DOE solar cell programs.

Slicing is needed for grown or cast ingots of silicon. Present trends in these ingot technologies involve combination of reasonably pure starting silicon, growth to provide large grains (>mm size), and for reduced costs, growth of large ingots →100 kg per growth sequence for continuous Czochralski or FZ methods, →50kg for cast ingots. Clearly these large ingots should be processed as large slices, and failure to meet this requirement [illegible]s the major disadvantage of the ODE method. As the cost of the starting silicon and the costs of growth are decreased, kerf losses can be accommodated, although the cost of generating ~50% scrap silicon will always be a heavy price to pay. Most casting methods give polycrystalline silicon, and ODE cannot be used in these cases: the mechanical methods have no similar limitations.

Present day technology (Czochralski crystals sliced by ID saws) shows that the slicing throughput is an early bottleneck in the whole cell processing sequence, and already much space and upkeep is required for the many ID machines needed. Assuming a working day of 20 hours, present ID machines can cut 4" wafers at ~2 m^2/day; at ≃0.7 m^2/kg yield, this means ≃3kg/machine/day. For the same working day, present Czochralski grower can generate at least 20kg per day and assuming ~50% kerf loss, requiring more than 3 slicing machines for each crystal grower. For all slicing methods, the slicing yield depends only on the sum of the (slice + kerf) thickness (Figure 7). It is clear that the yield rises rapidly as this sum decreases; also that for high yield it is important to reduce to slice thickness, as well as the kerf losses. To make such reductions, it is necessary to reduce the thickness of the slicing means, and to also reduce rate of slicing. This leads to methods for simultaneous formation of many slices at once to maintain a reasonable throughput. In this respect, the ODE slicing method can be regarded as the ultimate in simultaneous slicing, in that ≈100 slices can be formed per centimeter of silicon, and many centimeters can be simultaneously etched. Slicing to produce reduced kerf loss also tends to provide slices with less work damage. This has been demonstrated with damage depths ~25um for ID sawing, ~20um for MB sawing, and ~15um for MW sawing method; again the ODE method is the limiting case, with no damage produced.

Estimates of the practical limits for the various slicing methods show that the slice and kerf thicknesses fall off relatively slowly (with associated increase in the slicing yield) as the number of simultaneous cuts is increased. The results of these estimates are given in Table 1. Experience with the ODE methods shows that as more simultaneous cuts are made, reduced space is required for the equipment; if the throughput is similar to that of an ID machine, a similar number of machines will still be needed. Also, with increased number of simultaneous cuts to ensure effective slicing, the complexity may rise, and this added complexity (or the need for frequent maintenance) may add unwanted cost increments to the slicing process. When very high yields are obtained (resulting in thin slices), there may be the need for support of the slices, to avoid severe breakage. Also, to ensure lower overall costs, it is important that the slices formed should not be so thin that extra care in processing is required.

The ODE process had several other features which were favorable to large scale use. These included the need for only moderately complex methods (immersion in a solution below 100°C) an easily maintained condition (water bath), and modest equipment needs (large containers and exhaust fans). Also, there were two other possible features of interest. The OD etching process generates hydrogen, and it is possible that in a large scale process, this hydrogen could be collected, and used as fuel. Also, the etched silicon is left in the etching solution, and should be reasonably easy and economical to recover.

In conclusion, we have found that study of the ODE slicing method has focussed attention on the overall properties required of an effective slicing method. In its present state of development, ODE slicing is an example of a method which has many of the attractive features required, and yet cannot be regarded as a solution to meet the slicing goals of the DOE low cost silicon cell programs.

ACKNOWLEDGEMENTS

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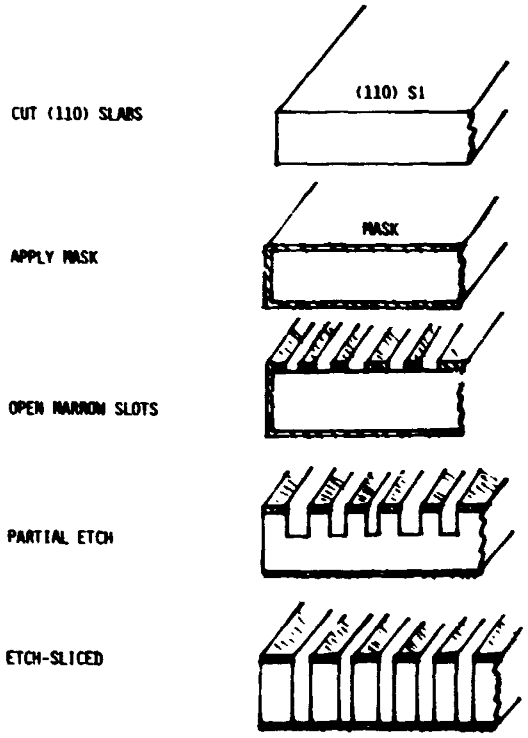

FIGURE 1

O.D. SLICING SEQUENCE

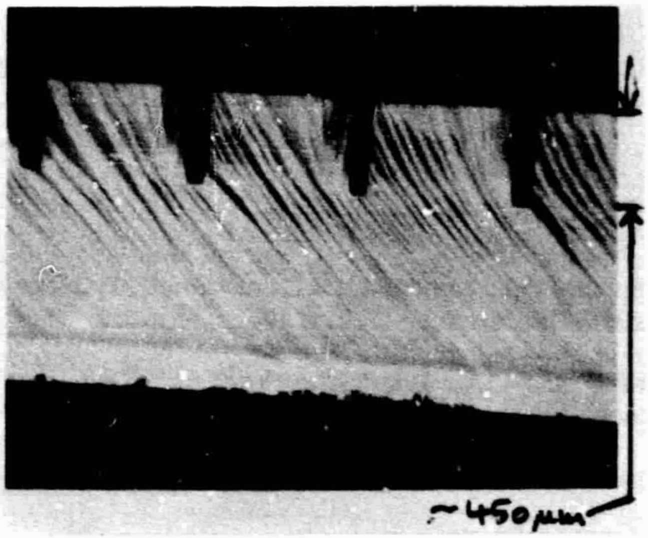

FIGURE 2

PARTIAL SLICING (SLOTS 0.5mm DEEP)

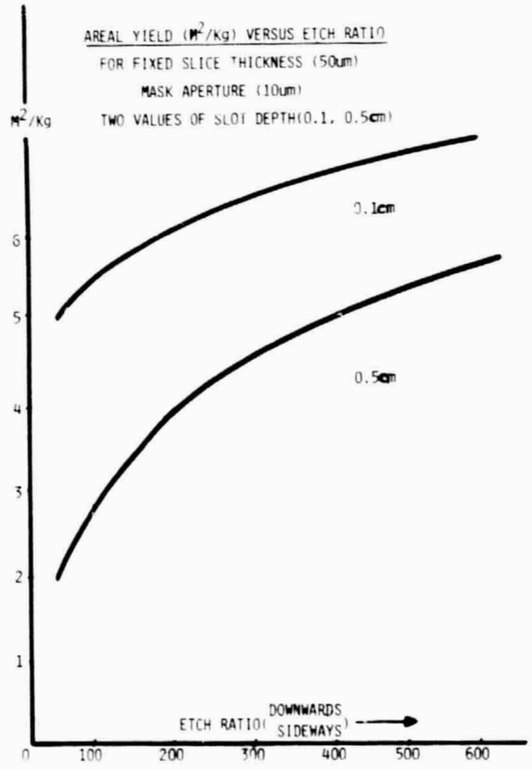

FIGURE 3

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

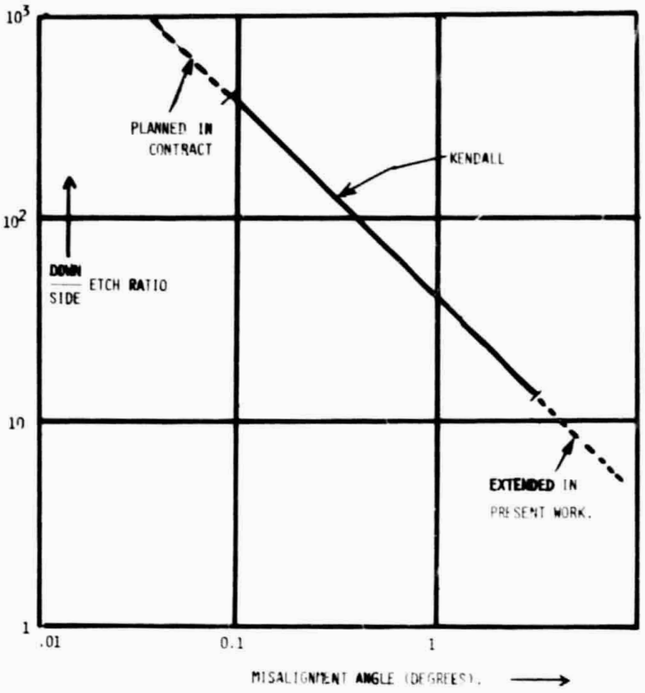

FIGURE 4

ETCH RATIO MISALIGNMENT ANGLE

(KOH ~85°C)

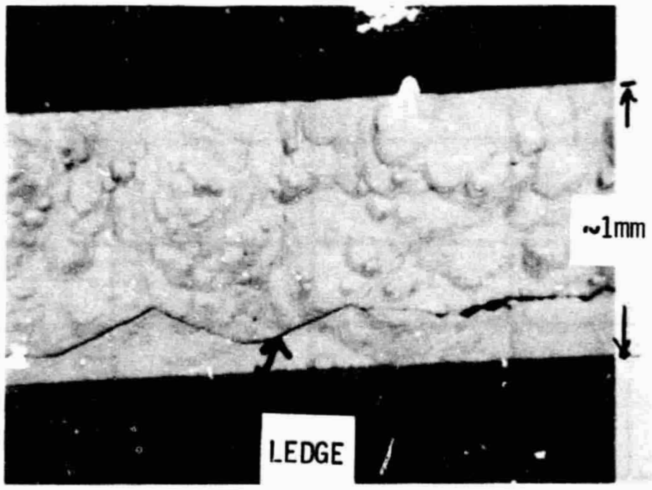

FIGURE 5

(111) FACE ETCH FEATURES

FIGURE 6

LIMITING LEDGES ON (111) FACE (AT BOUNDARY BETWEEN OD ETCHED AND CLEAVED SECTIONS)

TABLE 1

COMPARISON OF VARIOUS SLICING METHODS

METHOD	NO CUTS	PLAUSIBLE MIN.S (mils)	PLAUSIBLE MIN.K (mils)	THROUGHPUT cm^2/min.	YIELD m^2/kg
ID	1	6-8	8-10	15	0.7-1
ID ADVANCED	3	6-8	8-10	45.	0.7-1
MBS	X00	6-8	6-8	*	0.8-1.4
MWS	Y000	4-6	[illegible]-7	*	1-1.8
ODE	Z000	2-4	1-3	*	4-6
RIBBONS	-	4-8	-	20-50 Ø	2.1-3.2

* CAN ADJUST X, Y, OR Z TO GIVE 10-25cm^2/min.

Ø RECENTLY 145cm^2/min. for EFG.