ABSTRACT: The surface morphologies of alkaline etched pyramid and tilted pyramid textures have been accurately mapped using a specially adapted atomic force microscope. The resulting height scans were used as input for the ray-tracing program BIRANDY whereby light trapping is directly related to the height data. Double and single sided textures were etched on (100), (210) and (311) wafers of approximately 100 µm thickness and reflectance and light trapping properties measured and modelled for various back surface reflectors and under encapsulation. Although the light trapping for tilted pyramid textures is high, the angles and symmetry of the {111} facets of upright pyramids on (100) leads to slightly better light trapping overall. The maximum short-circuit current density Jsc(max) for tilted pyramids approaches that of (100) when these textures are encapsulated due to the resulting reflection reduction.

Keywords: Texturisation - 1: Ray-tracing - 2: Multicrystalline - 3

1. INTRODUCTION

Alkaline etchants, such as NaOH and KOH, are routinely used in the processing of monocrystalline (100) solar cells, leading to the formation of pyramidal etch structures on the wafer surface when used at low temperatures and concentrations. The high anisotropy of the etch solution exposes slow etching {111} faces, which intersect to form four-sided upright pyramids with facets at 54.7° to the wafer surface. These structures are well known to promote reflection reduction through the possibility for multiple incidence of light at the highly faceted front surface, as well as improved light trapping due to the oblique passage of light through the cell.

Similarly in the case of alkaline texture etched multicrystalline wafers, it is often assumed that etch textures on any particular crystal orientation will be described geometrically by the positions of the {111} planes closest to the surface orientation. However this assumption is somewhat simplistic; it has been shown [1] that not only {111} planes but also a range of orientations between {110} and {111} orientations are stable in a standard texture etch, also influencing the resulting etch structures.

2. MODELLING OF OPTICAL PROPERTIES

2.1 Modelling methods

The level of reflection reduction and light trapping which can be achieved for a textured multicrystalline wafer is inherently linked to the geometry of the etch surface for the individual crystals. In order to be able to explain the optical properties of such textures fully, it is necessary that the texture be properly quantified so that the passage of the light throughout the wafer may be described completely.

For lightly faceted textures, such as those obtained with a concentrated alkaline saw-damage etch where facet tilts vary between 10 and 20° for the different orientations [1,2], optical properties can be well approximated for the entire multicrystalline wafer by assigning a roughness factor to the scattering surfaces [3]. However in the case of alkaline texture etched wafers, the highly faceted texture geometries lead to highly directional and angular dependent (multiple) reflections which are poorly modelled by such approximations to a scattering surface.

Solar cell ray-tracing programs such as “Sunrays” [4] allow a restricted range of texture geometries to be defined in terms of a unit cell with chosen dimensions, facet angles and cell thickness. Tilted pyramids are described by the angle of tilt and/or rotation of an upright pyramid about its peak, assuming that exclusively {111} planes are exposed. For crystals oriented close to {100}, such as {311} and {210}, the shape of the textures modelled by Sunrays is in good agreement with the actual texture observed, since these orientations yield textures dominated by {111} facets. However, it is not possible to model variations in texture size or untextured regions between pyramids, nor to accommodate for other stable facets or the development of the etch texture. Also, modelling is restricted to single sided front surface textures.

2.2 Ray-tracing with program “Birandy”

A ray-tracing program where the defined texture geometry is no longer refined to restricted unit cell structures is the program Birandy [6]. Here, detailed height scans obtained using atomic force microscopy (AFM) provide the quantitative description of the textured surface.

When the incident light ray reaches the textured interface at a point (x,y) of the AFM scan with height z, the surface normal is determined locally from the vector product of the lines linking 4 adjacent data points in the AFM scan (left and right, above and below) and the angle between the ray and surface normal determined. The decision for reflection or refraction is made according to the reflection coefficients, which are pre-calculated as a function of wavelength and incident angle. It is hereby possible to quantify the true surface geometry for areas large enough to encompass several texture features, so that the texture input is representative of the texture present over the entire crystal. The program has been tested against Sunrays and other modelling programs for simple layered structures and periodic textures and results were found to be in good agreement. Figure 2 shows results of ray tracing for bare and encapsulated texture etched (210) wafer using a good AFM scan as input for Birandy, giving very good agreement with measured reflectance data.
3. ATOMIC FORCE MICROSCOPY

A contact mode atomic force microscope was used to obtain height data for the samples used. In order to obtain AFM scans for the large height differences and particularly rough textures present in texture etched wafers, an AFM scanner was used with an 8 µm range in the z direction, having a maximum scan size of 200 x 200 µm. In addition, a scanning needle with a tip angle of 32° (c.f. 74° for a standard AFM needle) allowed for accurate scanning of steep textures.

Nevertheless, for very rough textures, e.g. upright pyramids on (100), it was only possible to scan textures for relatively small areas (~30 µm) due to the extreme height variations in the texture, and it is not always possible to avoid scanning to the limit of the scanner range. This can lead to artefacts in the AFM scan whereby a small scan area of heights will be “chopped off” and thus have zero facet angle; in Birandy, such areas will lead to a higher modelled reflectance than is measured. In general, a scan size of 50 x 50 µm was used, with 256 x 256 data points (x/y resolution ~0.2 µm) for experimentation.

4. EXPERIMENTAL

The aim of this experiment is to quantify the light trapping properties of thin, alkaline texture etched multicrystalline wafers, on a per orientation basis, without the use of a back surface reflector (BSR), and encapsulation. Assuming that future wafer techniques will be capable of producing increasingly thin wafers, a wafer thickness of approximately 100 µm is chosen for the textured wafers.

4.1 Sample preparation

Monocrystalline wafers with (210), (311) and (100) orientations are used, since the upright or tilted pyramid textures which result from the etch are expected to give a high level of light trapping. The wafers (~30 x 30 mm) are first etched down from an initial thickness of ~500 µm using a concentrated saw-damage texture etch. The resulting etch surface is evened out using sand-blasting with fine Al₂O₃ powder. The wafers then receive a 15 minute texture etch at 80°C using 90 vol. % water + 10 vol. % iso-propyl-alcohol + 2 wt % NaOH.

Both single and double-sided textures are made experimentally for the different orientations. A silver BSR of approximately 250nm thickness was applied using vacuum deposition. The encapsulation comprised of 1 mm glass + ethyl vinyl acetate (EVA) at the front, with either the same encapsulation at the back or with an EVA-white tedlar backing. An integrating sphere/spectroradiometer set-up was used to perform reflectance measurements on the bare, coated and encapsulated samples.

4.2 AFM mapping of the surface

AFM height scans were made of the bare textured wafers and were used as input for ray-tracing with Birandy. Calibration of the AFM was performed using a photolithographically etched inverted pyramid texture on (100) oriented silicon, with pyramid bases of 9 µm (thus a pyramid height 6.36 µm). In this way there are 5 points for height and angle calibration; the peak height of the pyramid, plus the angles of the {111} facets which must correspond to 54.7° in four azimuthal directions. This is best visualised by means of an AFM facet transform [1,2]. By this method, every point of the AFM scan is fitted locally with a plane to which normal vectors are calculated, so that a density function of normal vectors per solid unit angle can be plotted in terms of angular components of tilt and azimuth. The determination of surface normals in this way is comparable to that used in Birandy.

5. RESULTS

5.1 Wafers without encapsulation

Measured and modelled reflectance values were in good agreement for the (210) and (311) orientations; for the (100), the modelled values were approximately 3 % absolute above the measured values. The AFM scans for (100) were the most difficult to perform due to the roughness and height variations of the texture.

For bare silicon, light trapping properties were best for single sided etch textures, with textures at the back preferential to those at the front texture, although for (100) these differences were very slight. This difference between front and rear textures arises since scattering at a textured back surface by reflection is greater than that by refraction on entering at the front surface. The double textures lose a relatively high fraction of light (~ 10%) by transmission through the back surface on the first pass, an effect which is far less for the single sided etched samples.
Applying a silver BSR reduces the difference in light trapping between the three texture types, with the light trapping improving for both double sided and front surface textures. However, for single sided back surface texture, the application of a BSR reduces the light trapping quality. This is because of the frustration of total internal reflectance (TIR) of light with transmittance into the silver at the silicon rear surface. In the case of the bare silicon, light incident at the back surface of the silicon often approaches at an angle large enough to allow total internal reflectance.

5.2 Modelling of encapsulated wafers

5.2.1 Determining optical characteristics of glass, EVA and backing foil

In order to correctly model the optical characteristics of the encapsulated wafers, the wavelength dependent n and k components of the refractive index for the glass, the backing foil and for the EVA must be determined. These components were derived for glass and EVA from calculations based on reflectance and transmission measurements on the glass and on the glass-EVA-glass sandwich (Fig 5). The large absorption peak in the EVA at 1200 nm has minimal influence on silicon absorption since it is beyond the silicon bandgap; the absorption in the glass, which gradually increases with wavelength is more significant.

In the case of the white backing foil, which comprises of a primer layer on top of a film of PETP, followed by Al and PVF as base, the reflectance characteristics were determined through simulation by approximating the Tedlar to an aluminium film. By comparison to measurements of a 100 µm polished silicon wafer encapsulated under glass and EVA with foil as backing, the reflectance characteristics could be simulated by setting the backing foil equivalent to a 20 nm aluminium layer with 100% random scattering (Fig 6).

5.2.2 Reflection reduction under encapsulation

The measured reflectances of samples with front surface tilted pyramid textures are strongly influenced by the introduction of an encapsulating layer. The reflectances of (311) and (210) front surface textures decrease from ~25% to 7% in the visible on encapsulation.

In air, double bounce reflectance is minimal since low angle facets dominate the etch surface (the (111) facet is angled at 29.5°to the surface for (311), and for (210) the (111) and (11-1) facet angles of 39°). However under encapsulation, these angles are large enough to allow total internal reflection (TIR) at the glass-air interface, which redirects light reflected away from the low angled facets towards the etch surface for re-incidence. For (100), reflectance is only reduced by ~4% on encapsulation, since benefits from TIR are minimal as compared to the double reflectances achieved for the bare (111) facets at 54.7° to the surface. This effect is seen in the modelled short circuit current densities; for (100), Jsc increases from 37.3 to 40.7 mA/cm² under encapsulation, compared with an increase from 31.4 to 40.1 mA/cm² for the (210).
5.2.3. Effect of the back surface

5.2.3.1 Intimate Ag BSR

Comparing bare and encapsulated textures, the pathlength distributions in the case of double and rear sided textures are equivalent (Figure 8). This suggests that light escaping at the silicon front surface after multiple passes through the silicon is emitted at less than 16° to the surface normal, so that light does not benefit from TIR at the glass-air interface.

The light trapping performance of front sided textures with Ag BSR under encapsulation is reduced with respect to the bare case. This is because light is lost at the front surface on the second pass, due to the easier coupling of light out of the front encapsulant compared to TIR at the Si-air interface for the bare wafer.

5.2.3.2 Bifacial encapsulation

For the bifacial encapsulation (glass-EVA-Si-EVA-glass), light trapping is poor in all cases, with light (~20-30%) coupled out of the rear glass on the first pass (Figure 8). The noteworthy exception is that of the (100) with single sided texture; the 54.7° [111] facet angles ensure that all light incident at the rear silicon-EVA interface experiences TIR on the first pass, the angle of incidence being 33° c.f. a critical angle of 26°. However, the light escapes easily at the front surface after two passes (~17% transmitted). For the tilted pyramid structures, light passes into the encapsulant after the first pass where it can be absorbed in the glass and/or transmitted into air.

5.2.3.3 White Tedlar backing foil as a detached reflector

For the wafers encapsulated as glass-EVA-Si-EVA-Tedlar, light trapping was similar for both double and back surface textures with less than 5% of light being lost by absorption at the rear in the first pass (Figure 8). However, for front surface textures, where initially light trapping is equivalent to an intimate Ag reflector, a relatively high proportion of light (10-15% c.f. ~5% for an intimate Ag BSR) escapes through the front surface after two passes so that light trapping is strongly reduced. If the scattering of the backing foil is set to zero for modelling, i.e. specular R, the light trapping is equivalent to Ag for the first four passes, and is higher thereafter. For the double and rear textures, the level of Tedlar scatter has minimal effect on the pathlength distribution, with slightly better trapping for the 100% scattering case.

6. CONCLUSIONS

Light trapping of bare tilted pyramid structures is high despite visible R ~ 25%. The reflection reduction achieved for tilted pyramids under encapsulation increases $J_{sc}(max)$ to the level of upright pyramids on (100).

White Tedlar foil as detached reflector gives the highest light trapping for the rear surfaces investigated, except for single sided front textures where its scattering is detrimental to trapping. The scattering of the foil has little influence on light trapping for double and rear sided textures. For front surface textures the Ag BSR is best; according to modelling a specular detached reflector would give light trapping better than or equal to the intimate Ag reflector in this case. The effectiveness of detached reflectors for improved light trapping implies particular benefits for the case of cells with open rear-side metallisation.

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