

## Insights into c-Si Processing for Photovoltaic Applications

#### Ismail Kashkoush and David Jimenez NCCAVS PAG Meeting, Semicon West, July 15, 2010



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#### Outline

#### Introduction

#### Experimental

#### ✤ Results

- Impact of Surface Contamination and Importance of Pre-cleaning
- **Surface Analysis**
- **IPA Replacement**
- **Concentration Control**
- **COO Modeling**

#### Summary



#### Introduction

- Effective light absorption at pyramidal surfaces of c-Si solar wafers texturized with alkaline solutions is commonly applied in the PV industry
- Small pyramid dimensions resulting in low surface reflectance is normally considered a key factor for enhancing solar cell efficiency
- With introduction of HIT (heterojunction intrinsic thin-layer) technologies, increased densities of the peak and valley with decreased pyramid size have been found to be detrimental to solar cell performance
- Optimization of pyramidal textures with appropriate surface morphology is desired for advanced solar cell development
- The effect of cleaning pre- and post-texture treatment on alkaline texturization and cell efficiency needs to be addressed



#### Basic Process Flow and POR





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#### Typical Surface Morphologies (Tests Performed in Akrion Systems Tool)



As-cut Surface (topdown 500X)



As-cut Surface (topdown 2500X)



As-cut Surface (45° tilted 2500X)



Partially Textured Surface (topdown 500X)



Fully Textured Surface (topdown 500X)



Fully Textured Surface (60° tilted 500X)



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#### **Basic Characterization**

**Texturization Characterization** 

Surface Preparation Techniques



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#### Silicon Etch Rate vs. KOH/IPA Concentration



#### Reflectance and Etch Rate $\uparrow$ as KOH $\uparrow$ , while Etch Rate $\downarrow$ as IPA $\uparrow$ To minimize Si loss, it is preferable to decrease KOH but increase IPA



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#### KOH Concentration Effects (KOH Solution Only)

Mono-Si Wafers, 30minutes @ 80 deg C



High KOH% reduces pyramid sizes/densities and therefore surface reflectance

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Without IPA, pyramid distribution is not uniform





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#### Wafer Type A, No Pre-clean



Etch rate: 0.25  $\mu$ m/min/side Reff @ 950nm: 10.95% Rw 300-950: 13.66% Rw 300-1200: 15.58% Pyramid base width: -min. = 1.95  $\mu$ m -max. = 8.14  $\mu$ m -ave. = 3.98  $\mu$ m -sigma = 1.55  $\mu$ m









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#### Efficiency Data

| Recipe               | Source      | No. wfrs | Efficiency % | FF %   | lsc, A | Voc, V | Rshunt  | Rseries  | P, watt |
|----------------------|-------------|----------|--------------|--------|--------|--------|---------|----------|---------|
| NPC                  | S2          | 10       | 17.15        | 78.454 | 8.44   | 0.619  | 166.158 | 0.0028   | 4.099   |
| NPC                  | S2          | 10       | 17.15        | 78.443 | 8.449  | 0.618  | 174.829 | 0.0026   | 4.098   |
| NPC                  | S2          | 10       | 16.92        | 77.495 | 8.465  | 0.616  | 175.268 | 0.0026   | 4.044   |
| NPC                  | S2          | 10       | 17.1         | 78.267 | 8.44   | 0.618  | 158.213 | 0.0032   | 4.086   |
| NPC                  | S2          | 60       | 17.11        | 78.464 | 8.443  | 0.618  | 160.928 | 0.0026   | 4.09    |
| 1                    | S3          | 100      | 16.94        | 77.853 | 8.421  | 0.617  | 175.074 | 0.0026   | 4.048   |
| 2                    | S4          | 99       | 16.97        | 77.897 | 8.402  | 0.619  | 187.697 | 0.0029   | 4.054   |
| 3                    | S5          | 88       | 16.84        | 76.872 | 8.496  | 0.616  | 196.945 | 0.0026   | 4.023   |
| NPC                  | X2          | 10       | 17.06        | 77.404 | 8.54   | 0.617  | 159.078 | 0.0028   | 4.077   |
| NPC                  | X2          | 69       | 17.21        | 78.056 | 8.531  | 0.618  | 172.942 | 0.003    | 4.113   |
| NPC                  | X2          | 10       | 17.15        | 77.759 | 8.529  | 0.618  | 165.69  | 0.0036   | 4.098   |
| NPC                  | X2          | 10       | 16.98        | 77.142 | 8.518  | 0.618  | 163.08  | 0.0044   | 4.058   |
| 1                    | X3          | 101      | 16.78        | 78.29  | 8.307  | 0.617  | 167.094 | 0.0061   | 4.01    |
| 2                    | X4          | 100      | 16.77        | 77.251 | 8.392  | 0.618  | 151.986 | 0.0037   | 4.007   |
| 3                    | X5          | 87       | 16.95        | 77.904 | 8.43   | 0.617  | 156.205 | 0.0031   | 4.051   |
|                      |             |          |              |        |        |        |         |          |         |
| Average, Round 1     |             | 774      | 16.94        | 77.797 | 8.426  | 0.618  | 170.927 | 0.0034   | 4.048   |
| Round 2, 3 splits, 2 | 2 suppliers | 142      | 16.93        | 78     | 8.463  | 0.613  | 153.1   | 0.002485 | 4.046   |

FF and lsc are good and show stable process

Voc may need to increase and indicate material bulk or surface quality issues



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#### Pyramid Sizes and Distribution



or without post texturization chemical polishing



Textured wafers with different average pyramid sizes:

- a) 1-3 µm height pyramids
- b) 5-15 µm height pyramids
- c) 10-25 µm height pyramids

Small pyramids present a challenge to film deposition for HIT cells: Local epitaxial growth and chemical contamination potential



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L. Fesquet, et al, IEEE PVSEC 34 A 18106 akrionsystems.com wwk.com

#### High Efficiency Cells and Effect of Surface Preparation



#### SEM picture of textured c-Si wafer (5-15 µm pyramids) a) before, and b) after post-texturization chemical polishing



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### Importance of Pre-Cleaning



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# Reflectance Non-Uniformity by Surface Contamination (1)



Pre-cleaning can reduce reflectance non-uniformity by removing surface contaminants



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#### Texture Morphology of Contaminated Area (1)



#### Contaminated areas induce smaller pyramids

Areas with smaller pyramids show lower reflectance



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#### **Texturization Analysis**



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### Confocal 3D Laser vs. SEM Analysis



- Critical and careful examination is still required
- Confocal is a quick and easier tool than SEM.
   Yet, it does not reveal the whole picture
- Sophisticated image analysis is typically needed



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#### Wafer Texturing Comparison



- ~10 µm texture
- Moderate Uniformity
- No Non-Etched Areas



- Supplier-A
- ∼ ≤10  $\mu$ m texture
- High Uniformity
- No Non-Etched
  Areas





- Supplier-B ~≤10 µm texture • Moderate Uniformity
- No Non-Etched Areas

## Small variation in texturization patterns but all meet post-processing carrier lifetime requirements



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#### Process Stability vs. Si Content

 $Si + 2KOH + H_2O \rightarrow K_2SiO_3 + 2H_2$ 





Silicates concentration in the bath must be controlled to obtain a stable ER i.e. feed/bleed and chemicals concentration control

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#### **IPA Replacement**



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#### IPA Replacement (SCD2000)





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## IPA Replacement (SCD2000)

#### Efficiency data being generated

| Test #           | Date           | Chemistry    | Sample ID    | Pro      | Post   | Weight Loss | Si Loss / side | Reflectance @ 950nm |         | Remarks    |
|------------------|----------------|--------------|--------------|----------|--------|-------------|----------------|---------------------|---------|------------|
|                  |                | Chemistry    |              | T IC     | 1 031  | (g)         | (um)           | side A              | side B  |            |
| 1                | 5/19/10 2:58pm | KOH/SCD-2000 | SCD Verify-1 | 10.394   | 9.2649 | 1.1291      | 10.6           | 10.231%             | 10.191% | Fresh      |
|                  |                |              | SV2-1        | 10.9021  | 9.8785 | 1.0236      | 9.6            | 10.531%             | 10.677% | Bath       |
| 2 5/19/10 4:08pm | KOH/SCD-2000   | SV2-25       | 10.4618      | 9.4216   | 1.0402 | 9.7         | 10.545%        | 10.827%             |         |            |
|                  |                | SV2-50       | 10.5492      | 9.5123   | 1.0369 | 9.7         | 10.643%        | 10.619%             |         |            |
| 3 5/20/10 9:40am |                |              | SV2-51       | 10.5447  | 9.4603 | 1.0844      | 10.2           | 10.553%             | 10.463% | Fresh      |
|                  | KOH/SCD-2000   | SV2-75       | 10.5947      | 9.5025   | 1.0922 | 10.2        | 10.816%        | 10.446%             | Bath    |            |
|                  |                | SV2-100      | 10.562       | 9.472    | 1.0900 | 10.2        | 10.595%        | 10.759%             |         |            |
| 4 5/20/10 1:42pm |                |              | SV2-101      | 10.4744  | 9.0943 | 1.3801      | 12.9           | 10.334%             | 10.401% | Fresh      |
|                  | KOH/SCD-2000   | SV2-120      | 10.5106      | 9.0955   | 1.4151 | 13.3        | 13.649%        | 10.703%             | Bath    |            |
|                  |                | SV2-140      | 10.4491      | 9.0404   | 1.4087 | 13.2        | 12.414%        | 10.920%             |         |            |
| 5 5/24/10 4:05pm | 5/24/10 4:05pm |              | SCD Vorify 2 | 10 / 939 | 0 017  | 1 6669      | 15.6           | 0.126%              | 0 1210/ | Fresh      |
|                  | KUI //FA       | SCD veniy-z  | 10.4030      | 0.017    | 1.0000 | 15.0        | 9.12070        | 9.13170             | Bath    |            |
| 6 5/24/10        |                | KOH/IPA      | SV2-141      | 10.5396  | 9.267  | 1.2726      | 11.9           | 9.436%              | 9.199%  | Adjusted   |
|                  | 5/24/10 6:25pm |              | SV2-153      | 10.4582  | 9.0475 | 1.4107      | 13.2           | 9.374%              | 9.188%  | by spiking |
|                  |                |              | SV2-165      | 10.6532  | 9.3138 | 1.3394      | 12.6           | 9.498%              | 9.202%  |            |

- Reflectance is typically higher in surfactant compared to BKM
- Encouraging results but uniformity needs to be improved (scatter between small and large pyramids)
- Effect of surfactant on etch mechanism yet to be understood. Pyramids are not as sharp compared to BKM results



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#### **Chemical Concentration Control** for Solar Applications



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#### Akrion Systems' ICE-1<sup>™</sup> Benefits

ICE technology accurately predicts the concentration of chemicals and produces the desired process results e.g. texturization pattern

- The technology is effective in <u>reducing the COO</u> and overall cost of manufacturing by extending the bath lives
- The technology <u>extends up-time and overall utilization</u> of the tool and hence lowers cost of manufacturing
- The technology <u>reduces the time for field installation</u> by eliminating the time and resources required to dial-in the right chemicals' concentration over many hours and days. With a closed loop concentration control, this process will no longer require many iterations and tedious work until the results are achieved
- The technology significantly reduces rework and wafer mis-processing



#### ICE for Solar (NIR Sensor)





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#### COO Modeling





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#### Cost of Ownership Algorithm

$$COO = \frac{F\$ + (R\$ + Y\$)}{L x T x Y x U}$$

F\$ = Fixed Costs R\$ = Recurring Costs

- Y\$ = Yield Costs L = Tool Life
- T = Throughput Y = Composite Yield

## U = Utilization



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#### Pareto of Cost Drivers

- Top 3 cost drivers account for 90% of COO
- Examine the cost sensitivities to input parameters that drive Labor (40%), Depreciation (30%), and Material (20%) costs

| Cost Drivers per Good Wafer Equivalent |         |         |
|--|---------|---------|
| Labor                                  | 0.02940 | Dollars |
| Depreciation                           | 0.02154 | Dollars |
| Material/Consumables                   | 0.01491 | Dollars |
| Maintenance                            | 0.00338 | Dollars |
| Floor Space Costs                      | 0.00167 | Dollars |
| Support Personnel                      | 0.00134 | Dollars |
| Scrap                                  | 0.00120 | Dollars |
| Training                               | 0.00010 | Dollars |
| System Qualification Costs             | 0.00009 | Dollars |
| ESH Preparation and Permits            | 0.00000 | Dollars |
| Moves And Rearrangements               | 0.00000 | Dollars |
| Other Materials                        | 0.00000 | Dollars |
| Other Support Services                 | 0.00000 | Dollars |



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### Labor Sensitivity

Labor content represents 40% of the COO for these integrated process steps

- Labor is defined as direct operator labor
  - Model is based on one operator overseeing one machine
- Since these are highly automated machines with sufficient throughput to support a 30 MW line, it is not likely that the factory would be significantly larger in order to allow for further amortization of labor content
- However, the next slide does examine COO sensitivity to labor content should such opportunities present themselves



### Labor Sensitivity (continued)



#### Move from 1-2 machines per operator decreases COO by 20%



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#### Depreciation Sensitivity

#### Two possible impacts on depreciation costs

- Purchase price
- Throughput



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#### Purchase Price Sensitivity



#### The COO impact is approximately 6% per \$300,000 (20%) change in purchase price



#### Throughput Sensitivity



7% change in COO for a 100wph change around the nominal value It is assumed that variable costs per cell do not increase with throughput

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#### Supplies and Consumables

- One of the issues in defining a sensitivity analysis for any of the above items is their interrelationship with other factors
  - Increasing or decreasing KOH concentrations will have an impact not only on throughput, but also caustic drain costs
  - IPA is volatile at typical process temperatures (up to 90°C) and that has a significant impact not only on IPA refresh but also exhaust volumes, which require oxidation
  - It is less likely that KOH concentrations can be significantly impacted due to the fact that it is the etchant, it is more likely that IPA can be impacted since it is acting as a wetting agent

| Supply/Consumable             | Annual Cost per System |
|-------------------------------|------------------------|
| DI Water                      | \$ 16,046              |
| HCI                           | \$ 433                 |
| HF                            | \$ 518                 |
| IPA                           | \$ 20,131              |
| КОН                           | \$ 28,966              |
| CDA                           | \$ 234                 |
| H <sub>2</sub> O <sub>2</sub> | \$ 1,638               |
| Acid Drain                    | \$ 7,127               |
| Caustic Drain                 | \$ 7,729               |
| Exhaust                       | \$ 20,741              |



#### IPA Usage Sensitivity



## IPA, surprisingly, is not a major cost driver even as the industry moves to eliminate its usage



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### IPA Usage Sensitivity continued

Reducing the volume of IPA or even eliminating it remains an industry concern

- Studies show that alternatives can be found although no solution has been endorsed by manufcaturing sites as of yet
- If we assume that an alternative surfactant can be used at:
  - 50% the cost of IPA
  - 10% the volume (with a corresponding 90% reduction in exhaust)
  - We calculate a COO of \$0.07035 or a reduction of 4.5%
- Again, unless there are environmental or other strategic reasons, it appears replacement of a relatively inexpensive chemical like IPA is not a highly leveraged investment



#### Feed and Bleed COO

- Frequently, when using COO a proposed improvement results in an impact on multiple inputs
- For example, a feed and bleed approach to refreshing chemistry results in longer bath life and, hence, higher tool utilization
- The benefits of this approach can be quickly analyzed as follows:
  - A typical tool uses a bath for about 8-10 hours at the end of which the bath has to be changed
  - The time needed for the change out is approximately 1-2 hours, including the time needed to verify the right chemical concentration and the desired etch rate
  - A typical feed and bleed rate is to add additional chemicals of about 50% of the initial mix
  - This extends bath life and reduces chemical consumption

COO calculations indicates that a feed and bleed system reduces the cost per wafer by nearly 16%



#### Conclusions

- Surface prep techniques will become more critical to obtain high efficiency solar cells and more robust processing
- Current POR and experience reasons may not be enough to understand effect of contamination. In-depth analysis to surface contamination and texturization patterns is indeed needed
- Industry continues to find ways to reduce cost of manufacturing e.g. IPA replacements, thinner wafers, automation, and higher throughput
- COO calculations indicates that a feed and bleed system significantly reduces the cost per wafer

