"Plasma CVD passivation; Key to high efficiency silicon solar cells",

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Summary:

• Remarkable efficiency improvements of silicon solar cells have been realized over the last 25 years.

• The key technical developments are:
  – Improvements in silicon quality for both mono and multi-crystalline type wafers.
  – Development of new silver pastes
  – Development of new fine-line capable SS screens
  – Development of p and n type passivating dielectrics.

• Coupled with new cells designs, the above technologies have allowed for interactive improvements of the solar cell performance
Silicon Solar Cell Efficiency Improvements

There have been large improvements of silicon solar cell commercial efficiencies since 1990.

Surface passivation using plasma deposition of dielectric layers has played a large role in driving and enabling the large efficiency improvements.

Figure 3. Evolution of crystalline and multicrystalline silicon solar cell efficiency

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Silver Paste and Diffusion Optimization

- Improved silver pastes have dropped the typical contact resistance about 4X.
- This allowed for retuning the POCl3 diffusion process to higher sheet resistance and thinner junctions (better cell voltage and current).
- This also allows for the Si3N4 anti-reflection coating passivating coating to be more effective. The surface passivation quality is directly related the surface doping concentration.
Silver Paste and New Screen Technology

Narrow Finger Designs

• With new screen technology with small diameter wire with the new silver paste formulation can be printed with 45-55um finger widths.
• This reduces the shadowing of the contacts and reduces the area of the contacts making the surface passivation more effective.
Anti-Reflective Coatings and Passivation

- These can be used for both the front and back of the cell depending on the bulk silicon dopant type.

- In reality these two issues have separate functions and have very different requirements.

- In prevalent cell process flows these two steps have been combined for many reasons – highest among them is cost and process simplicity.

- Using suitable dielectrics researcher have found suitable materials that have the correct index of refraction, low light absorption and a fixed charge for surface passivation requirements.
Requirements for a Functional Anti-Reflection Layers

- All light incident on a solar cell DOES NOT get converted to carriers do mainly to a small number of loss mechanisms which can be devastating to cell performance.

- Anti-Reflective Coatings are employed to minimize the reflective losses which can exceed 30% of the incident energy depending on process.

- Typically these layers are on the sun side of the cells, but new bifacial cell approaches require ARC tuning on both sides.

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Requirements for Materials for Surface Passivation

n-surface passivation, fixed + charge
Holes are driven away, recombination reduced

n-surface passivation, fixed - charge
Holes attracted, recombination/inversion enhanced

On the p-type surface a negative fixed charge is desired in order to drive away electrons and avoid inversion.
Surface Passivation and the Effect of Hydrogen

- With high quality material (very low defect single crystal) the lifetimes achievable in a solar cell are often limited by the surface passivation.
- The addition of hydrogen to the films has a tendency to passivate the dangling bonds. These effects have been shown to be stable for most types of defects.
ARC and Passivation: Material Choices

- Several dielectrics fit the requirements;
  - the Index of refraction in the range of 1.7-2.1
  - low absorption of light between 400-1000nm,
  - A substantial fixed charge that is positive or negative
  - Can be deposited by techniques that generate a significant amount of hydrogen that improve surface passivation even more.

- Silicon Nitride (Si₃N₄) is a typical choice for a positively charged dielectric for use on n-type doped silicon (front or back).
  - The index can be easily adjusted to 19.5-2.05 by adjusting the Si/N ratio.
  - Using SiH₄/NH₃ or a SiH₄/N₂ gas mix one can obtain films with 2-5% elemental hydrogen.

- Aluminum Oxide (Al₂O) is a typical choice for a negatively charged dielectric for use on p-type doped silicon (front or back).
  - The index can be adjusted to 1.6-1.7 range. Typically a Si₃N₄ cap is used.
  - Using TMA/H₂O/N₂ or TMA, N₂O gas mixes can obtain films with 2-5% elemental hydrogen.
Si$_x$N$_y$H$_z$ and Al$_x$O$_y$H$_z$ Process tool designs/methodologies

- **Indirect Plasma processes**
  - Tools/Processes designed such that the arriving reactant species are generated multiple mean free paths away from the substrate (outside of the plasma)
  - Microwave (MW), inductively coupled, remote plasma PECVD (Roth and Rau)
  - Typically SiN films use SiH4 and N2 / AlO films use TMA (or similar) and N2O reactants. PECVD (Roth and Rau)

![Diagram of MW antenna within Quartz tube, high density plasma region, substrates linearly transported in low plasma density region]
Typical Solar Process tool designs/methodologies

- **Direct Plasma processes**
  - **Low Frequency**, parallel plate (capacitively coupled)/tube furnace type direct plasma PECVD reactors (Centrotherm/ 48th Institute)
  - Parallel plate, showerhead/subsector, **High Frequency** (capacitively coupled), direct plasma (Avanti, Jusung)

![Quartz Tube Furnace Diagram]

- Process Gases supplied through showerhead
- RF Electrodes, Si Wafers affixed
- Capacitively Coupled Plasma
- Substrates (Si within plasma region)
- Grounded Subsector with integrated PID controlled resistive heaters

**Typical Solar Process tool designs/methodologies**
Typical Production Scale Passivation Equipment
QUESTIONS?