Challenges of Low-Defect Thin Film Deposition for High Efficiency Solar Cells

Dr. M. H. Weng

Medical Devices & Opto-Electronics Equipment Department, Metal Industries R&D Center (MIRDC)
Outlines

• Current status of solar cell development
• Requirement of passivation for high efficiency solar cell
• Methods to achieve the high quality a-Si:H passivating film
• Why VHF PECVD is desired
• Design issues of VHF PECVD
• Quality of a-Si:H film by VHF PECVD
• Summary
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...
Developing efficiencies of solar cells in past 30 years

PERC: passivated emitter rear cell
HIT: heterojunction with intrinsic thin-layer

Diffused junction cell

PERC
What is different between the diffused junction cell and HIT cell?

<table>
<thead>
<tr>
<th></th>
<th>Diffused junction cell</th>
<th>PERC cell</th>
<th>HIT cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>17~18%</td>
<td>20~22%</td>
<td>22~24%</td>
</tr>
<tr>
<td>Wafer</td>
<td>Multicrystal P-type</td>
<td>Monocrystal P-type</td>
<td>Monocrystal N-type</td>
</tr>
<tr>
<td>P/N formation</td>
<td>Simple/Diffusion</td>
<td>Simole/Diffusion</td>
<td>PECVD deposition</td>
</tr>
<tr>
<td>LID/PID</td>
<td>yes</td>
<td>Might be</td>
<td>no</td>
</tr>
<tr>
<td>Vacuum dependent</td>
<td>Less</td>
<td>some (ALD might be needed)</td>
<td>Highly dependent</td>
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What is different between the silicon thin film cell and HIT cell?

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<th>HIT cell</th>
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<tr>
<td>Efficiency</td>
<td>Not high enough 6<del>8% (Tandem 10</del>12%)</td>
<td>High efficiency 22~24%</td>
</tr>
<tr>
<td>Substrate</td>
<td>glass</td>
<td>Monocrystal N-type</td>
</tr>
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<td>P/N formation</td>
<td>p/i/n by PECVD deposition</td>
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<tr>
<td>Cost</td>
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Advantages of HIT solar cell

- **Low temperature fabrication:**
  - process at low temperature (200 °C), which reduces the wafer breakage and the energy necessary to invest in the fabrication process.

- **Low temperature coefficient:**
  - as compared to the standard c-Si solar cells, i.e. a reduction from $-0.5%/°C$ to $-0.25%/°C$.

- **Low illumination absorption property:**
  - as compared to the standard c-Si solar cells, i.e. an increase around 10%.

- Therefore, an ultra-low **levelized cost of electricity (LCOE)** is anticipated with the expected high energy yield.

Ref.: Recent Technological Progress of High-efficiency HIT Solar Cells, Sanyo Electric. Co., Ltd.
Will HIT cell be next generation mainstream?

- The heterojunction silicon wafer solar cell concept is one of the promising candidates with cell efficiencies exceeding 24%.
- Key processing challenges, including or the need for high-quality surface cleaning and unstable processes for contact formation, can be turned into a competitive advantage of HIT cell that are not easy to copy.
- The big challenge for HIT cells is to enter into the market with high enough volume to surpass the existing players.
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HIT solar cell efficiency revolution

Sanyo’s HIT development schedule

Kamlesh Patel et al., INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH, Vol. 4, No. 2, 2014
Effect of interface defects in HIT

- Lower the interface defect -> Increase the carrier life time -> Increase the diffusion length -> Lower the reverse saturation current -> Improve the open voltage

- It was suggested that a high \(10^{-6} \, \text{A/cm}^2\) reverse saturation current observed at the c-Si/a-Si hetero interface in comparison to c-Si/c-Si homo junction, may be because of high interface defect density.
Correlation of Interface defect density I layer with solar cell performance

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<tr>
<th>Dit (cm$^{-2}$ eV$^{-1}$)</th>
<th>Simulated $t_{\text{eff}}$ (nms) @ $10^{15}$ cm$^{-3}$</th>
<th>$J_{\text{SC}}$ (mA/cm$^2$)</th>
<th>$V_{\text{OC}}$ (V)</th>
<th>FF (%)</th>
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Influence of a-Si:H(i)/c-Si interface defect density Dit on simulated effective carrier lifetime curves and standard heterojunction solar cell performance. Improving Dit directly improves the one-sun solar cell performance.

Variation of I layer thickness for (a) $V_{\text{OC}}$, (b) $J_{\text{SC}}$, (c) FF, and (d) Efficiency

Yutaka hayashi, IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 3, no. 4, october 2013
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High quality passivating a-Si:H film

1. **Damage of the c-Si surface** during deposition has to be limited as much as possible.
2. **Passivating intrinsic a-Si:H layers** are deposited in plasma regimes close to the *amorphous-to-(micro-)crystalline transition* for the device-grade, without epitaxial growth to have high passivation quality.
3. Such layers are generally **hydrogen rich**, and have a low bulk defect density due to a hydrogen bonding configuration dominated by monohydrides (Si–H).
4. These regimes can be produced either
   - with SiH4 plasmas highly diluted with H2
   - with highly depleted pure SiH4 plasmas.

Descoeudres, A., Appl. Phys. Lett. 97, 2010
H2 plasmas treatment for passivating a-Si:H film

A possible method to further approach the transition without epitaxial growth on the c-Si surface is the use of H2 plasma treatments, either during or after the a-Si:H deposition. It is observed:

- An increase of disorder in the silicon network or improved film quality, leading to better film stability with regard to light-induced degradation,
- an increase in the hydrogen content, widening the bandgap.

Hydrogen diffuses from the bulk of the very thin a-Si:H layer (around 5~7 nm) toward the a-Si:H/c-Si interface, efficiently passivating silicon dangling bonds at the interface.

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Why VHF PECVD is desired

Common RF PECVD has an operating frequency of 13.56 MHz and has high ion bombardment on the substrate during deposition. **Effect of ion bombardment** might create defects in the a-Si:H matrix and reduce the **a-Si:H/c-Si interface passivation**, thus limiting the effect of the surface passivation.

**VHF PECVD** with an operating frequency of 40.68 MHz or 70 MHz has two main advantages over the typical one:
1. **higher deposition rates** because of increased dissociation of silane molecules,
2. **lower ion bombardment** on the substrate because of lower sheath voltages.
Standing wave effect

Standing wave issue appeared in large area VHF PECVD thus causes deposited film inhomogeneity in large-area (>1 m²) PECVD systems.

It is thus a problem to suppress the standing wave issue appeared in large area VHF PECVD.
Ladder type electrode by MHI

Patent number 7141516, November 28, 2006

Inventors: Kawamura; Keisuke (Nagasaki, JP), Yamada; Akira (Nagasaki, JP), Mashima; Hiroshi (Nagasaki, JP), Takeuchi; Yoshiaki (Nagasaki, JP)
Assignee: Mitsubishi Heavy Industries, Ltd. (Tokyo, JP)

Filed: October 1, 2003

Ladder type electrode
Size: 1.25 x 1.55 m
for glass = 1.1 x 1.4 m

Normalized $\alpha$-Si:H film thickness uniformity deposited on a 1.1x1.2 m$^2$ substrate placed on the ground floor of a KAI-1200 asymmetric reactor at 40.7 MHz excitation frequency, 0.5 slm of silane and 0.5 slm of hydrogen at 0.5 mbar, and 400 W input power.

Antenna type electrode by UHI

Homogeneous a-Si:H depositions using VHF PECVD have already been demonstrated in industrial systems in past 8 years, benefited from the knowledge gained in recent years by the thin-film transistor and thin-film silicon solar cell industries. The cost of apparatus shall be much further reduced.
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Our self developed VHF PECVD

In-Line VHF 40.68MHz PECVD Development

23% High efficiency

Flow design

RF matching

In-line Chamber

Vacuum components design

Interface software
Key components in chamber for VHF PECVD

Coating substrate: change the input impedance for RF power
1. glass (size: G1~G11)
2. wafer (size: 4 ~ 8 inch)

RF generator
Function: supplying power to ignite plasma
Function: matching the impedance of power generator and vacuum chamber

Matching box
Function: changing electric field magnitude (V/m) with different geometry
Function: Value of electric field distribution and chamber input impedance under different RF feeding location
Function: Effect of electric field distribution for coating uniformity

RF electrode and gas showerhead
Plasma
Lower electrode
Why VHF PECVD is expensive

One reason is that too many consumer RF designs such as RF electrode, RF feeding, RF matching and RF power delivery shall be considered.
Coating geometry is the same as the simulated result of E field distribution by HFSS.
In-Line VHF 40.68MHz PECVD totally developed by MIRDC

- In line process
- Integration ability
- Turnkey Vacuum Process Systems
- Cost down effectively
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Low defect solution of a-Si:H/c-Si wafer for HIT cell in MIRDC

To provide a research processing platform for HIT cell with cost effective VHF PECVD (reactive plasma deposition), and to expand them to industrial use.
Uniformity & stability analysis of a-Si:H film deposited by self-developed VHF PECVD

- Due to standing wave effect of VHF-PECVD, electrode feed is designed based on precisely electric field simulation, and stability and uniformity are two important index.
- Process stability is verified on Electrode dimension of 30x30 cm², by run to run, day to day, week to week, month to month, with non-uniformality around 4.1~4.2%.

<table>
<thead>
<tr>
<th>Item</th>
<th>Dep. rate</th>
<th>Non-uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run to run</td>
<td>1.11Å/s</td>
<td>4.1%</td>
</tr>
<tr>
<td>Day to day</td>
<td>0.92Å/s</td>
<td>4.1%</td>
</tr>
<tr>
<td>Week to week</td>
<td>0.77Å/s</td>
<td>4.2%</td>
</tr>
<tr>
<td>Month to month</td>
<td>0.90Å/s</td>
<td>4.1%</td>
</tr>
<tr>
<td></td>
<td>0.88Å/s</td>
<td>4.2%</td>
</tr>
</tbody>
</table>
A Si:H thin film deposited by self-developed VHF PECVD

- Deposition rates: 0.4~1.0 Å/s, are increased with substrate temperature and power density increasing.
- Optical bandgap: 1.58eV~1.83eV, can be adjusted by substrate temperature and power density.
- Absorption coefficient: $9 \times 10^4$ to $3 \times 10^5$ cm$^{-1}$ at 550 nm
Interface defect density analysis

- Interface defect density can be obtained by means of the C-V measurement with MIS structure ((Al/Si film/Si wafer/ Al)).

\[
D_{it} = \frac{C_{ox}}{q} \left( \frac{d \Psi_s}{d V_g} \right)^{-1} - 1 - \frac{C_{dep}(\Psi_s)}{q}
\]

- \( D_{it} \): Defect density
- \( \Psi_s \): surface potential
- \( V_g \): gate voltage
- \( C_{dep} \): depletion capacitor

MIS device structure

CV measurement platform
Interface defect density analysis for VHF PECVD

- The a-Si:H our 40.68 MHz PECVD a-Si:H film with Dit=10^{11}~10^{12}\text{eV}^{-1}\text{cm}^{-2}, optimum value is 2.9\times10^{11}\text{eV}^{-1}\text{cm}^{-2}, mush lower than that produced by 13.56 MHz PECVD.
- It is believed that the low ion bombardment on the substrate of VHF PECVD reduces the interface defects of a-Si:H/c-Si wafer.

<table>
<thead>
<tr>
<th>Sample process parameters</th>
<th>Interface Defect density (Dit) eV^{-1}\text{cm}^{-2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.56 MHz PECVD</td>
<td>1.4\times10^{13}</td>
</tr>
<tr>
<td>40.68MHz PEVCD</td>
<td></td>
</tr>
<tr>
<td>150°C-30mW-800mtorr</td>
<td>1.4\times10^{12}</td>
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<tr>
<td>150°C-60mW-800mtorr</td>
<td>2.9\times10^{11}</td>
</tr>
<tr>
<td>250°C-30mW-800mtorr</td>
<td>1.4\times10^{12}</td>
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<tr>
<td>250°C-40mW-800mtorr</td>
<td>4.4\times10^{12}</td>
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TEM image

Raman analysis
a-Si : H thin film passivation for C-Si wafer

- Substrate: flat substrate
- PECVD parameters:
  1. Substrate temperature: 250°C
  2. Power density: 50mW/cm²
  3. Working pressure: 800 mtorr
  4. H₂/SiH₄ ratio = 19
- Dit: 3.1x10¹¹ eV⁻¹ cm⁻²
- Lifetime: 506 μs
- Implied Voc = 0.67V

<table>
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<tr>
<th>Dit (cm² eV⁻¹)</th>
<th>Simulated nₑff (m/s) @ 10¹³ cm⁻³</th>
<th>JSC (mA/cm²)</th>
<th>Voc (V)</th>
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Ling zhi peng, design, solar cells, (2014)
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Summary (1/2)

It is believed that silicon wafer-based solar cells will prolong well for years to come. a-Si:H passivates c-Si surfaces very well with chemical passivation because of hydrogenation of surface states. Plasma-enhanced chemical vapor deposition (PECVD) is the most usable method to deposit these very thin layers by mixing silane (SiH4) and hydrogen (H2). The preferable passivation quality is in regimes close to the amorphous-to-crystalline transition without epitaxial growth. The effect of ion bombardment during deposition might create defects in the a-Si:H matrix and reduce the a-Si:H/c-Si interface passivation, thus limiting the effect of the surface passivation.
VHF PECVD with an operating frequency of 40.68 MHz or 70 MHz has main advantage over the typical one: lower ion bombardment on the substrate because of lower sheath voltages, thus reducing the interface defects. The standing wave of the larger area VHF PECVD shall be considered and moreover the cost of VHF PECVD shall be further reduced.

The high quality thin films of hydrogenated amorphous silicon (a-Si:H) deposited by self-developed VHF PECVD have been shown. The film quality have been proven to achieve the regimes close to the amorphous-to-crystalline and the passivation quality have been verified to obtain a enough high carrier life time.
Team members
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Dr. Min-Hang Weng, mhweng@mail.mirdc.org.tw

Thanks for your attention!