Directed Energy

Definition: Directing energy or mass to specific areas on solar cells to produce an effect.
This compares with exposing solar cells to a thermal or mass flow environment to produce an effect.

Examples of environmental exposures for cell processing include:
- Thermal diffusion, furnace anneal
- Metal sintering, cleaning, etching
- CVD, belt furnace operations

The above might be considered as first-generation processing.

Examples of directed-energy processing include:
- Ion implantation: Pulsed electron beam anneal (PEBA)
  Pulsed excimer laser anneal (PELA)
- Laser cutting
- Laser assisted metallization
- Laser-assisted deposition
- Laser drive-in of liquid dopants
- Microwave-enhanced chemical vapor deposition (MECVD)
- Rapid thermal processing (RTP)

The above might be considered as second-generation processing.
PLenary Sessions

Advantages of Directed Energy and Mass Processing

- Surface heating
  - Allows bulk temperature of cell to remain near ambient
  - Thereby preserving bulk lifetime; (laser processing, heat lamps)
- Better process control:
  Tighter control of process parameters should yield better control of
  junction profiles, junction depths, metal sintering, etc.
- Lower process energy costs:
  - Energy is used directly on the cell instead of into the total cell
    environment
- Less working space:
  - e.g., laser space versus furnace space
- Should produce higher-efficiency cells at lower costs

Disadvantages of directed energy and mass processing

- High throughput not yet demonstrated
- High equipment costs and maintenance costs. Reliability not yet demonstrated

Directed-Energy Contracts

DOE/FSA has funded the following directed-energy/mass
contracts in FY/84/85; Earlier contracts included ion
implantation, pulsed electron beam annealing

- Pulsed excimer laser anneal: special DOE funding, competitively awarded to Spire Corporation, No. 956797 and ARCO Solar, Inc., No. 956831; ARCO also investigating laser-assisted metal and film deposition on No. 956831.
- Laser-assisted metallization: Westinghouse, No. 956615
- Laser drive-in of liquid dopants: Westinghouse, No. 956616 (rapid thermal processing also investigated)
- Microwave-enhanced chemical vapor deposition (MECVD), Superwave Technology, Inc., No. 956828
Results of Excimer Laser Annealing Studies

- Textured surfaces not ideal for laser annealing; difficult to control surface melting conditions. Stress buildup after annealing decreased Voc substantially.

- Surface cleanliness affects cell performance after laser anneal much more than it affects cell performance after thermal anneal. Particles left on surface may form nucleation sites during laser anneal. Preferential etching confirmed this.

- Optimum laser density determined to be between 1.4 J/cm\(^2\) and 1.6 J/cm\(^2\). Energy densities outside these limits were characterized by poor fill factors and low Voc.

- Laser parameters that produced the best cells were: 1.4 to 1.6 J/cm\(^2\), 50% overlap, 25 nanoseconds pulse duration, 1 mm\(^2\) spot size.

- Ion implantation parameters that produced the best cells were: 5 keV implant energy, 1 to 2 x 10\(^{15}\) atoms/cm\(^2\) fluence.

Excimer Laser Annealing

- Economic analysis
  - Assumptions:
    - 1985 dollars
    - 80% up time
    - 0.886 yield
    - 600 wafers/hour throughput
    - 1850 hours/shift/year
    - 3 shifts
    - 100 mm diameter, as-cut, silicon wafers

<table>
<thead>
<tr>
<th>Module Efficiency, %</th>
<th>PELA, $/watt</th>
<th>Diffusion, $/watt</th>
<th>Output, MW/yr</th>
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<tbody>
<tr>
<td>12</td>
<td>6.85</td>
<td>6.79</td>
<td>2.22</td>
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<td>13</td>
<td>6.32</td>
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<tr>
<td>14</td>
<td>5.87</td>
<td>5.87</td>
<td>2.69</td>
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<tr>
<td>15</td>
<td>5.48</td>
<td>5.44</td>
<td>2.78</td>
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<tr>
<td>16</td>
<td>5.14</td>
<td>5.10</td>
<td>2.96</td>
</tr>
</tbody>
</table>

- Cell fabrication
  - Best 2 x 2 cm cell: 15.5%
Excimer Laser-Assisted Metal Deposition

Surface passivation

Goal: To deactivate the silicon dangling bonds at the surface

\[ V_{oc} \propto \text{LN} \frac{1}{U} \]

where \( U \) = rate of recombination

Conventional method: thermal oxide

Propose: Laser-assisted photochemical dissociation of oxide

\[ \text{SiH}_4 + \text{N}_2\text{O} + h\nu \ (193 \text{ nm}) \rightarrow \text{SiO}_2 + \text{products} \]

Fine grid-line metallization

Goal: Laser-assisted metal deposition; eliminate "wet" steps in photolithography process. Process could also be applicable to thin-film solar cells

E.G. \( \text{WF}_6 + h\nu \rightarrow \text{W} + \text{PRODUCTS} \)
Excimer Laser-Assisted Film Deposition

Surface passivation (Continued)

Rate of deposition = 600-800 Å/min

Excimer Laser-Assisted Metal and Film Deposition

- Experiments have just started
- No data on metal and film deposition
Microwave-Enhanced Chemical Vapor Deposition System

Objective:
Design, fabricate and demonstrate a microwave-enhanced CVD system to show feasibility of depositing silicon nitride.

Rationale:
Microwave-enhanced chemical vapor deposition of passivation coatings has the potential advantages of:

- Higher electron plasma density ($10^{13}/\text{cm}^2$ vs $10^9/\text{cm}^2$ for RF) where $\nu_p$ is 2.45 GHz instead of 13.56 MHz
- Long lifetime in species, which allows reaction chamber and plasma generation chamber to be separated
- More control of deposition kinetics with less damage to substrate
- Controlling film gradients or doping profiles
- Lower power requirements
- Lower reactive gas consumption

Schematic of Microwave-Enhanced Chemical Vapor Deposition System
PLENARY SESSIONS

Results of Microwave-Enhanced Chemical Vapor Deposition

- Contractor effort completed
- Feasibility has been demonstrated; silicon nitride deposited using MECVD technique
- Adhesion problems noted and problem solved by substrate heating
- Film non-uniformity noted; possible solution involves hardware redesign for a more even reactant gas distribution
- Follow-on development effort desirable: funding problems

Laser-Assisted Metallization

A photolithographic system for fine line metallization employs sequential multistep process
- Spin-on photoresist
- Bake
- Expose pattern
- Develop (remove polymerized layer)
- Rinse
- Vacuum evaporate metal
- Lift-off (remove excess metal and photoresist)
- Clean

Laser-assisted metallization steps are significantly reduced
- Cover cell with metal film (spin-on, vacuum evap., etc.)
- Laser-write on metal film
- Plate-up on "written" surfaces
- Remove excess metal film
Laser Pyrolysis of Spun-on Metallo-Organic Film

SAMPLE BASE TEMPERATURE 75°C
FOCUSED LASER SPOT DECOMPOSES SPUN-ON FILM
METALLIZATION PATTERNS ARE FORMED BY DIRECTWRITING
PLENARY SESSIONS

Lighted I-V Data

<table>
<thead>
<tr>
<th>Photolithography Baseline</th>
<th>Short-Circuit Current, mA</th>
<th>Open-Circuit Voltage, V</th>
<th>Fill Factor</th>
<th>Efficiency, %</th>
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<tbody>
<tr>
<td>Best Cell</td>
<td>36.5</td>
<td>0.579</td>
<td>0.738</td>
<td>15.6</td>
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<tr>
<td>Average Cell</td>
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<td>0.569</td>
<td>0.703</td>
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<td>Worst Cell</td>
<td>30.1</td>
<td>0.566</td>
<td>0.570</td>
<td>9.7</td>
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<tr>
<td>Laser-Metallized</td>
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<tr>
<td>Best Cell</td>
<td>36.1</td>
<td>0.589</td>
<td>0.776</td>
<td>16.5</td>
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<tr>
<td>Average Cell</td>
<td>33.9</td>
<td>0.576</td>
<td>0.768</td>
<td>15.0</td>
</tr>
<tr>
<td>Worst Cell</td>
<td>32.0</td>
<td>0.571</td>
<td>0.751</td>
<td>13.7</td>
</tr>
</tbody>
</table>

• High-quality solar cells obtained by laser metallization technique: AR-coated cell efficiency = 16.7%

• IN-SITU sintering occurs during laser writing process: low series resistance obtained with no further heat treatment

• Laser processing does not degrade solar cell characteristics: high shunt resistance and low leakage currents are achieved

• Higher efficiency possible by writing finer lines and optimizing grid pattern

• Program continuing to add high efficiency processes

Excimer Laser Drive-in of Liquid Dopants (Westinghouse)

• Simultaneous drive-in of front and back junctions by thermal diffusion was unsuccessful. Cross-contamination of dopants occurred under all diffusion conditions using different diffusion masks. Cell efficiencies varied between <1% to 7%

• Investigation of laser-drive-in of liquid dopants was started

• Three sets of web strips subjected to laser drive-in tests performed by Spectra Technology, Bellevue, Washington

• No cross-contamination of dopants occurred on any laser drive-in tests

• Front-junction profile looks good. See profile figure

• Back-junction profile is not good. See profile figure

• Laser parameters for front junction: 1.5 J/cm², 25 nanoseconds pulse duration, 1 mm² spot size, 50% overlap

• Laser parameter for back junction not yet established

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\( n^+ p \) Front Junction by Excimer Laser Drive-in

\[
\begin{align*}
&\text{DISTANCE INTO CELL, } \mu \text{m} \\
&10^{19} \quad 10^{18} \quad 10^{17} \quad 10^{16} \quad 10^{15}
\end{align*}
\]

\( p^+ p \) Back Junction by Excimer Laser Drive-in

\[
\begin{align*}
&\text{DISTANCE INTO CELL, } \mu \text{m} \\
&10^{19} \quad 10^{18} \quad 10^{17} \quad 10^{16} \quad 10^{15}
\end{align*}
\]

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Results and Status of Excimer Laser
Drive-in of Liquid Dopants

- Best cells produced to date: 8% to 10% efficiency; inadequate back ohmic contact identified as cause of poor cell performance
- One final set of low-resistivity (0.4 ohm-cm) web strips to be subjected to laser drive-in tests. Back ohmic contact should be improved
- Successful demonstration of laser drive-in of liquid dopants will achieve the simultaneous junction drive-in goals
- Exploratory tests using rapid thermal processing (RTP) to simultaneously drive-in liquid dopants
- Initial results are very encouraging; 15% efficient cells produced
- Will conduct more tests to obtain statistical data
Application Potential

- Excimer laser anneal (after ion implantation)
  - Near term (<3 yr):
    Not good. Only marginally equal to thermal anneal; probably will not supplant it
  - Far term (3-15 yr):
    Fair. Has best chance if lasers are used in other parts of the process sequence

- Laser-assisted metallization (laser writing) (pyrolytic)
  - Near term (<3 yr):
    Good potential for near-term use. Eliminates photolithography; immediate cost savings
  - Far term (3-15 yr):
    Same good potential. May dominate metallization processes

- Excimer laser drive-in of liquid dopants
  - Near term (<3 yr):
    Not good. Back-junction problems, needs more test evaluation
  - Far term (3-15 yr):
    Not good. Must compete with rapid thermal processing (RTP)

- Microwave-assisted deposition (MECVD)
  - Near term (<3 yr):
    Fair. Needs more evaluation
  - Far term (3-15 yr):
    Good. Microwave-assisted techniques have good potential in other processes -i.e., baking, sintering

- Laser-assisted deposition (photolytic)
  - Near term (<3 yr):
    Cannot assess. No data available yet; may require extensive research
  - Far term (3-15 yr):
    Cannot assess. May have good potential for amorphous silicon

- Rapid Thermal Processing (RTP)
  - Near term (<3 yr):
    Good. Limited data very encouraging. Has good potential for junction formation and annealing
  - Far term (3-15 yr):
    Good. May dominate ion implantation anneal