Next Generation DuPont™ Solamet®
Metallization Paste for Ultra Fine Line

SNEC: April 2017

Qijie (QJ) Guo, Ph.D., Senior Research Investigator
DuPont Photovoltaic Solutions

For over 40 years
our material innovations have led the photovoltaics industry forward, and helped our clients transform the power of the Sun into power for us all. Today we offer a portfolio of solutions that deliver proven power and lasting value over the long term. Whatever your material needs, you can count on quality DuPont Photovoltaic Solutions to deliver the performance, efficiency and value you require, day after day after day...
DuPont™ Solamet® Technologies Drive Higher P-type Cell Efficiency

- Advancing fine line technology by paste improvements on new screen technology
- Enabling higher $R_{\text{sheet}}$ and ultra LDE by novel paste chemistry

Note: Screen opening is wide side
Solamet® Modeling Indicates >0.1% Efficiency Entitlement by Ultra Fine Line

Technical challenges from metallization paste point of view:
- Line-width control
- Finger line resistance (aspect ratio and bulk resistivity)
- Paste transfer
- Long term printability
- Contact resistivity

*Assuming PV19B solids, resistivity, using a 360.16 screen

F. Lemmi & D. Inns, DuPont SVTC
Factors that Affect Ultra Fine Line Printing

- Screen printing is commonly regarded as an art due to the multitude of factors that can affect print quality

<table>
<thead>
<tr>
<th>Key Factors:</th>
<th>Print Quality:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printing process</td>
<td>Line width</td>
</tr>
<tr>
<td>Paste formulation</td>
<td>Aspect ratio</td>
</tr>
<tr>
<td>Screen design</td>
<td>Uniformity</td>
</tr>
<tr>
<td>Wafer type</td>
<td>Line breaks</td>
</tr>
</tbody>
</table>

**DuPont Approach:** Fundamental science drives our materials innovation

1. Understand the science behind screen printing
2. Understand the complex interactions in FS Ag paste formulation and the relevant rheological properties for ultra fine line printing
Understanding the Science of Screen Printing

Innovative experimental techniques combined with mathematical modeling to identify critical rheological properties
- High speed videography to capture the various aspects of Ag paste screen printing

<table>
<thead>
<tr>
<th>Print Step</th>
<th>Time Scale</th>
<th>Est. Shear Rate</th>
<th>Key Rheological Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>&lt; 1 s</td>
<td>500 – 2,000 s(^{-1})</td>
<td>flow stress/strain, moderate shear viscosity</td>
</tr>
<tr>
<td>Printing</td>
<td>&lt; 1 s</td>
<td>1,000 – 10,000 s(^{-1})</td>
<td>flow stress/strain, high shear visc., extensional and slip visc.</td>
</tr>
<tr>
<td>Peel-off</td>
<td>~ 1-2 ms</td>
<td>100 – 300 s(^{-1})</td>
<td>Viscoelasticity, extensional and slip viscosities</td>
</tr>
<tr>
<td>Leveling</td>
<td>Long</td>
<td>0.1 – 1 s(^{-1})</td>
<td>Relaxation time, recovery time, flow stress</td>
</tr>
</tbody>
</table>

Example: Print stroke video from underneath the screen

Example: Peel-off

Paste transfer and line morphologies affected by slip and extensional viscosities

Pressure driven process
Advanced Rheological Tools to Guide Materials Innovation

Measurement challenges:
- Multiple rheological properties are critical to printing performance
- Time scale of interest is very short comparing to typical rheological measurements

Transient Responses to Shear Deformation

Time Averaged Responses

Transient Responses

Sequence of Physical Processes Formalism*

Structure breakdown and reformation times → Flooding, paste transfer, line shape

Capillary Breakup Extensional Rheometry (CaBER)

Paste A

Paste B

Slip Velocity (mm/s)

10mm/s

1mm/s

Pastes A and B:

- 220ms for Paste A
- 23ms for Paste B
- 92ms for Paste A
- 35ms for Paste B

Gao and Nettesheim, DuPont CCAS

*Rogers, 2012

Nettesheim, DuPont CCAS

Quantify the key rheological properties and unravel the complex interactions in Ag paste

Copyright © DuPont 2017. All rights reserved.
Solamet® PV20A - New Generation FS Silver for Fine Line Printing

- Superior fine line print quality on both conventional and advanced mesh technologies
- Super low contact resistivity on ultra low doped emitters by novel paste chemistry

PV20A maintains finger resistance at -3um opening by higher aspect ratios

Unlock the efficiency potential for LDE and PERC

Note: Screen opening is the wide side.
# Efficiency Optimization by Finer Line Screen

- >0.1% Efficiency gain demonstrated
- Higher Isc without FF drop while moving to finer line

### Wafer: 6” M2 Mono 90 ohm/sq

<table>
<thead>
<tr>
<th>Paste</th>
<th>Screen</th>
<th>Eff</th>
<th>Voc</th>
<th>Isc</th>
<th>FF</th>
<th>Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV20A</td>
<td>380.14.34um-110F</td>
<td>+0.12</td>
<td>0.639</td>
<td>9.311</td>
<td>80.50</td>
<td>1.59</td>
</tr>
<tr>
<td>PV20A</td>
<td>380.14.36um-105F</td>
<td>+0.06</td>
<td>0.640</td>
<td>9.299</td>
<td>80.25</td>
<td>1.72</td>
</tr>
<tr>
<td>PV20A</td>
<td>360.16.38um-105F</td>
<td>+0.04</td>
<td>0.639</td>
<td>9.290</td>
<td>80.43</td>
<td>1.62</td>
</tr>
<tr>
<td>PV19B</td>
<td>360.16.38um-105F</td>
<td>Ref</td>
<td>0.639</td>
<td>9.299</td>
<td>80.16</td>
<td>1.75</td>
</tr>
</tbody>
</table>

*Note: Screen opening is wide side.*
Lower Temperature Firing Capability for >0.1% Efficiency on PERC

- **Solamet® PV20A** delivers superior efficiency at lower firing temperatures through propriety paste chemistry
- >0.1% efficiency demonstrated in production
New generation Solamet® PV20A FS paste demonstrate +0.1% efficiency gain on p-type standard LDE and PERC cell architectures by fine line screen and novel paste chemistry.