KNOTLESS SCREEN PRINTING FOR CRYSTALLINE SILICON SOLAR CELLS

7th Workshop on Metallization Konstanz - October 23, 2017

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- Knotless Screen Features
- Knotless Screen Application Overview
- Status and Trend
- Conclusion
INTRODUCTION

KNOTLESS SCREEN PRINTING - HERAEUS 10/23/2017

Paste
- Ultra-fine line print
- Contact resistivity for ultra-fine fingers

Screen
- Mesh-emulsion screen
- Knotless screen

Printability

Printer
- Single Print
- Double Print
- Dual Print
INTRODUCTION
- EFFICIENCY GAIN FROM FINE LINE PRINTING

Δ Eta = 0.06 % from 45 μm to 30 μm for 4 BB

Remark: AR=0.4, Gaussian Finger Shape

4BB & 5BB (same coverage areas) , 30 ~ 45 μm

● BL: FW = 45 μm, 5BB, 101 FL

Δ Eta = 0.09 % from 45 μm to 30 μm for 5 BB

Optimal finger numbers for different busbar count & line shape

<table>
<thead>
<tr>
<th>Busbar numbers</th>
<th>Finger width (30 μm)</th>
<th>Finger width (35 μm)</th>
<th>Finger width (40 μm)</th>
<th>Finger width (45 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Gauss</td>
<td>146</td>
<td>131</td>
<td>122</td>
<td>113</td>
</tr>
<tr>
<td>5 Gauss</td>
<td>137</td>
<td>125</td>
<td>116</td>
<td>110</td>
</tr>
<tr>
<td>4 Rectangular</td>
<td>134</td>
<td>122</td>
<td>116</td>
<td>107</td>
</tr>
<tr>
<td>5 Rectangular</td>
<td>131</td>
<td>119</td>
<td>113</td>
<td>107</td>
</tr>
</tbody>
</table>
**INTRODUCTION**

*Knotless Screen* is a mesh-emulsion screen with 0° mesh angle (mesh angle: orientation of wire mesh to screen frame). It provides a solution for ultra fine line printing.

- **Knotless Screen**
  - 325/16/28 μm
  - 0° mesh angle, 80% open ratio
  - ‘Knot-free’, ‘Super Screen’

- **Conventional Mesh-Emulsion Screen**
  - 325/16/35 μm
  - 22.5° mesh angle, 63% open ratio
  - Knot in opening area

- **Conventional Mesh-Emulsion Screen**
  - 360/16/28 μm
  - 22.5° mesh angle, 60% open ratio
  - Knot in opening area
INTRODUCTION
- TYPE OF KNOTLESS SCREENS

**Selected Wire Removal**
- Advantages:
  - High yield ratio
- Disadvantages:
  - Fixed finger number
  - Fixed opening ratio
- 400/16, 500/16

**Normal**
- Advantages:
  - Flexible finger number
- Disadvantages:
  - Lower yield ratio – 70-80%
  - Fixed opening ratio
- 290/20, 325/16, 360/16

**Hybrid**
- Advantages:
  - Flexible finger number and opening ratio
- Disadvantages:
  - High cost
**KNOTLESS SCREEN FEATURES**

**- KNOTLESS SCREEN VS CONVENTIONAL SCREEN**

**Less Blocking, Smaller Finger Opening**

Conventional screen generally has a 22.5° mesh angle and unavoidably introduces mesh knot to finger opening area, which blocks paste transfer.

**Knotless Screen vs High Conventional Screen**

<table>
<thead>
<tr>
<th>Screen</th>
<th>Mesh Count (pcs / inch)</th>
<th>Mesh Angle</th>
<th>Knot in Opening Area</th>
<th>Typical Opening (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>290, 325, <strong>360, 380</strong>, 430, 440</td>
<td>22.5</td>
<td>YES</td>
<td>28 - 35</td>
</tr>
<tr>
<td>Knotless Screen</td>
<td>290, <strong>325</strong>, 360, 400, 500</td>
<td>0</td>
<td>NO</td>
<td>24 - <strong>27</strong></td>
</tr>
</tbody>
</table>

**Larger Screen Open Ratio of Given Mesh Count**

Open ratio is larger for knotless screen thanks to 0° mesh angle.

**Example Knotless 290/20 mesh**

\[
\text{Formula Open}\% = \frac{(a - b)^2}{a^2} \\
\text{Actual Open}\% = \frac{(a - b)^2}{a^2} = a - b \quad a^2\mu m
\]

\[
a = \frac{1}{290} = 0.003448'' \\
b = 20 \mu m = 0.0007874'' \\
\% \text{ Open} = \frac{(a-b)}{a} = 77.2 \%
\]
# KNOTLESS SCREEN FEATURES
- KNOTLESS SCREEN VS CONVENTIONAL SCREEN

## Knotless Screen Technology

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Less mesh blocking</td>
<td>• Finger shape control</td>
</tr>
<tr>
<td>• Narrower finger opening</td>
<td>• Finger-busbar collecting area breaks</td>
</tr>
<tr>
<td>• Larger open ratio of given mesh</td>
<td>• Wafer print appearance</td>
</tr>
<tr>
<td></td>
<td>• Worse transfer on DWS surface</td>
</tr>
</tbody>
</table>

## Conventional Screen Technology

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mature fabrication process</td>
<td>• Reaches its opening limit</td>
</tr>
<tr>
<td>• Easy for finger shape building – from mesh shear force &amp; pull up</td>
<td>• High-mesh screens have higher price than knotless</td>
</tr>
<tr>
<td>effect</td>
<td></td>
</tr>
</tbody>
</table>
Advantages of Knotless Screen

- Cell Efficiency gain is above \(0.05 \text{ – } 0.15\%\) absolute value over conventional screen
  - Achieved with equal or lower paste deposit with 24 - 27 \(\mu\text{m}\) screen opening
  - Achieved through higher \(\text{Isc}\) and FF
  - Without additional equipment cost
  - Mainstream knotless screen has competitive price with high mesh conventional screen

- Cell technology compatibility
  - Compatible with multi, mono, PERC, DWS, black silicon (MCCE) solar cell technologies
  - Applicable in Dual printing

- Production Flexibility
  - Paste for knotless screen works well with high mesh conventional screen (380/14, 430/13) in most cases
  - Fast switch in-between knotless screen and high mesh conventional screen in cell manufacturing
KNOTLESS SCREEN FEATURES
- PASTE READINESS

Superior contact resistivity on ULDE

Contact resistivity prepared for ultra-fine fingers

\[ \rho_{\text{C}} [\text{mΩcm}^2] \]

VS

\[ R_{\text{sh}}[\Omega/\text{sq}] \]

Contact Resistivity vs Screen Finger Opening (on 100 ohm/sq wafer)

<table>
<thead>
<tr>
<th>Finger Opening</th>
<th>BL</th>
<th>9641B</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 μm</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>35 μm</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>30 μm</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>
# KNOTLESS SCREEN APPLICATION OVERVIEW

## Typical parameters

<table>
<thead>
<tr>
<th></th>
<th>Double Print</th>
<th>Single Print</th>
<th>Knotless Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen opening (μm)</td>
<td>23 - 26</td>
<td>29 - 35</td>
<td>26 - 28</td>
</tr>
<tr>
<td>Paste laydown (mg)</td>
<td>100 - 115</td>
<td>100 – 115</td>
<td>100 – 115</td>
</tr>
<tr>
<td>Paste laydown extreme case (mg)</td>
<td>95 - 130</td>
<td>85 – 130</td>
<td>90 - 125</td>
</tr>
<tr>
<td>Fired Finger Width (μm)</td>
<td>45</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Fired Finger Height (μm)</td>
<td>20</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

## High Mesh Conventional Screen & Knotless Screen Parameters

<table>
<thead>
<tr>
<th>Mesh Count (pcs / inch)</th>
<th>Wire Diameter (μm)</th>
<th>Calendar (μm)</th>
<th>Open Ratio (%)</th>
<th>EOM (μm)</th>
<th>Opening Limit (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>16</td>
<td>22</td>
<td>59.8</td>
<td>15</td>
<td>25 - 30</td>
</tr>
<tr>
<td>380</td>
<td>14</td>
<td>20</td>
<td>62.5</td>
<td>15</td>
<td>28 - 29</td>
</tr>
<tr>
<td>430</td>
<td>13</td>
<td>21 - 25</td>
<td>60.8</td>
<td>15 - 17</td>
<td>26 - 28</td>
</tr>
<tr>
<td>Knotless 290</td>
<td>20</td>
<td>25</td>
<td><strong>77.2</strong></td>
<td>13 - 15</td>
<td>24 – 25</td>
</tr>
<tr>
<td>Knotless 325</td>
<td>16</td>
<td>25 - 27</td>
<td><strong>79.5</strong></td>
<td>13 - 15</td>
<td>24 – 26</td>
</tr>
<tr>
<td>Knotless 360</td>
<td>16</td>
<td>22</td>
<td><strong>77.3</strong></td>
<td>14 - 15</td>
<td>24 – 28</td>
</tr>
<tr>
<td>Knotless 400</td>
<td>16</td>
<td>25</td>
<td><strong>74.8</strong></td>
<td>14</td>
<td>24 – 25</td>
</tr>
<tr>
<td>Knotless 500</td>
<td>16</td>
<td>25</td>
<td><strong>68.5</strong></td>
<td>12</td>
<td>24 – 26</td>
</tr>
</tbody>
</table>

![Mesh Count vs Efficiency Gain](image-url)
## KNOTLESS SCREEN APPLICATION OVERVIEW
- KNOTLESS SCREEN VS CONVENTIONAL SCREEN

### Conventional Screen vs Knotless Screen – same paste

<table>
<thead>
<tr>
<th>Screen type</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
<th>FF (%)</th>
<th>Eta (%)</th>
<th>Paste Laydown (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360/16/22/15EOM 35μm</td>
<td>633.5</td>
<td>8876</td>
<td>80.45</td>
<td>18.59</td>
<td>128</td>
</tr>
<tr>
<td>360/16/22/15EOM 28μm Knotless</td>
<td>634.9</td>
<td>8918</td>
<td>80.37</td>
<td>18.70</td>
<td>117</td>
</tr>
</tbody>
</table>

### Knotless Screen + Multi PERC + MCCE Black Silicon Technology

<table>
<thead>
<tr>
<th>Cell type</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
<th>FF (%)</th>
<th>Eta (%)</th>
<th>Paste Laydown (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi PERC + MCCE Black Silicon 360/20/15EOM/33μm</td>
<td>653.5</td>
<td>9432</td>
<td>79.18</td>
<td>19.86</td>
<td>116</td>
</tr>
<tr>
<td>Multi PERC + MCCE Black Silicon Knotless 500/16/11EOM/28μm</td>
<td>655.6</td>
<td>9474</td>
<td>78.93</td>
<td>19.96</td>
<td>100</td>
</tr>
</tbody>
</table>
## KNOTLESS SCREEN APPLICATION OVERVIEW
### KNOTLESS SCREEN AND DOUBLE PRINT, DUAL PRINT

**Double Print vs Knotless Screen Single Print**

<table>
<thead>
<tr>
<th>Screen type</th>
<th>$V_{oc}$ (mV)</th>
<th>$I_{sc}$ (mA)</th>
<th>FF (%)</th>
<th>Eta (%)</th>
<th>Paste Laydown (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360/16/22/12+11EOM/26+26μm</td>
<td>634.9</td>
<td>8997</td>
<td>79.56</td>
<td>18.50</td>
<td>106</td>
</tr>
<tr>
<td>290/20/25/15EOM/28μm Knotless</td>
<td>633.8</td>
<td>9006</td>
<td>79.78</td>
<td>18.54</td>
<td>105</td>
</tr>
</tbody>
</table>

**Double Print vs Dual Print (Knotless Screen used in Finger Layer)**

<table>
<thead>
<tr>
<th>Mono Crystalline Silicon Wafer</th>
<th>$V_{oc}$ (mV)</th>
<th>$I_{sc}$ (mA)</th>
<th>FF (%)</th>
<th>Eta (%)</th>
<th>Paste Laydown (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double Print</strong> (360/16/18/15-18EOM/28-26μm)</td>
<td>650.3</td>
<td>9446</td>
<td>80.68</td>
<td>20.28</td>
<td>107</td>
</tr>
<tr>
<td><strong>Dual Print</strong> (Finger layer-Knotless 325/16/22/15EOM/27μm)</td>
<td>649.6</td>
<td>9477</td>
<td>80.59</td>
<td>20.31</td>
<td>99</td>
</tr>
</tbody>
</table>
STATUS AND TREND

- In use extensively in solar cell manufacturing
  80+ mass production lines for multi, multi PERC, mono, DWS crystalline solar cells
  Typical screen opening is 27 μm

- Co-existence with high mesh screen this year
  Knotless screen 325/16 mesh, 26-27 μm opening VS 430/13, 380/14 high mesh, 29-31 μm opening
  Similar cell efficiency gain and printed finger morphology

- Possible more usage in dual-print application
- Move forward to higher mesh and narrower opening
CONCLUSION

Bullet points for knotless screen

✓ A mesh-emulsion screen with 0° mesh angle
✓ No need for equipment upgrading
✓ Screen fabrication cost drops
✓ A solution for ultra fine line printing
✓ An alternative method to double-printing
✓ Move forward to higher mesh and narrower opening

Thank you for your attention!