Nano-patterning for better and more efficient photonic devices

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Photonic Crystals on LEDs

- GaN refractive index >2.5; Total internal reflection angle ~23 degrees
- Light produced in LED chips *trapped inside* due to high refractive index
- Photonic crystal on surface diffracts light out; reduces confined modes
- Complete photonic crystal can totally inhibit confined modes

Sapphire Substrate Patterning

- Micro-patterned sapphire substrates used today to enhance crystal growth and light extraction
- Reducing pattern dimensions to sub-micron scale
  - Enhances crystal quality and internal quantum efficiency by more than 2x*
  - Reduces buffer layer thickness – lower cost

LED Stacks on PSS

Conventional LED
- Simpler process
- Low thermal conductivity
- Light absorption by p-GaN and TCL
- Current crowding

Thin-film LED
- Process complex
- Good thermal conductivity
- Good transmission by thin n-GaN
- Larger active area
Nanowire LEDs

- Semiconductor layers grown as nanowires on pre-patterned template
- Very high quality crystals due to small size – high quantum efficiency

* GLO AB, Sweden
**PSS Lithography Problem**

- Resolution: 0.5-2 um
- Wafer size: 2", 4", 6"
- Wafer bow: 10-50um !
- Sapphire/photoresist etch selectivity: 0.5-0.8

<table>
<thead>
<tr>
<th>Product</th>
<th>Period</th>
<th>Height</th>
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<tbody>
<tr>
<td>PSS</td>
<td>3 um</td>
<td>1.5 um</td>
</tr>
<tr>
<td>High-density PSS</td>
<td>2 um</td>
<td>1.0 um</td>
</tr>
<tr>
<td>Nano PSS</td>
<td>1 um</td>
<td>0.5 um</td>
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</tbody>
</table>
Projection Photolithography (steppers)
• Widely used in PSS fabrication
• Capital Cost: >1M$ (strong rise with resolution)
• Depth of focus: big issue for nPSS

Nanoimprint Lithography
• Significant process difficulties
• Pattern aspect ratio
• Soft consumable stamp
• Mask lifetime, quality

There is a need for low-cost, high resolution lithography that works on warped/bowed substrates
Displacement Talbot Lithography

\[
\text{DOF} < \frac{p^2}{2\lambda} \quad \lambda \approx \text{i-line} \quad < 0.5\mu m
\]

Talbot imaging of a 600nm-period linear grating

Requires:
- Precise gap
- Precise parallelism
- No topography
- Thin resist
Solution: Integrate the intensity distribution over a Talbot distance.

An image with practically unlimited depth of focus obtained.

H. Solak, C. Dais, F. Clube, Optics Express, Vol.19, No.11 (2011)
PhableR 100 Exposure System

- Resolution: 150nm half-pitch
- Pitch range: 300nm - 3µm
- Exposure wavelength: near-UV
- Wafer size: up to 4"
- Mask size: 5"
- Operation: Manual load, automatic exposure
- Control interface: Touch panel
Pattern transformations with DTL

Mask

Wafer

Lines

Square

Hexagonal

30 October 2014
DTL-printed patterns

Linear Grating
- 300 nm period
- 250 nm period

Square Lattice
- 350 nm period
- 500 nm period

Hexagonal Lattice
- 520 nm period
- 1.5 μm period
High Quality Patterns

Pillars etched into Si — 3µm-period hexagonal lattice
High-aspect ratio photoresist pattern

Patterned 2” sapphire wafer
Conclusions

• New lithography method for high-resolution periodic structures

• Low and high volume tools are in the market

• Suitable for PSS-nPSS fabrication