Innovations in Solid State Lighting

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Materials and ECE Departments
University of California, Santa Barbara
Outline

1. Introduction
   - History
   - Is sun light the best for humans and plants?

2. LED Lighting
   - Tunnel-Junction (TJ) blue/green LEDs with EQE over 70%/50%
   - Micro LED, green LED for red LED

3. Laser Lighting
   - High Power Semipolar LDs
   - Li-Fi with LEDs and LDs
Introduction
<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher(s)</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>Maruska &amp; Tietjen</td>
<td>GaN epitaxial layer by HVPE</td>
</tr>
<tr>
<td>1973</td>
<td>Maruska et al.</td>
<td>1st blue Mg-doped GaN MIS LED</td>
</tr>
<tr>
<td>1983</td>
<td>Yoshida et al.</td>
<td>High quality GaN using AlN buffer by MBE</td>
</tr>
<tr>
<td>1985</td>
<td>Akasaki &amp; Amano et al.</td>
<td><strong>High quality GaN using AlN buffer by MOCVD</strong></td>
</tr>
<tr>
<td>1989</td>
<td>Akasaki &amp; Amano et al.</td>
<td><strong>p-type GaN using LEEBI</strong> (p is too low to fabricate devices)</td>
</tr>
<tr>
<td>1991</td>
<td>Nakamura</td>
<td><strong>Invention of Two-Flow MOCVD</strong></td>
</tr>
<tr>
<td>1991</td>
<td>Moustakas</td>
<td>High quality GaN using GaN buffer by MBE</td>
</tr>
<tr>
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<td>Nakamura</td>
<td>High quality GaN using GaN buffer by MOCVD</td>
</tr>
<tr>
<td>1992</td>
<td>Nakamura et al.</td>
<td><strong>p-type GaN using thermal annealing, Discovery hydrogen passivation</strong> (p is high enough for devices)</td>
</tr>
<tr>
<td>1992</td>
<td>Nakamura et al.</td>
<td>InGaN layers with RT Band to Band emission</td>
</tr>
<tr>
<td>1994</td>
<td>Nakamura et al.</td>
<td><strong>InGaN Double Heterostructure (DH) Bright Blue LED (1 Candela)</strong></td>
</tr>
<tr>
<td>1995</td>
<td>Nakamura et al.</td>
<td><strong>InGaN DH Bright Green LED</strong></td>
</tr>
<tr>
<td>1996</td>
<td>Nakamura et al.</td>
<td>1st Pulsed Violet InGaN DH MQW LDs</td>
</tr>
<tr>
<td>1996</td>
<td>Nakamura et al.</td>
<td>1st CW Violet InGaN DH MQW LDs</td>
</tr>
<tr>
<td>1996</td>
<td>Nichia Corp.</td>
<td>Commercialization <strong>White LED using InGaN DH blue LED</strong></td>
</tr>
</tbody>
</table>
Contributions towards efficient blue LED

*p-type GaN* activated by thermal annealing by *Nakamura et al.*, 1992

Hydrogen passivation was clarified as an origin of hole compensation

*p-type GaN* activated by Electron Beam Irradiation by *Akasaki & Amano*, 1989

InGaN Emitting (Active) Layer by *Nakamura & Mukai*, 1992

*n-type GaN*

Sapphire substrate

GaN Buffer by *Nakamura*, 1991

AlN Buffer by *Akasaki & Amano*, 1985
First Source of Light for Life: Our Sun
Conventional White LED (Blue LED + Phosphor)

Strong Blue LED light disrupts the circadian cycle or suppresses melatonin?

Figure 2. The typical emission spectrum of a white LED using a YAG phosphor at 20 mA. $T_{cp}$ is 6500 K.

Figure 3. The spectra of the ultra-high $R_a$ white LED, the conventional white LED and CIE Standard Illuminates ($D_{50}$). All of $T_{cp}$ are 5000 K.

Plant Factory using Blue/Red LEDs in Clean Room

Growth rate is 2.5 times (the latest: 5 times) higher. Yield from the plants is 50% to 90% Water usage is only 1% compared with in the field
What’s VP₃?

VP₃ = Violet and 3 Phosphor

1. GaN on GaN Tri-LED Die (Emit Violet Light)
2. Phosphor Particles suspended in a polymer convert Violet to Blue, Green, and Red
3. Resulting in Full-visible-spectrum light
What’s VP₃?

VP₃ = Violet and 3 Phosphor
Soraa’s New Helia Bulb Lamp

http://www.digitaltrends.com/home/soraa-helia/#/7
THE BLUE LIGHT SOLUTION

Standard LED

“Sleep” LED

SORAA

Large Blue Light Peak
Faded Colors & Whites
Efficient

Moderate Blue Light
Unnatural Yellow Tint
Efficient

No Blue Light
Beautiful Colors & Whites
Efficient
Soraa’s New Helia Bulb Lamp

http://www.digitaltrends.com/home/soraa-helia/#/7

2017 CES Innovation award (January 4, 2017)

Using Soraa’s BlueFree LEDs, David says the Helia emits almost zero blue light while still retaining a “soft white color.” The bulb adapts to your home’s sunrise and sunset times as well as your habits to trigger the night mode. Helia also provides “plenty of blue light” in the morning to wake you up.

Read more: http://www.digitaltrends.com/home/soraa-helia/#ixzz4UvVGdiro

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THE MYOPIA BOOM
LED Lighting: Tunnel Junction Devices
GaN Tunnel Junction Advantages

By Professor Jim Speck
Use of MBE for N-GaN regrowth (eliminate H)

Tunnel junction eliminates need for standard p-contacts

Increased Internal Quantum Efficiency (IQE) for LEDs
Could lower voltage in edge emitting laser diodes
Reduction in optical loss and increase of design space for GaN VCSELs
Increase in process design space due to buried p-GaN
Combination of MOCVD and MBE allows for high quality MOCVD InGaN active regions with high doping density of MBE

- p-type GaN is activated under NH$_3$ MBE growth conditions

Multiple patents pending
Electrons tunnel directly from valence band in p-type layer to conduction band in n-type layer.

Reverse bias operation decreases tunnel distance.

Tunneling distance ~5.5 nm
TJ (2021) LED

0.1 mm² chip at 20 A/cm²

- Small area LED highlights voltage drop in tunnel junction
- LED with small n-contact illustrates current spreading abilities

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti/Au</td>
<td></td>
</tr>
<tr>
<td>100 nm n-GaN:Si</td>
<td></td>
</tr>
<tr>
<td>20 nm n⁺-GaN:Si</td>
<td></td>
</tr>
<tr>
<td>10 nm p⁺-GaN:Mg</td>
<td></td>
</tr>
<tr>
<td>100 nm p-GaN:Mg</td>
<td></td>
</tr>
<tr>
<td>InGaN MQW Active Region</td>
<td></td>
</tr>
<tr>
<td>n-GaN:Si</td>
<td></td>
</tr>
<tr>
<td>(2021) Free Standing GaN</td>
<td></td>
</tr>
</tbody>
</table>
Multi-Junction LEDs (Triple Contact Design)

- Thin metal current spreading layer for top LED
- Two contacts so each active region can be operated independently or in series
Dual Wavelength (2021) LEDs
Multiple Junction LED Voltage

- LED turns on near sum of photon energies
Patterned Sapphire Substrate LEDs

<table>
<thead>
<tr>
<th>p$^+$-GaN:Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-GaN:Mg</td>
</tr>
<tr>
<td>InGaN Active Region</td>
</tr>
<tr>
<td>n-GaN:Si</td>
</tr>
</tbody>
</table>

- c-plane PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality
Patterned Sapphire Substrate LEDs

<table>
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<th>Layer</th>
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<tbody>
<tr>
<td>n-GaN:Si</td>
<td></td>
</tr>
<tr>
<td>n⁺-GaN:Si</td>
<td></td>
</tr>
<tr>
<td>p⁺-GaN:Mg</td>
<td></td>
</tr>
<tr>
<td>p-GaN:Mg</td>
<td></td>
</tr>
<tr>
<td>InGaN Active Region</td>
<td></td>
</tr>
<tr>
<td>n-GaN:Si</td>
<td></td>
</tr>
</tbody>
</table>

- c-plane PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality
Patterned sapphire LED epi-wafers

- *c-plane* PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality
Tunnel junction regrowths

- Initial tunnel junction devices had higher voltages compared with reference samples than devices on nonpolar and semipolar planes.
Acid treatments prior to regrowth

- **HF treatment provides lowest voltage for c-plane TJs**
  3.08 V at 20 A/cm²

Patent Pending: “III-Nitride tunnel junction improvement through reduction of the magnesium memory effect”
TJ Flip chip LEDs

- Omnidirectional reflector has higher reflectivity than silver
- Only a small fraction of aluminum contact area is needed
High reflectivity coating

- Multilayer dielectric coating under wire bond pads increases reflectivity to over 97%
Flip chip LED design

- HR coating and metal surrounds mesa to reflect more light
- LEDS are flipped onto a patterned SiC submount
- Wire bonded to header

Patent Pending: “III-Nitride flip chip LED with dielectric based mirror”
Tunnel Junction Blue LED

Peak EQE 78%, peak WPE 72%
World Record-Low Droop compared to commercial LED

0.1 mm² (1 mA = 1 A/cm²)

“Silver free III-nitride flip chip LED with wall plug efficiency over 70% utilizing GaN tunnel junction”
Tunnel Junction Edge Emitting Laser

- Tunnel junction could allow for novel laser designs employing n-GaN cladding on both sides
- Highly doped p-GaN has a resistivity of $\sim 1 \, \Omega \text{cm}$, giving $1 \times 10^{-5} \, \Omega \text{cm}^2$ resistivity per 100nm p-GaN
- Lower doping used for low optical loss gives higher resistivity
Tunnel-junction 525 nm Green LEDs on PSS

Commercial PSS green LED epi-wafer

Power (mW) vs. Current (mA)
Voltage (V) vs. Current (mA)
Percent EQE or WPE vs. Current (mA)

0.1 mm² (1 mA = 1 A/cm²)

Peak EQE 50%, peak WPE 40%
LED Lighting: Micro LED, and Green LED for Red LED
Displays are extremely energy inefficient.

Liquid Crystal Display

Efficient Light Source
+ Inefficient Filtering Process
5% Light Out
(95% Power Lost)

Organic LED Display

No Filtering Process
+ Inefficient Light Source
10% Light Out
(90% Power Lost)

Figure courtesy of Chris Pynn
RGB µLED displays can be much more efficient.

- Self-emissive – no loss through filters
- Inorganic material (GaN) – more efficient
Electroluminescence reveals emission patterns.

10 A/cm²

Smaller μLEDs have less area over which to spread current.

Current crowds around the edges of larger LEDs at low current densities.
Small µLEDs maintain high EQE.

- The max EQE for all µLEDs are similar (40-50%).
- Reduction of the EQE is due to sidewall damage as µLEDs have higher perimeter to area ratios.

Smaller µLEDs exhibit less droop, which is due to better current spreading.
Growth of Green LEDs with 3 Step Active Region
Previous high efficiency green LED

$$0.1 \text{ mm}^2 \ (1 \text{ mA} = 1 \text{ A/cm}^2)$$

<table>
<thead>
<tr>
<th></th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Wavelength (nm)</th>
<th>EQE%</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaged LED</td>
<td>20</td>
<td>3.54</td>
<td>526.6</td>
<td>30.2</td>
<td>33</td>
</tr>
</tbody>
</table>

A. Alhassan et al., Optics Express. **24**(16), 17868-17873 (2016)
Active region study

- Further study of the surface morphology of MQW

- High density of v-defect in green MQW

5 × MQW

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT GaN barrier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al$<em>{0.30}$Ga$</em>{0.70}$ cap layer</td>
<td>2 nm</td>
<td></td>
</tr>
<tr>
<td>In$<em>{0.25}$Ga$</em>{0.75}$ QW</td>
<td>3 nm</td>
<td></td>
</tr>
<tr>
<td>GaN UID</td>
<td>10 nm</td>
<td></td>
</tr>
<tr>
<td>S.L In$<em>{0.05}$Ga$</em>{0.95}$/GaN: Si $5 \times 10^{18}$ cm$^{-3}$</td>
<td>300 nm</td>
<td></td>
</tr>
<tr>
<td>GaN: Si $5 \times 10^{18}$ cm$^{-3}$</td>
<td>3 μm</td>
<td></td>
</tr>
<tr>
<td>Patterned Sapphire Substrate (PSS)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pits $\sim 6 \times 10^8$ cm$^{-2}$

Atomic-force microscopy (AFM) scan of the last GaN barrier
Understanding V-defect problem

- V-defect initiates at threading dislocation (TD).
- Kinetically controlled by reduced Ga incorporation which is the primary cause for V-defect.
  - Growth rate of {0001} plane > {1011} planes

- Increase surface mobility to overcome the problem.
  - Lower V/III ratio.
  - Higher temperature.
  - H₂ carrier gas.

Limitation.
- Temperature difference $\Delta T = 75^\circ \text{C}$.
- Thin GaN barrier.
3 step Active region

- Growth of Active region in 3 steps with different carrier gas.
  - QW and AlGaN cap layer growth in N2 environment.
  - 1\textsuperscript{st}HT GaN barrier with H\textsubscript{2}(200 sccm)+N\textsubscript{2}(1.9 slm) at \(\Delta T = 75^\circ C\).
  - 2\textsuperscript{nd}HT GaN barrier with H\textsubscript{2}(1.9 slm)+N\textsubscript{2}(1.9 slm) at \(\Delta T = 140^\circ C\).
### Final device

- Three steps photolithography fabrication process.
- 0.1mm$^2$ active area.
- Vertical transparent LEDs packaging.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>5 × MQW</td>
<td>Patterned Sapphire Substrate (PSS)</td>
</tr>
<tr>
<td>10 nm p+-GaN contact layer</td>
<td></td>
</tr>
<tr>
<td>70 nm GaN: Mg 7 × 10$^{19}$ cm$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>10 nm Al$<em>{0.20}$GaN$</em>{0.80}$ EBL</td>
<td></td>
</tr>
<tr>
<td>7 nm 2$^{nd}$HT GaN barrier</td>
<td></td>
</tr>
<tr>
<td>3 nm 1$^{st}$HT GaN barrier</td>
<td></td>
</tr>
<tr>
<td>2 nm Al$<em>{0.30}$GaN$</em>{0.70}$ cap layer</td>
<td></td>
</tr>
<tr>
<td>3 nm In$<em>{0.25}$GaN$</em>{0.78}$ QW</td>
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<tr>
<td>10 nm GaN UID</td>
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<td>300 nm S.L In$<em>{0.05}$GaN$</em>{0.95}$ /GaN:Si 5 × 10$^{18}$ cm$^{-3}$</td>
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</tr>
<tr>
<td>3 um GaN: Si 5 × 10$^{18}$ cm$^{-3}$</td>
<td></td>
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</tbody>
</table>
3 vs 2 step Active region results

- 0.1mm² chip size.

"Multi-step active region for high performance nitride LEDs" (patent pending)
Green LED results

<table>
<thead>
<tr>
<th></th>
<th>Current density (A/cm²)</th>
<th>Voltage (V)</th>
<th>Wavelength (nm)</th>
<th>EQE%</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaged LED</td>
<td>20</td>
<td>4.6</td>
<td>525.4</td>
<td>33</td>
<td>34</td>
</tr>
</tbody>
</table>
Laser Lighting:
High Power Semipolar (2021) LDs
UCSB’s Vision

LED based White Light is great, **Laser based** is even better!

- **Device**
- **60 W Incandescent Equivalent**
- **External Quantum Efficiency LED/Laser vs. Current Density**

**LED**
- Sapphire

**Laser**
- Bulk GaN

- **Phosphor Strip**

- **28 mm²**
- **0.3 mm²**

**M. Cantore et al., UCSB**

**Commercial LED & Laser**

**Current Density (kA/cm²)**

**External Quantum Efficiency (%)**
Substantially more LD devices per sq in of wafer (vs. LED)

LDs are higher brightness by several orders of mag (vs. LED)

LD WPE is increasing and cost is decreasing

Small source -> simpler optics, novel phosphor designs

“Delivered” Lm/W and $/Lm for LD sources is increasingly appealing for specialty lighting applications
UCSB Blue Laser Structure

Field Insulator SiO₂

$p$-contact

$p^{++}$ GaN

650 nm $p$-GaN cladding

65 nm $p$-In$_{0.06}$Ga$_{0.94}$N waveguide

15 nm $p$-Al$_{0.18}$Ga$_{0.82}$N EBL

# × 3.5 nm/7 nm MQW Active Region

65 nm $n$-In$_{0.06}$Ga$_{0.94}$N waveguide

1.2 μm $n$-GaN cladding

330 μm (20$ar{1}$1) GaN Substrate

$n$-contact

Internal Loss and $\eta_i$ for $\langle 20\bar{2}1 \rangle$ LD

\[ \frac{1}{\eta_d} = \frac{\langle \alpha_i \rangle}{\eta_i \ln(1/R)} L + \frac{1}{\eta_i} \]

From this fit, we calculate:

<table>
<thead>
<tr>
<th>$\langle \alpha_i \rangle$</th>
<th>$10 \text{ cm}^{-1} \pm 2 \text{ cm}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_i$</td>
<td>$0.80 \pm 0.1$</td>
</tr>
</tbody>
</table>

Previous measurement on Violet Lasers on m-plane at UCSB:

$\langle \alpha_i \rangle = 9.8 \text{ cm}^{-1}$  $\eta_i = 66\%$
Simulation of Confinement & Loss

<table>
<thead>
<tr>
<th>Layer</th>
<th>Loss %</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-metal</td>
<td>1.0%</td>
</tr>
<tr>
<td>p-clad</td>
<td>7.7%</td>
</tr>
<tr>
<td>p-SCH</td>
<td>4.0%</td>
</tr>
<tr>
<td>EBL</td>
<td>9.5%</td>
</tr>
<tr>
<td><strong>subtotal: p-top</strong></td>
<td><strong>22.3%</strong></td>
</tr>
<tr>
<td>QW</td>
<td>52.6%</td>
</tr>
<tr>
<td><strong>subtotal: active region</strong></td>
<td><strong>53.3%</strong></td>
</tr>
<tr>
<td>n-SCH</td>
<td>3.1%</td>
</tr>
<tr>
<td>n-clad</td>
<td>19.6%</td>
</tr>
<tr>
<td><strong>subtotal: n-bottom</strong></td>
<td><strong>24.4%</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effective Index</th>
<th>Confinement Factor</th>
<th>Calculated $\langle \alpha_i \rangle$</th>
<th>Experimental $\langle \alpha_i \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.47</td>
<td>0.36</td>
<td>7.65 cm$^{-1}$</td>
<td>10 cm$^{-1}$ ± 2 cm$^{-1}$</td>
</tr>
</tbody>
</table>
2 QW Laser

1200 μm x 5 μm LD λ=428nm
Single facet, uncoated

InGaN m-plain VCSEL with tunnel junction intracavity contact

Loss in ITO - 30 cm\(^{-1}\)
Loss in Tunnel Junction - 3 cm\(^{-1}\)


10 times less loss for tunnel junction (TJ) contact layer compared with ITO

7x enhancement in peak power with TJ
VCSEL Results – Polarization

Conventional VCSEL Array

Nonpolar VCSEL Array

Fiber-Coupled Measurement

Polarization Ratio = 100%!
Laser Lighting

Li-Fi with LEDs and LDs
Intelligent LED Light and Communication Systems

- Li-Fi communication network
- Sensor, Alarm System, Social Preference
- Higher capacity than Wi-Fi.

Data Rate: \( \text{LED Li-Fi} > 10 \times \text{Wi-Fi}, \text{Laser Li-Fi} > 100 - 1000 \times \text{Wi-Fi} \)

Source: www.electronicsbus.com

A new technology called LiFi can transfer data using LED lights. In this video, we'll watch a demo of a LiFi system made with off-the-shelf parts, as it streams a video.
Motivation

- **RF spectrum crisis**
  - Mobile data demands are exponentially increasing but spectrum efficiency is saturated

- **Advantages of VLC**
  - ~hundreds THz of unlicensed spectrum available
  - No EM interference (EMI)
  - High security
  - Cost-efficient
Motivation

- RF spectrum crisis
  - Mobile data demands are exponentially increasing but spectrum efficiency is saturated

- Advantages of VLC
  - ~hundereds THz of unlicensed spectrum available
  - No EM interference (EMI)
  - High security
  - Cost-efficient
Bandwidth limits in VLC transmitter

**Commercial LED**

- **BW of ~ 20 MHz, 100 Mbps OOK**

**Single micro-LED**

- **BW of 200 ~ 800 MHz, 1.7 Gbps OOK**

**Commercial LD**

- **BW of > 2 GHz, 4 Gbps OOK**

**Higher speed LD?**

H. L. Minh, et al., IEEE PTL, 2009
J. J. D. McKendry, et al., IEEE PTL, 2010
Records in III-nitride LDs and LEDs

\[ BW_{\text{max}} \text{ of LEDs: } 1 \text{ GHz (carrier lifetime limit)} \]
\[ BW_{\text{max}} \text{ of LDs: } 5 \text{ GHz (photodetector bandwidth limit)} \]
Semipolar (20-2-1) Laser Diode

Violet CW LD on (20-2-1) plane (2 µm x 1200 µm)

<table>
<thead>
<tr>
<th>CW data</th>
<th>(I_{th}) (mA)</th>
<th>(J_{th}) (kA/cm²)</th>
<th>(V_{th}) (V)</th>
<th>(dP/dI) (W/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2µm x 1200µm</td>
<td>150</td>
<td>6.25</td>
<td>5.1 (4-pt)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Injection efficiency have good agreement with semipolar blue LD by D. Becerra et al., Appl. Phys. Express, 2016**

*Only 1 nm wavelength shift*

Modulation bandwidth

**PD response**

- Electrical response
- Fitted curve

- 3.65 GHz bandwidth

*Measured by Ti:Sapphire modelocked laser*

**Recovered LD response**

- Normalized frequency response (dB)
- Frequency (GHz)

- 150 mA
- 240 mA

- 3 dB

**On-off keying (OOK) modulation**

- 5 Gbit/s OOK with clear open eyes
  - (Higher data rate could be achieved by high speed PD and higher order modulation)

---

After correcting PD response:

**Record BW > 5 GHz** due to the noise floor

**5 Gbit/s OOK** with clear open eyes

(Higher data rate could be achieved by high speed PD and higher order modulation)

• LEDs – 14 MHz without phosphor and 2.5 MHz with phosphor
• LDs – 1.2 GHz without phosphor and 1.1 GHz with phosphor (limited by photodetector)
• LDs are ~1,000 times faster than LEDs for white lighting data transmission
White LED vs. LD VLC


τ = 73 ns

YAG:Ce phosphor limit ~ 4 MHz

1 GHz APD limit
Laser Diodes – Light of the Future

- Laser Projectors
  - 100 inch TV

- Laser Headlights
  - LED spread 100 m
  - LED spread 300 m
  - Laser 600 m
BMW with Laser Lighting Headlights

BMW with laser headlights (available in US!)
Researchers at UCSB: SSLEEC in 2016