Acknowledgement:
Professor Mohamed Sameh Amr, The Chairperson of the Executive Board of UNESCO
Ms. Irina Bokova, Director-General of UNESCO
Excellencies, Distinguished delegates

Development of GaN-based blue LEDs and future prospects

Monday June 8, 2015
United Nations Educational, Scientific and Cultural Organization, Paris

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Professor, Graduate School of Engineering,
Director, Akasaki Research Center,
Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan
To contribute to solving global issues such as, “Energy”, “Water”, “Food”, “Environment”, and “Health” and to realize sustainable society.
Our group members

Faculty
Prof. Hiroshi Amano
Assoc. Prof. Yoshio Honda
Assist. Prof. Deki Manato

Post Doctoral Fellow
Kaddour Lekhal
Si-Young Bae
Kentaro Nagamatsu
Atsushi Tanaka

PhD. Candidates
Marc Olsson
Kohei Yamashita
Oh-Byung Jung
Maki Kushimoto
Seunga Lee
Sun Zheng
Hojun Lee
Barry Ousmane 1

13 MC Students
5 Undergraduate Students
3 Secretaries

36 people
Dr. Kaddour Lekhal, Alegrila
PhD at Blaise Pascal University

World’s longest GaN nanowire
**Electronic Devices**

Growth of High-Aspect Ration GaN Nanowires

Waveguiding in 1D-nanostructures for Multi-Communication

**Light Emitting Diode (LED)**

Solar Cells
Dr. Si-Young Bae, Korea
PhD at GIST

Ga-polar NR LEDs

GaN nanowire LEDs
Representative of Guinean students at the third International Conference on Quality Assurance in Higher Education in Africa and the capacity building workshop held respectively in Dakar and St. Louis (Senegal) by UNESCO Bamako Cluster Office in collaboration with partners in 2008.

Mr. Barry Ousmane 1
Guinea
Flame detector (UV light)
www.directindustry.com

Back-illuminated AlGaN Schottky barrier diode (SBD)

Back-illuminated UV-Visible light multi-band image sensor.

Flame detector (UV light)
www.directindustry.com

8/55
History of blue LEDs
In this presentation, I would like to explain how “the seed” of blue light emitting diode, that is “Nitride Semiconductors”, have been developed and handed over by many researchers.

I also would like to show some perspective of the new development and applications of nitride-based light emitting devices.
History of artificial lighting

- **19C fire**: 1st generation
- **1878 incandescent lamp**: 2nd generation
  - (Long history, Joseph Swan, UK, Thomas Edison, USA)
- **1938 Fluorescent lamp**: 3rd generation
  - (Long history, 1901 Peter Cooper Hewitt, USA, 1927 Edmund Germer, 1938 Germany, George Innman, USA)
- **1962 Commercial LED**: 4th generation
  - (Long history, Henry J. Round 1907, Nick Holionyak Jr., USA)

- **Blackbody emission**: (Early stage of quantum mechanics)
- **Energy transfer**: (Quantum mechanics)
- **Chemical reaction**

Luciaball, Dec.13, 2014 at Stockholm

http://kagakukan.toshiba.co.jp/history/1goki/1940fluorescent.html
http://www.pawanavi.com/topics/2002/11/06/
http://www.audio-q.com/tyuumon.htm
Overview of development of LEDs

1962 N. Holonyak Jr., GaAsP red LD

1968 RCA LCD

1971 J. Pankove, GaN MIS blue LED

1952 H. Welker, GaAs, GaP

R. Haitz and J. Y. Tsao, phys. stat. sol. (a)208(2011)17
GaN research in 1950’s - 1970’s “Seed”

Über die Kantenemission und andere Emissionen des GaN

Von H.G. Grimmeiss und H. Koelmans
Aus den Philips-Forschungslaboratorien Aachen und Eindhoven

ZEITSCHRIFT FUR NATURFORSCHUNG A 14(1959)264.


Low-Temperature Luminescence of GaN

H. G. Grimmeiss and B. Monemar
Institute of Technology, Department of Solid-State Physics, Lund, Sweden
(Received 11 March 1970)


Professor Monemar at Lund University, Dec. 14, 2014

Lund Institute of Technology or Lunds Tekniska Högskola (LTH)
First GaN blue LED “Germination”

First GaN LED (MIS type)
Efficiency: $10^{-5} \sim 3 \times 10^{-4}$


http://www.colorado.edu/memorybox/jacquespankove.html

Dr. Kayann Short • Farrand Academic Program, University of Colorado at Boulder • 303-492-1267 • shortk@colorado.edu
GaN blue LED research in 1970’s “Endurance”

Violet luminescence of Mg-doped GaN

H. P. Maruska, D.A. Stevenson, J. I. Pankove

Mg

G. Jacob and D. Bois, Appl.

Zn


Oki Electric

http://www.sslighting.net/lighttimes/features/maruska_blue_led_history.pdf

Stanford University and RCA

Matsushita Research Institute, Tokyo
(Panasonic)

Y. Ohki, Y. Toyoda, H. Kobayashi and

May 1981, New York

Zn

Philips
In general, lattice mismatch should be <1%.

Lattice mismatch

\[
\frac{0.3185 - 0.2747}{0.2747} \approx +16\%
\]
Why I was interested in blue LEDs?

1975  Micro-soft by Bill Gates, Paul Allen
1976  Apple I by Steve Jobs, Stephen Wozniak

1970  GaN LED by MBE and HVPE
1981  Nagoya Univ.
1990

1975 Vapour-grown AlN
Matsushita Research Institute, Tokyo

I. Akasaki and M. Hashimoto

1982 Undergraduate

Graduation Research
"Nitride-Based Blue LED"

Braun tubes are too big!

If I can achieve blue LEDs, I will change the world!

Isamu Akasaki
1992- Meijo Univ.
(Prof. Emeritus Nagoya Univ.)
Change of growth method from HVPE to MOVPE

HVPE

GaCl + NH₃ \rightarrow GaN + H₂ + HCl

SiH₂Cl₂, H₂

HCl

NH₃, H₂

850 °C

~1000 °C

Outlet

Ga source

Substrate

Heater

Exhaust

Courtesy of Dr. Usui, Furukawa

- Multi zone temperature control
- Bi-product NH₄Cl
- High growth rate >50 μm/hr

MOVPE


- Single temperature control
- Low growth rate ~ a few μm/hr

HVPE: Halogen transport VPE
MOVPE: Metalorganic VPE
Funding situation of our lab. in mid 80’s

Students built MOVPE reactor by themselves.

1984

Lab-built MOVPE Reactor

cf. Commercial MOVPE reactor ~1M US$

Measuring susceptor temperature using pyrometer

Support by MEXT and JST

100,000 US$

1984

Students built MOVPE reactor by themselves.

Y. Koide

19/55
High speed gas flow $\sim 5 \text{ [m/s]}$  
(conventional $\sim 0.2\text{ [m/s]}$)


Learn by trial and error

Random nucleation

Selective growth

Poor coalescence

I have tried more than 1,500 times, but I could not grow high-quality GaN film.
Low-temperature-deposited buffer layer

I knew that the substrate temperature should be higher than $1200^\circ C$ for the epitaxial growth of AlN.

Old oscillator did not work well.

GaN growth

Deposition of AlN at low temp.

February 1985

I remembered the discussion in the lab.

I knew that the substrate temperature should be higher than $1200^\circ C$ for the epitaxial growth of AlN.
After the first success in Feb. 1985, I learned how to measure crystalline quality by X-ray rocking curve, luminescence property by photoluminescence, electrical property by Hall effect measurement, etc., etc.


1st journal paper for doctor thesis
Seeking p-GaN by Zn doping 1985-1988

Split of neutral acceptor bound excitation emission at 4.2 K by uniaxial anisotropy

LT PL measurement @ TG

MOVPE @ Nagoya Univ.

I was so excited with this result, and tried to present our efforts to JSAP annual meeting at 1987.

2\textsuperscript{nd} journal paper for doctor thesis
The anomalous kinetics of cathode luminescence in GaN:Zn


During my internship at NTT, 1988

...So, I could not finish Doctor thesis in three years.
Selection of the dopant
Activation energy of acceptor in GaP
Zn: higher ×
Mg: Lower ○

J. C. Phillips,
“Bonds and Bands in Semiconductors”
P-type GaN:Mg by LEEBI “Flowering”


(a) w LEEBI
(b) wo LEEBI

M. Kito

50μm
Thermal annealing


Hydrogen passivation

Lattice location of hydrogen in Mg doped GaN

We used hydrogen as the carrier gas.
They used nitrogen as the carrier gas.
Blue luminescence at room temperature


S. Nakamura and T. Mukai
1993 World’s first commercialization of InGaN-based LEDs

How our lives change with the emergence of blue LEDs?

1989
GAME BOY
1989 Released
Photo: Nintendo Co., Ltd.

1998
GAME BOY COLOR
1998 Released
Photo: Nintendo Co., Ltd.

1991
mova P
1991 Released
Website: DOCOMO CS Tohoku, INC.
Quoted from the history of the mobile phone

1999
Digital mova F502i HYPER
1999 Released
Website: DOCOMO CS Tohoku, INC.
Quoted from the history of the mobile phone
http://www.docomo-cs-tohoku.co.jp/museum/tanmatsu/f502i.html

Copyright ©: The Nobel Foundation
Increase of smartphone addiction?

http://gajethouse.blog3.fc2.com/blog-entry-791.html

http://blogs.yahoo.co.jp/fpdxw092/61943354.html

White LEDs “Contribution to society”

Isamu Akasaki
1967 Powdered AlN
1981 Nagoya Univ.
1992- Meijo Univ.
(Prof. Emeritus Nagoya Univ.)

Wide-gap GaN
Blue LED

Shuji Nakamiura
(Nichia, now UCSB)

1989-1993 : LT GaN
p-type by thermal annealing
InGaN/GaN DH

1985 LT buffer (MC, aged 24)
1989 P-type GaN (Research Associate, aged 28)

Hiroshi Amano
1988 RA, Nagoya
1989 Dr. of Eng., Nagoya Univ.
1992-2010 Meijo Univ.
2010 Nagoya Univ.

1987 JST
1995 Commercialization

Toyoda Gosei

Nichia

Three primary colors

1996 : White LED

Yellow Phosphor

© Gussisaurio

© Rotatebot
How InGaN LEDs contribute to saving energy

Electricity generation in Japan

The Federation of Electric Power Companies of Japan

Great East Japan Earthquake
March 11, 2011
How InGaN LEDs contribute to saving energy

Table ES.1 Total U.S. LED Forecast Results

<table>
<thead>
<tr>
<th>Baseline site electricity consumption (TWh)</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>Cumulative (2010-2030)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>694</td>
<td>635</td>
<td>631</td>
<td>641</td>
<td>648</td>
<td>13,535</td>
</tr>
<tr>
<td>Commercial</td>
<td>346</td>
<td>325</td>
<td>321</td>
<td>320</td>
<td>316</td>
<td>6,806</td>
</tr>
<tr>
<td>Industrial</td>
<td>58</td>
<td>49</td>
<td>44</td>
<td>41</td>
<td>38</td>
<td>947</td>
</tr>
<tr>
<td>Outdoor Stationary</td>
<td>116</td>
<td>119</td>
<td>128</td>
<td>135</td>
<td>141</td>
<td>2,676</td>
</tr>
</tbody>
</table>

**LED market share (% of lm-hr)**
- Residential: 9.5%
- Commercial: 35.8%
- Industrial: 59.0%
- Outdoor Stationary: 73.7%

**Site electricity savings (TWh)**
- Residential: 21
- Commercial: 122
- Industrial: 217
- Outdoor Stationary: 297

**Site electricity savings (%)**
- Residential: 3.3%
- Commercial: 19.4%
- Industrial: 45.8%
- Outdoor Stationary: 17%

Total consumption 4273 TWh

297/4273~7%

In Japan, we can reduce total electricity consumption by about 7% (=1T JP Yen) by 2020.
For the children living on Earth

Mr. Luvsannyyam Gantumur,
Minister for Education and Science of Mongolia
How long did it take from the first findings to contribute to mankind?

科学技術振興機構（Japan Science and Technology Agency:JST）
委託開発課題「窒化ガリウム（GaN）青色発光ダイオードの製造技術」
（新技術の代表発明者: 赤崎勇 当時、名古屋大学教授）、開発実施企業: 豊田合成株式会社)
1987年4月 〜 1990年3月

http://www.jst.go.jp/itaku/result/ef-1.pdf

28 years from the start of JST support
44 years from Pankove LED
56 years from Grimmeiss paper
Challenge to DUV region for water purification

\[ a_{\text{cubic}} = 3\sqrt{3} a_w^2 c_w \]

High frequency and high power HEMT

Violet LDs for Blu-ray Disc

Blue LEDs, White LEDs

http://blogs.unicef.org/2014/03/20/world-water-day-2014-the-forgotten-768-million/

People who cannot access to safe water

0.77 Billion people

Unicef
World Health Organization,
Progress on Drinking Water and Sanitation
2014 Update

2.6 Billion people

Sanitation facility coverage 2012
Our development of AlGaN based DUV LEDs

NEDO


Nagoya Univ.
Dr. Koide

AlGaN Growth by MOVPE

1990

1997 2006

Nikkiso

UV Craftry

1990

1997 2006

Flame sensor, Osaka Gas

UV LD
Meijo Univ.
Hamamatsu
Photonics
ASU
Univ. Bristol

DUV LED
Osaka Gas, Kyosemi

Applications

0V Flame response (d>4cm)
Room Light ON/No Room Light
No Filter/Filter


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Applications

0V Flame response (d>4cm)
Room Light ON/No Room Light
No Filter/Filter
Our development of AlGaN based DUV LEDs

DUV-LED Sterilization

DUV-LED array module

NIKKISO
Other applications of group III nitrides
Why nitrides are so attractive for power device applications?

GaAs

Si

GaN

http://www.edn.com/Pdf/ViewPdf?contentItemId=4409627
Energy savings with GaN-based power devices

Role of Power Devices
- Loss (Heat) 5W
- Inverter (Si based IGBT)

DC100W → AC95W

Highest efficiency power devices can be expected by using GaN

- Switching loss
- Transmission loss

5% Loss ⇒ 0.75% Loss

• By replacing Si-based IGBT to WBG devices, 9.8% of total electricity consumption can be saved.
• Super downsizing of power circuits is possible by using GaN-based devices.

http://electronicdesign.com/power/optimize-power-scheme-these-transient-times
Why nitrides are so attractive? Energy harvesting

\[ a_{\text{cubic}} = \sqrt[3]{a_w^2 \times c_w} \]

<table>
<thead>
<tr>
<th>Energy</th>
<th>AM1.5</th>
<th>Cost JPY/KWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaN</td>
<td>1.86eV</td>
<td>48</td>
</tr>
<tr>
<td>InGaN</td>
<td>2.35eV ((\lambda: 527\text{nm}))</td>
<td>55</td>
</tr>
<tr>
<td>InGaN</td>
<td>2.25eV ((\lambda: 551\text{nm}))</td>
<td></td>
</tr>
<tr>
<td>InGaN</td>
<td>3 cells</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\eta: 38% \text{ (1sun)})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\eta: 43.5% \text{ (1sun)})</td>
<td></td>
</tr>
</tbody>
</table>

\[ \eta: 38\% \text{ (1sun)} \]
\[ \eta: 43.5\% \text{ (1sun)} \]

\[ \eta: 45\% \text{ (1000sun)} \]

\[ \eta: 53.3\% \text{ (1000sun)} \]
Achievements of our students
Semi polar (1-101) GaN on (001) Si


- Chip to chip optical interconnection in Si LSI
- Last one mile POF for low cost 4K and 8K TV

Maki Kushimoto

Laser on (001) Si
+c oriented GaN nanorod on (111) Si

- Solar cells
- Long wavelength light emitting devices
- Super junction vertical power devices
The c-constant linearly increased with increasing the Mg concentration.
### Mechanical Stack Multi Junction PV Cell

- **3 junction InGaN junction**
- \( E_g: 1.86 \text{ eV} \)
- \( V_{oc}: 3.0 \text{ V} \)
- \( J_{sc}: 14 \text{ mA/cm}^2 \)
- \( \eta: 38\% \) (1sun)
- \( \eta: 45\% \) (1000sun)
- **3 junction InGaN junction**
- \( E_g: 2.35 \text{ eV} \) (InGaN)
- \( V_{oc}: 4.63 \text{ V} \)
- \( J_{sc}: 9.54 \text{ mA/cm}^2 \)
- \( \eta: 38.2\% \) (1sun)
- \( \eta: 47.4\% \) (1000sun)
- **3 junction InGaN junction**
- \( E_g: 2.25 \text{ eV} \) (InGaN)
- \( V_{oc}: 4.44 \text{ V} \)
- \( J_{sc}: 11.15 \text{ mA/cm}^2 \)
- \( \eta: 43.5\% \) (1sun)
- \( \eta: 53.3\% \) (1000sun)

### Mechanical Stack PV Cells

#### Non polar simulation

- **\( In_{0.6}Ga_{0.4}N/GaN 100QWs \)**
- \( V_{oc}(V) \): 1.83
- \( J_{sc} (\text{mA/cm}^2) \): 24.27
- \( CE (%) \): 24.61
- \( \text{Fill factor} (%) \): 81.32

- **\( In_{0.6}Ga_{0.4}N/In_{0.2}Ga_{0.8}N 100QWs \)**
- \( V_{oc}(V) \): 1.57
- \( J_{sc} (\text{mA/cm}^2) \): 31.56
- \( CE (%) \): 29.82
- \( \text{Fill factor} (%) \): 90.48
My visit is supported by

Ministry of Foreign Affairs of Japan

ANA, an official partner of UNESCO
Acknowledgements

All the nitride researchers in the world!

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Members of Akasaki and Amano Laboratory, Meijo University (1992-2010)
Members of Amano, Yamaguchi and Honda Laboratory (2010-)
Toyoda Gosei, UVCR and Nikkiso Members