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

名古屋大学
NAGOYA UNIVERSITY

Our mission

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

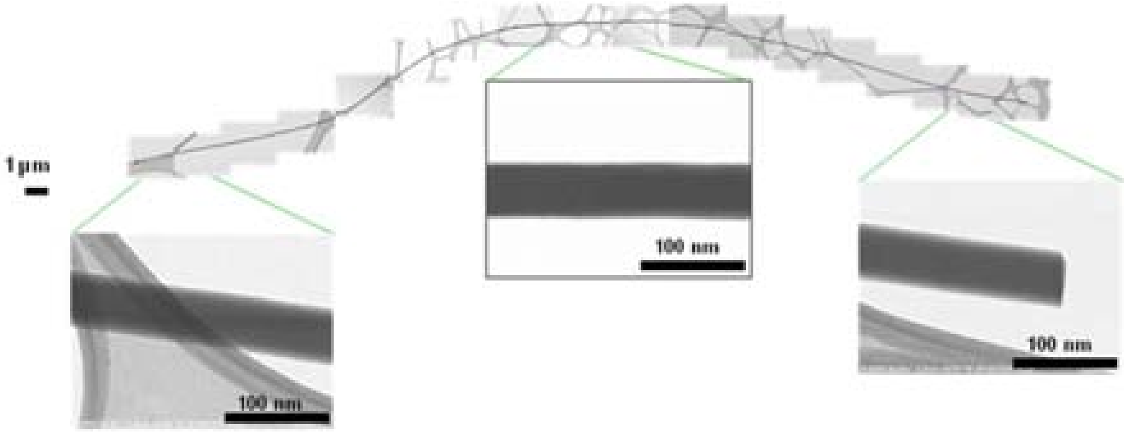
5 Undergraduate Students

3 Secretaries

36 people

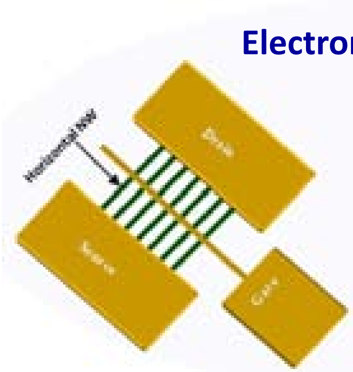
Post Doctoral Fellow

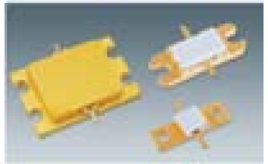
Dr. Kaddour Lekhal, Alegrila
PhD at Blaise Pascal University



World's longest GaN nanowire

Electronic Devices

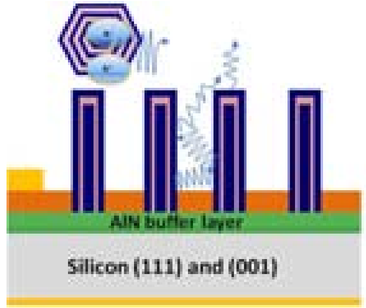




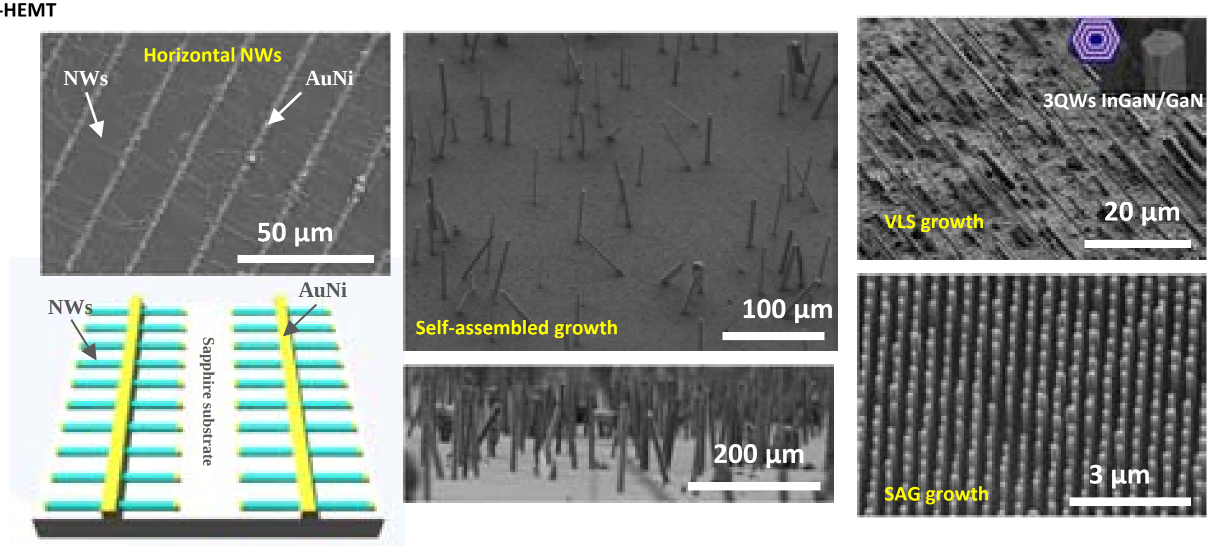
SUMITOMO Electric group

Device schematic of horizontal GaN NWs-HEMT

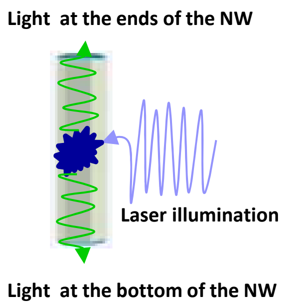
Light Emitting Diode (LED)

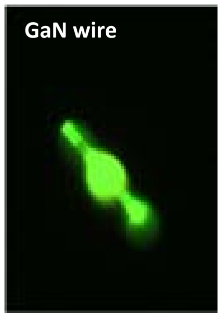


Growth of High-Aspect Ration GaN Nanowires

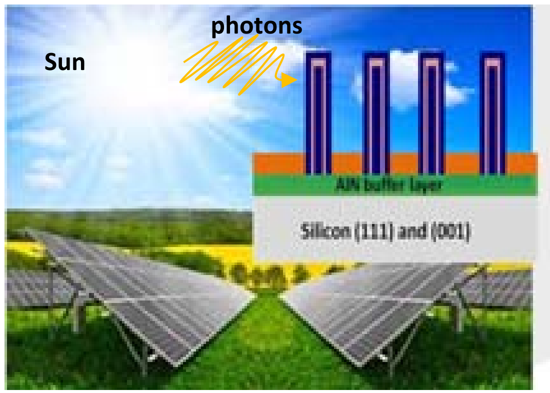


Waveguiding in 1D-nanostructures for Multi-Communication





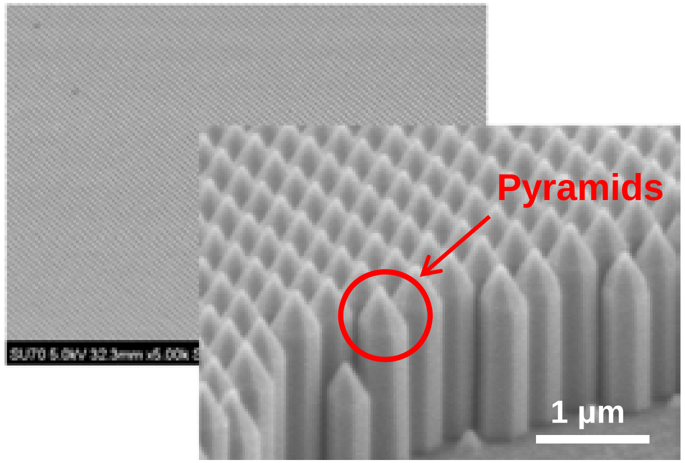
Solar Cells

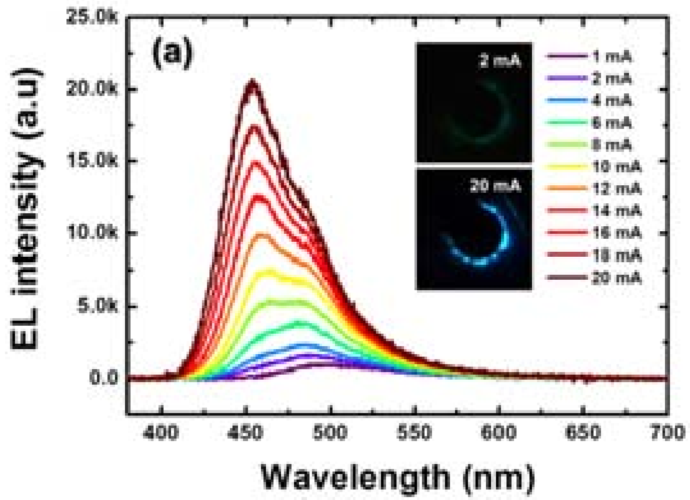


Post Doctoral Fellow

Dr. Si-Young Bae, Korea
PhD at GIST

✓ **Ga-polar NR LEDs**





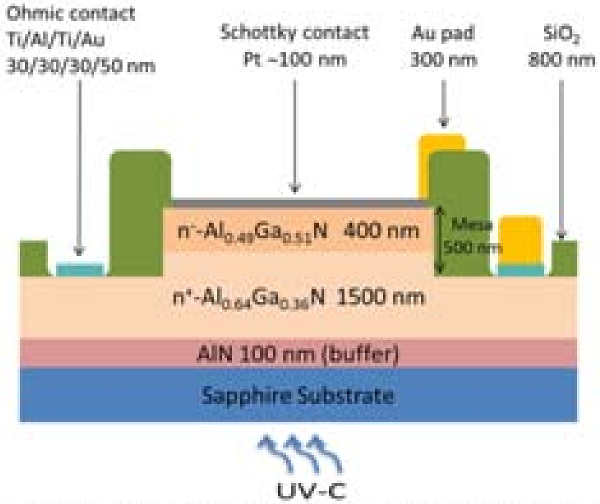
GaN nanowire LEDs

PhD Candidate

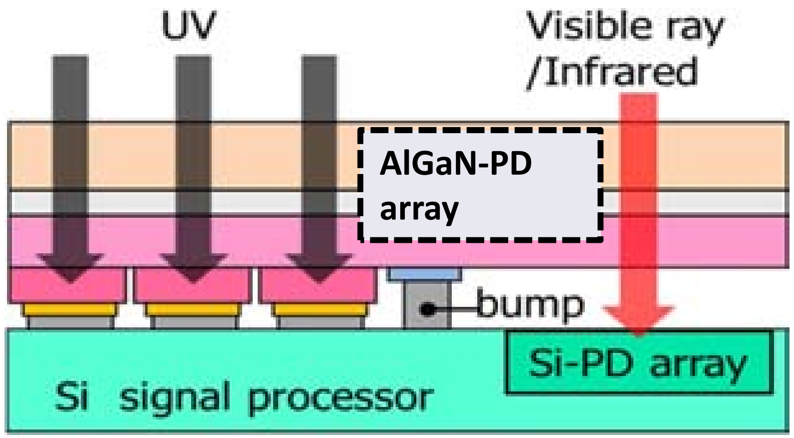
Representative of Guinean students at the third International Conference on Quality Assurance in Higher Education in Africa and the capacity building workshop held respectively in Dakar and St. Louis (Senegal) by UNESCO Bamako Cluster Office in collaboration with partners in 2008.

Mr. Barry Ousmane 1
Guinea

Achievement as a MC student at TUT



Back-illuminated AlGaN Schottky barrier diode (SBD)



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

Flame detector (UV light)
www.directindustry.com

onomy-GALEX
tesy NASA)

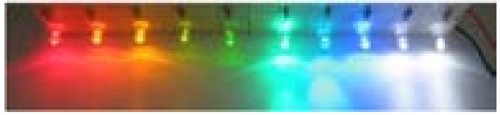
History of blue LEDs

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

Quantum mechanics based solid state lighting



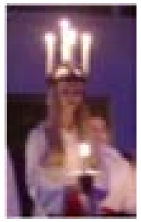
1962 Commercial LED
(Long history, Henry J. Round 1907, Nick Holionyak Jr., USA)
4^{th} generation

Energy transfer (Quantum mechanics)

1938 Fluorescent lamp
(Long history, 1901 Peter Cooper Hewitt, USA, 1927 Edmund Germer, 1938 Germany, George Innman, USA)
3^{rd} generation

1878 incandescent lamp
(Long history, Joseph Swan, UK, Thomas Edison, USA)
2^{nd} generation

Blackbody emission
(early stage of quantum mechanics)



～19C fire
1^{st} generation

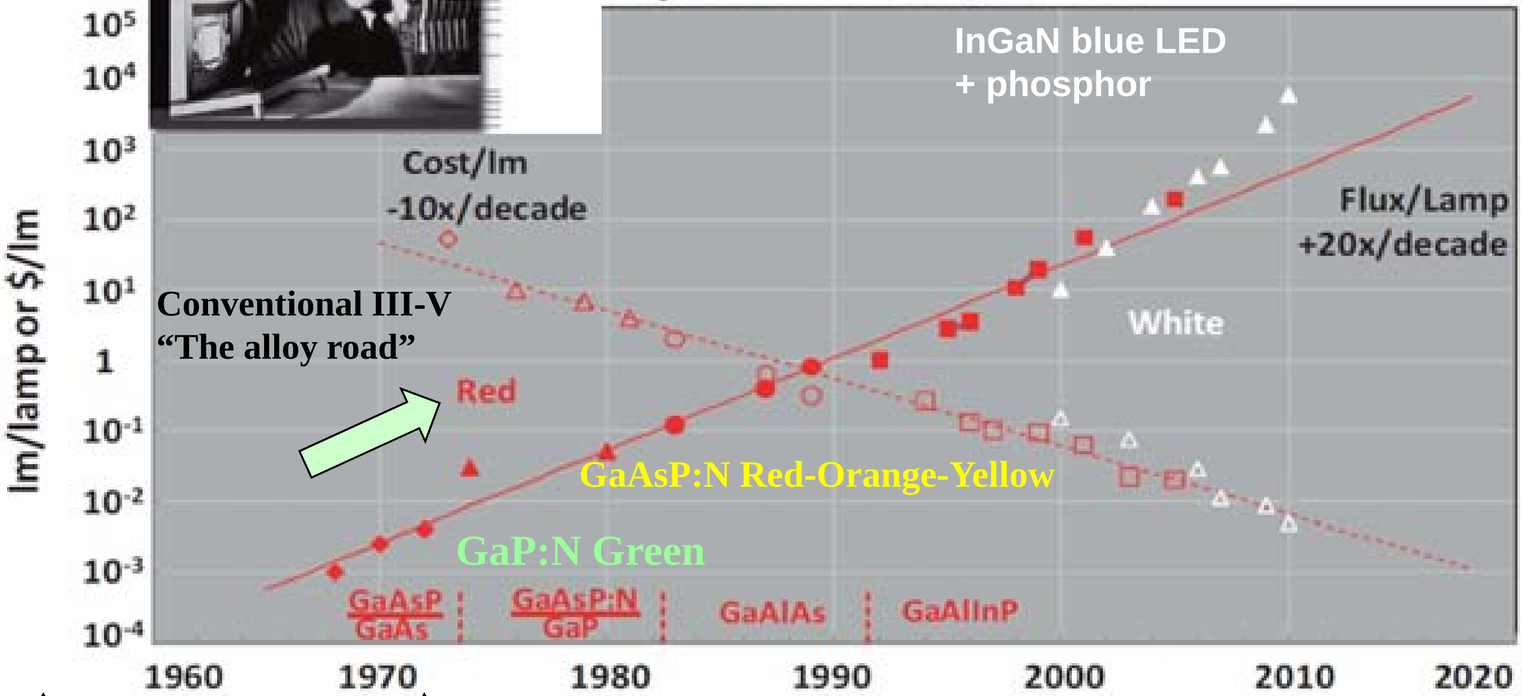
Chemical reaction

Luciaball, Dec.13, 2014 at Stockholm

http://www.gijyutu.com/kyouzai/mokei/ohki2/light.htm
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

1968 RCA　LCD



R. Haitz and J. Y. Tsao, phys. stat. sol. (a)208(2011)17

1971 J. Pankove, GaN MIS blue LED

1962 N. Holonyak Jr., GaAsP red LD

1952 H. Welker, GaAs, GaP

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
(Z. Naturforschg. 14 a, 264—271 [1959]; eingegangen am 18. Dezember 1958)

ZEITSCHRIFT FUR NATURFORSCHUNG A 14(1959)264.

H.G. Grimmeiss, H. Koelmans & I.B. Maak, *German patent*, DBP 1 077 330 (1960).

Dr. Grimmeiss at Lund University, Dec. 14, 2014 Aged 95

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)

J. Appl. Phys., 41(1970)4054.

Professor Monemar at Lund University, Dec. 14, 2014

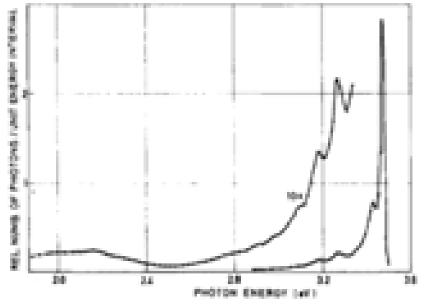
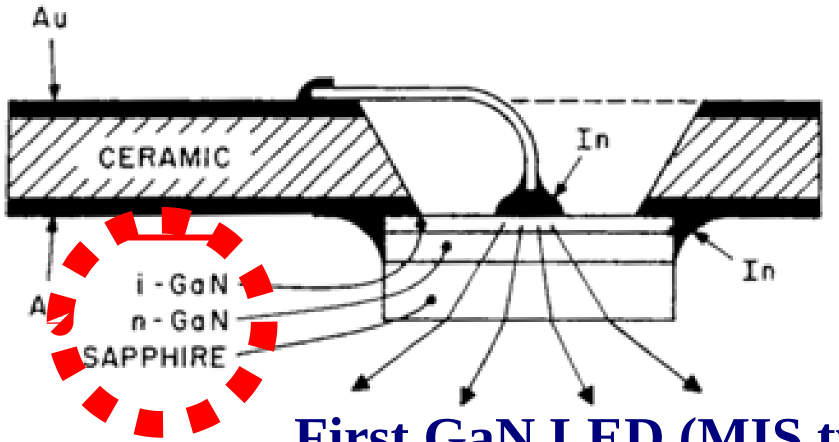


FIG. 1. Typical photoluminescence spectrum of Hg-doped GaN at 4.2°K. (The left curve is magnified 10 times.)

Lund Institute of Technology or Lunds Tekniska Högskola (LTH)

First GaN blue LED "Germination"



First GaN LED (MIS type)

Efficiency： 10^{-5}～3×10^{-4}

J. I. Pankove, E. A. Miller, D. Richman and J. E. Berkeyheiser: J.Lumin. 4 (1971) 63.

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

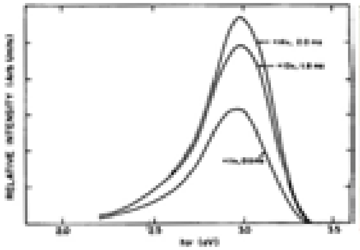
Dr. Kayann Short • Farrand Academic Program, University of Colorado at Boulder • 303-492-1267 • shortk@colorado.edu

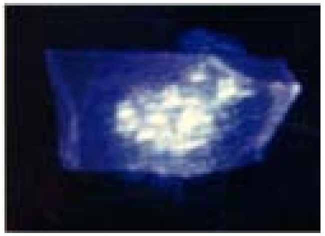
GaN blue LED research in 1970's "Endurance"

Violet luminescence of Mg-doped GaN **Mg**

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

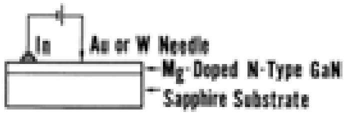
Appl. Phys. Lett., 22, 303 (1973).

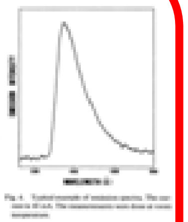




http://www.sslighting.net/lightimes/features/maruska_blue_led_history.pdf

Stanford University and RCA





Mg

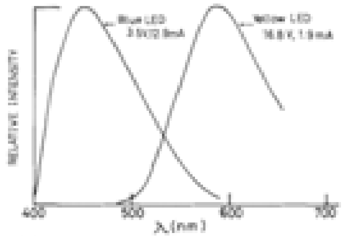
JAPAN. J. APPL. PHYS. Vol. 13 (1974), No. 8

Violet-Electroluminescence from Mg-Doped GaN Point Contact Diodes

Yasuo MORIMOTO

Research Laboratory, OKI Electric Industry Co., Ltd.,

Oki Electric



Optical Properties of GaN Light Emitting Diodes **Zn**

J. Electrochem. Soc., 123 (1978)1725.

Hitachi

Zn

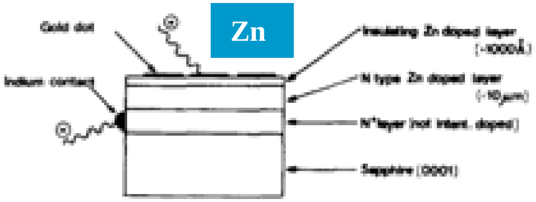
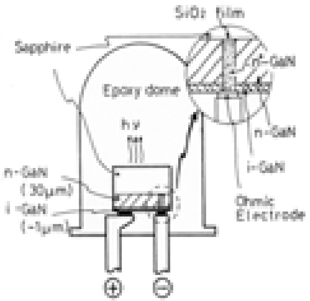


FIG. 3. Structure of the electroluminescent device.

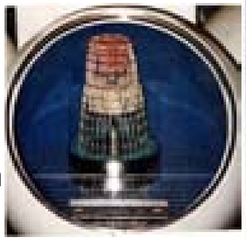
G. Jacob and D. Bois, Appl. Phys. Lett., 30 (1977) 412.

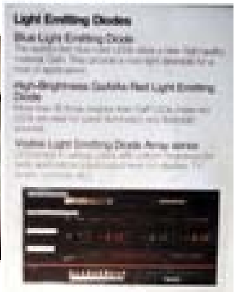
Philips



Zn

Matsushita Research Institute, Tokyo (Panasonic)





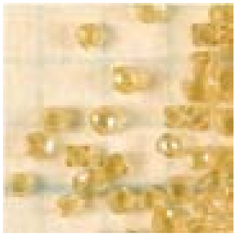
Y. Ohki, Y. Toyoda, H. Kobayashi and I. Akasaki, Intl. GaAs Symp., 479-484 (1981)

May 1981, New York

Why it was so difficult to grow high-quality GaN ?

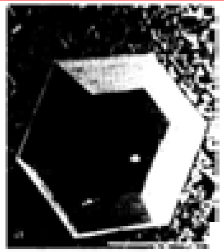
Bulk crystal Growth

Diamond
52,000 atm
1,200℃



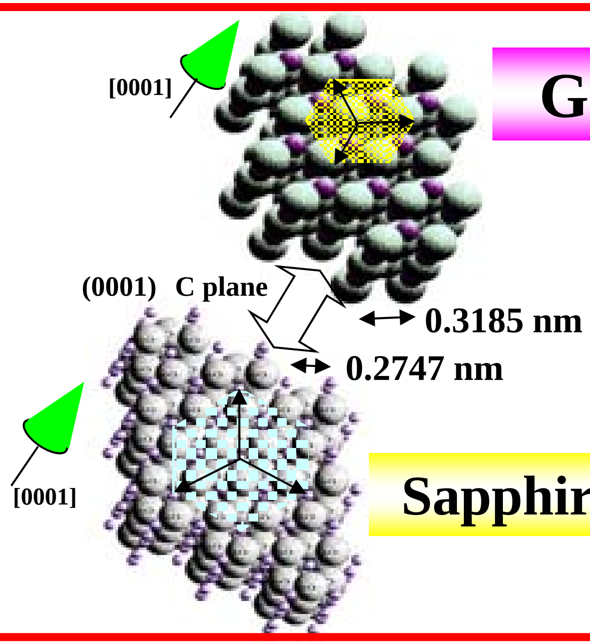
GaN
45,000 atm
2,530℃

J. Karpinski and S. Porowski, JCG, 66(1984)1.



50 µm

Thin film growth

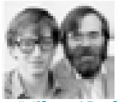


Lattice mismatch

$$\frac{0.3185 - 0.2747}{0.2747} \approx +16\%$$

In general, lattice mismatch should be <1%.

Why I was interested in blue LEDs?



Doug Wilson/Corbis

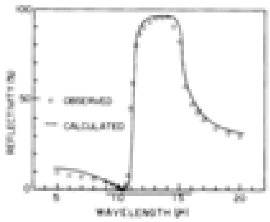
1975 Micro-soft by Bill Gates, Paul Allen
1976 Apple I by Steve Jobs, Stephen Wozniak

1970 | 1980 | 1990

GaN LED
by MBE and HVPE

1981
Nagoya Univ.

1967 Vapour-grown AlN
Matsushita Research Institute, Tokyo



I. Akasaki and M. Hashimoto
Solid State Commun.
5(1967)851.

Isamu Akasaki
1992- Meijo Univ.
(Prof. Emeritus Nagoya Univ.)

1982 Undergraduate

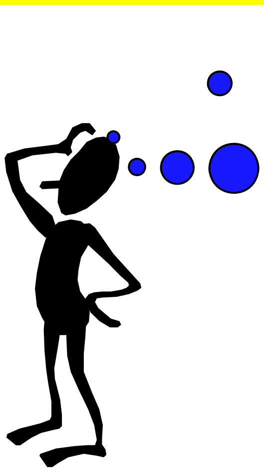
Graduation Research
"Nitride-Based Blue LED"

Braun tubes are too big !

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

http://www.mct.ne.jp/users/fjv/pc/pc8001.htm

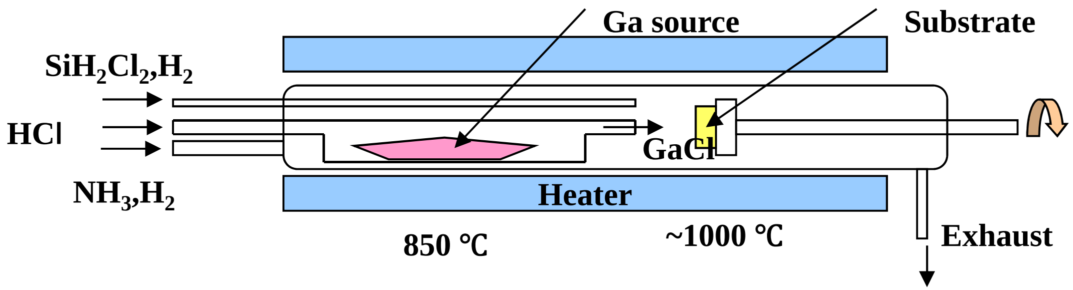
http://upload.wikimedia.org/wikipedia/commons/7/7e/Apple_II_IMG_4212.jpg



Change of growth method from HVPE to MOVPE

HVPE

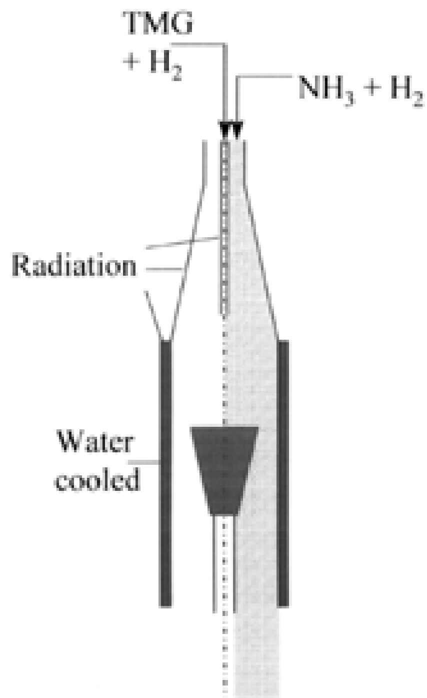
$GaCl + NH_3 \Rightarrow GaN + H_2 + HCl$



Courtesy of Dr. Usui, Furukawa

- Multi zone temperature control
- Bi-product NH_4Cl
- High growth rate >50 μm/hr

MOVPE



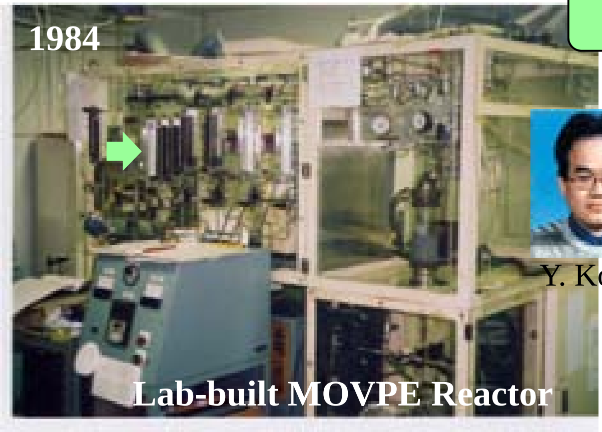
S. A. Safvi et al., J. Electrochem. Soc., 144(1997)1789.

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

HVPE: Halogen transport VPE
MOVPE: Metalorganic VPE

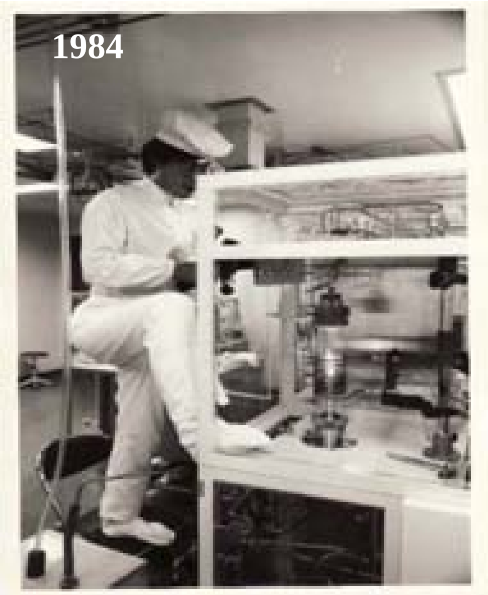
Funding situation of our lab. in mid 80's

Students built MOVPE reactor by themselves.

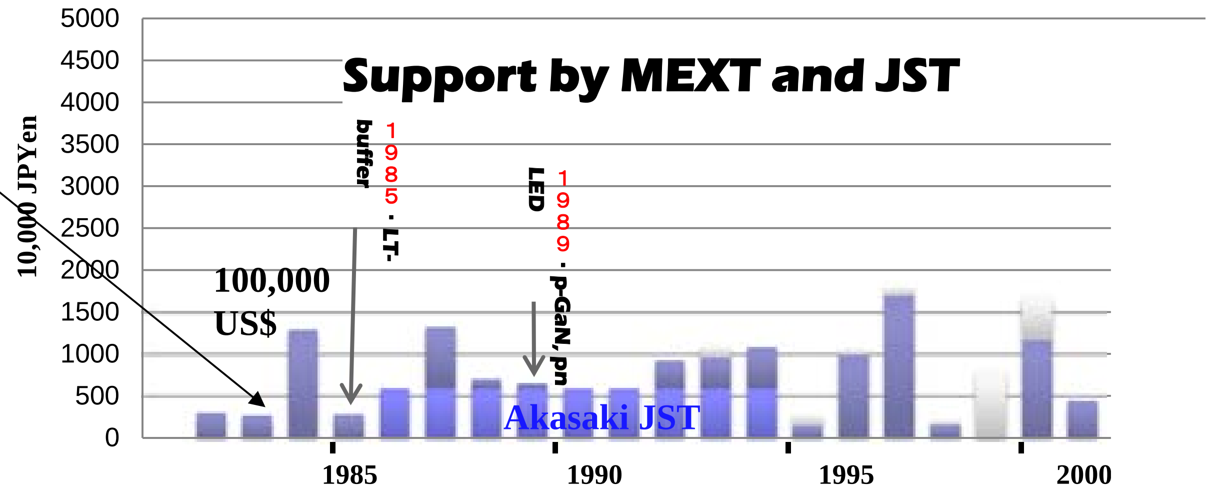


Y. Koide

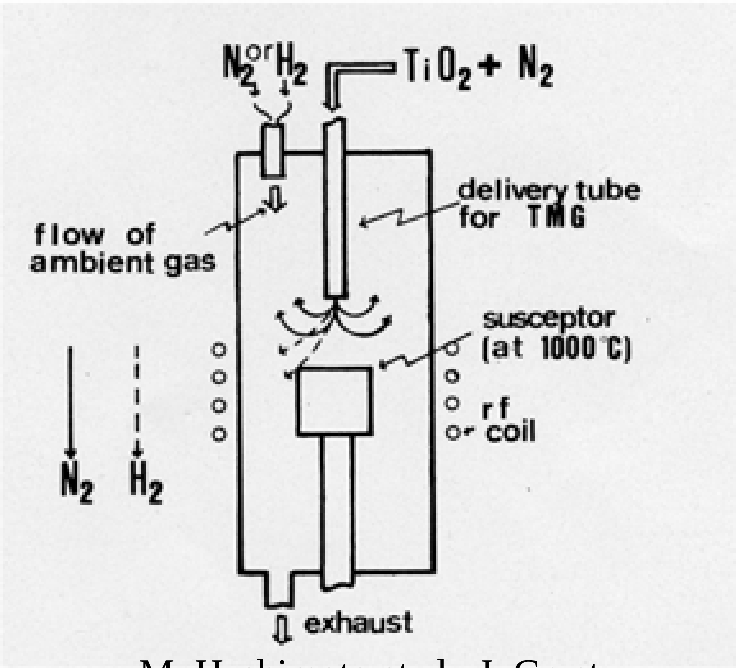
cf. Commercial MOVPE reactor ~1M US $



Measuring susceptor temperature using pyrometer

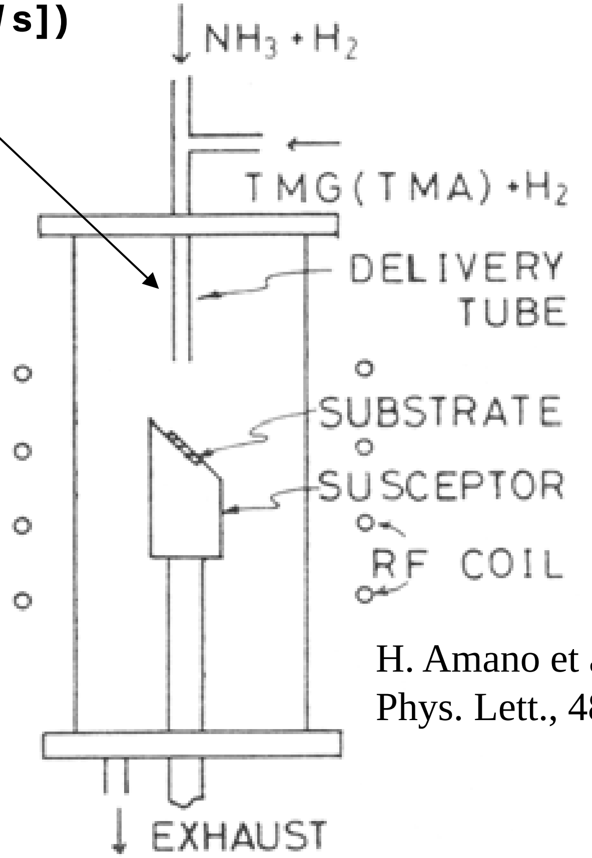


Reform of the MOVPE reactor by students



M. Hashimoto et al., J. Cryst, Growth, 68(1984)163.

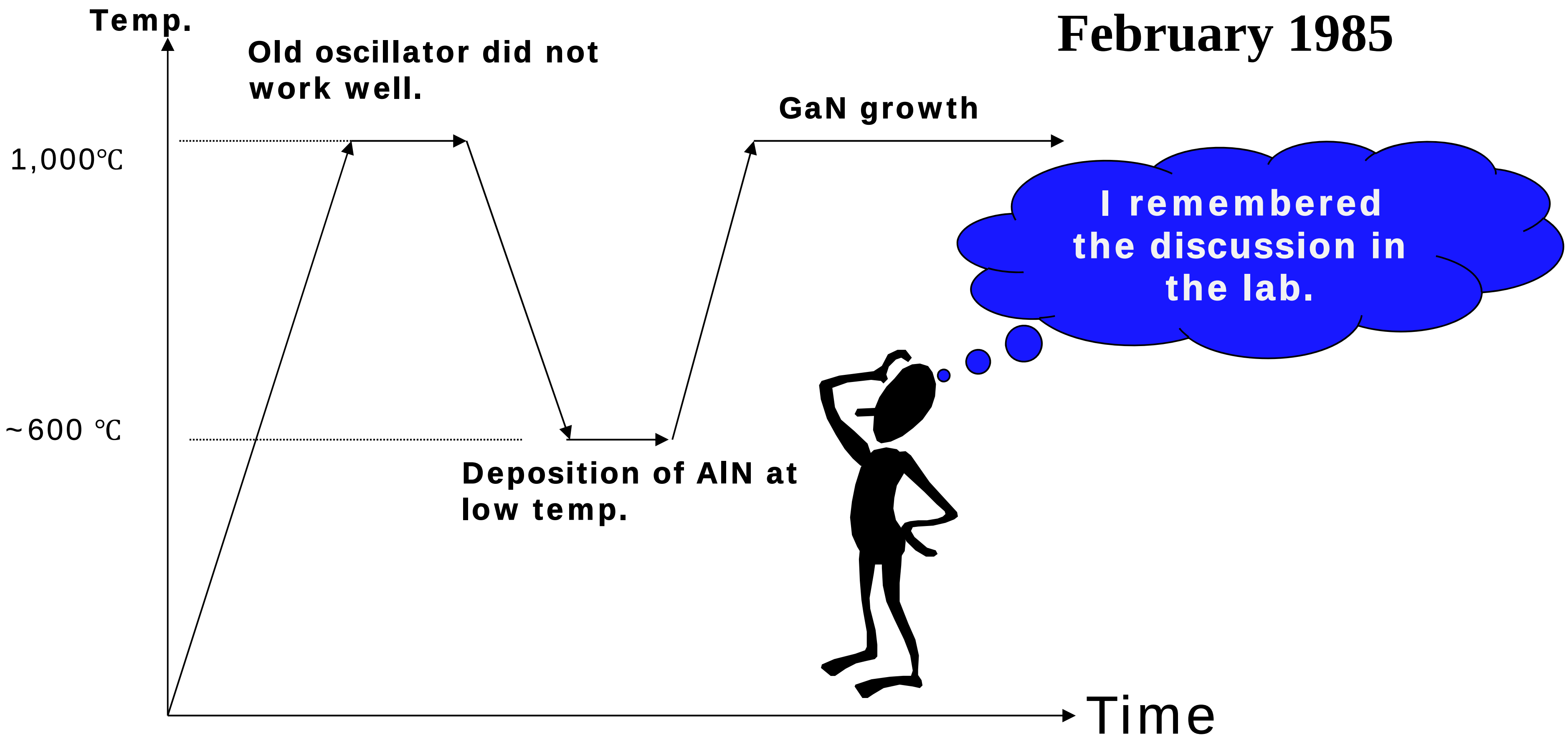
High speed gas flow ~5 [m/s]
(conventional ~ 0.2[m/s])



H. Amano et al., Appl. Phys. Lett., 48(1986)353.

Learn by trial and error

Low-temperature-deposited buffer layer

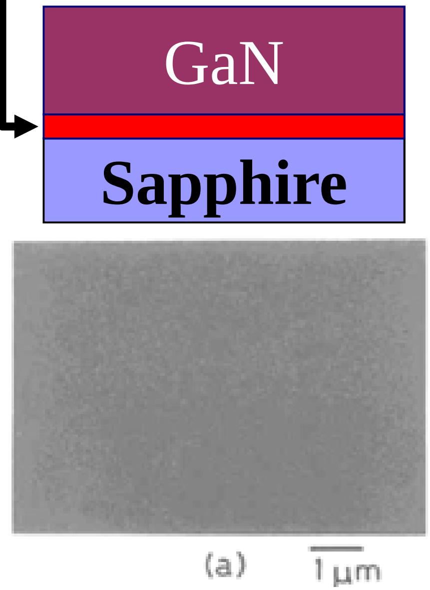


I knew that the substrate temperature should be higher than 1200℃ for the epitaxial growth of AlN.

Conventional

w/o LT buffer

1985 LT buffer



w LT buffer

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.

H. Amano et al., App. Phys. Lett., 48 (1986) 353.

1st journal paper for doctor thesis

Seeking p-GaN by Zn doping 1985-1988

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

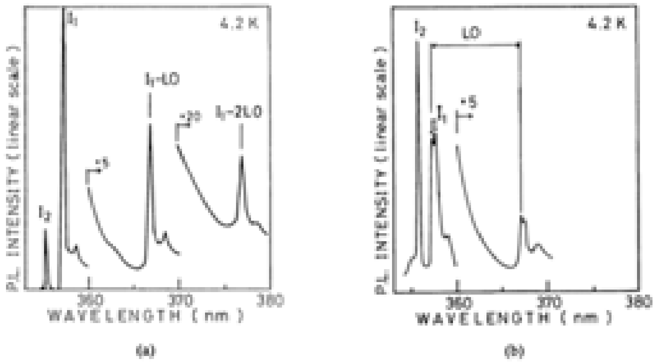
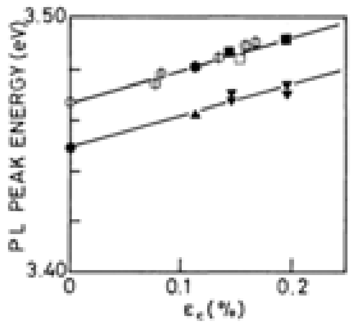
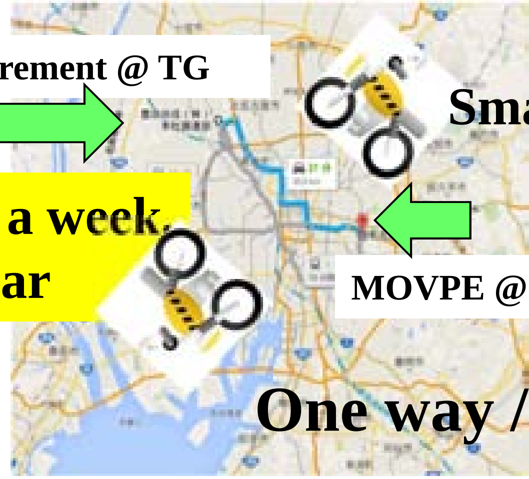


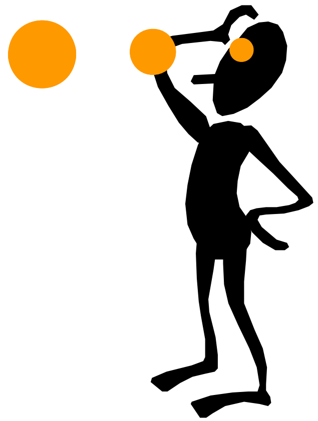
Fig. 3. 4.2 K PL spectrum of Zn-doped GaN grown on sapphire C-face (Fig. 3(a)) and A-face (Fig. 3(b)) substrates.



JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 27, NO. 8, AUGUST, 1988, pp. L1384-L1386

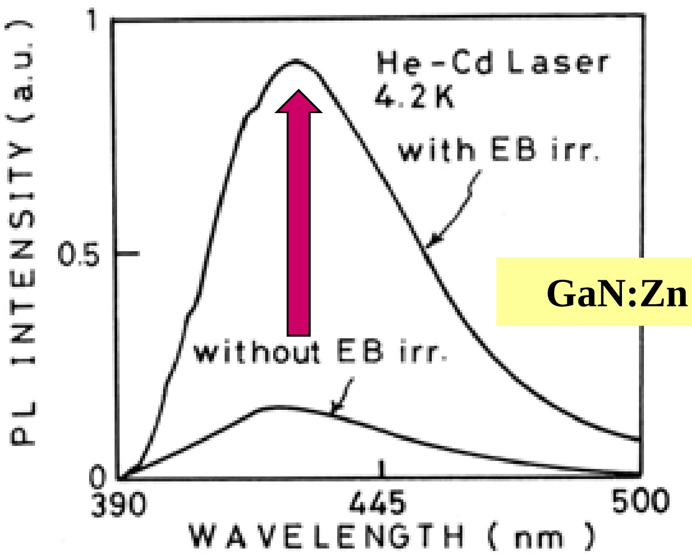


I was so excited with this result, and tried to present our efforts to JSAP annual meeting at 1987.



2nd journal paper for doctor thesis

Low energy electron beam irradiation (LEEBI)



GaN:Zn

FIGURE 3

Highly resistive

PL spectra of Zn-doped GaN with and without EB irradiation excited by 325nm of He-Cd laser

H. Amano et al., J. Lumin. 41&42 (1988) 121.

During my internship at NTT, 1988

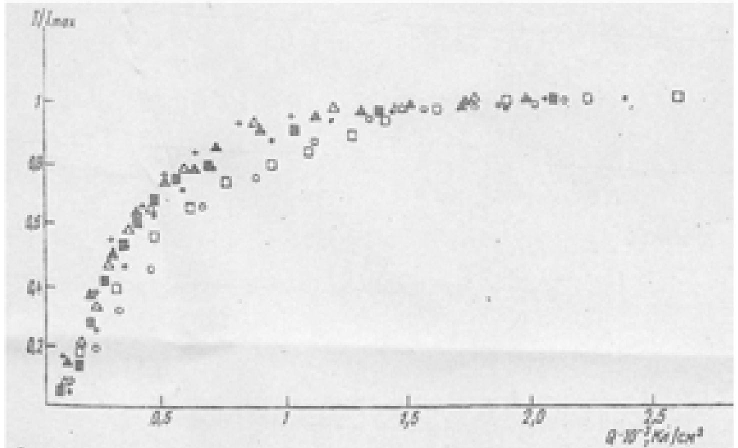
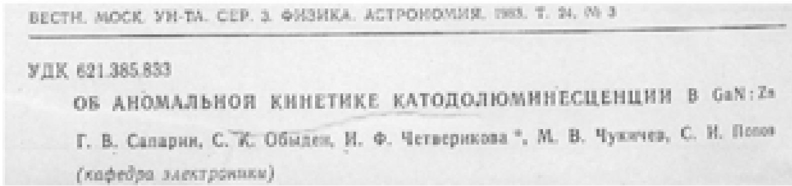


Рис. 2. Зависимость относительного изменения катодолюминесцентного сигнала вносимого заряда для GaN:Zn



ВЕСТН. МОСК. УН-ТА. СЕР. 3. ФИЗИКА. АСТРОНОМИЯ. 1983. Т. 24, № 3

УДК 621.385.833

ОБ АНОМАЛЬНОЙ КИНЕТИКЕ КАТОДОЛЮМИНЕСЦЕНЦИИ В GaN:Zn

Г. В. Сапарин, С. К. Обыден, И. Ф. Четверикова *, М. В. Чукичев, С. И. Попов

(кафедра электроники)

The anomalous kinetics of cathode luminescence in GaN:Zn
G. V. Saparin et al., Moskovskii Universitet, Vestnik, Seriia 3 - Fizika, Astronomiia (ISSN 0579-9392), vol. 24, May-June 1983, p. 56-59. In Russian

1983

…So, I could not finish Doctor thesis in three years.

Selection of best dopant

Selection of the dopant

Activation energy of acceptor in GaP

Zn : higher ×

Mg: Lower ○

第9章 不　純　物

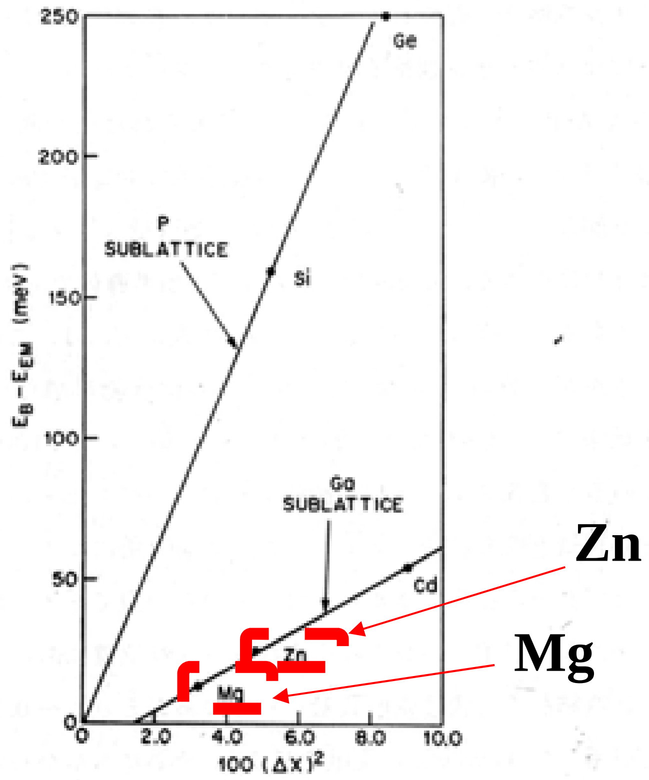


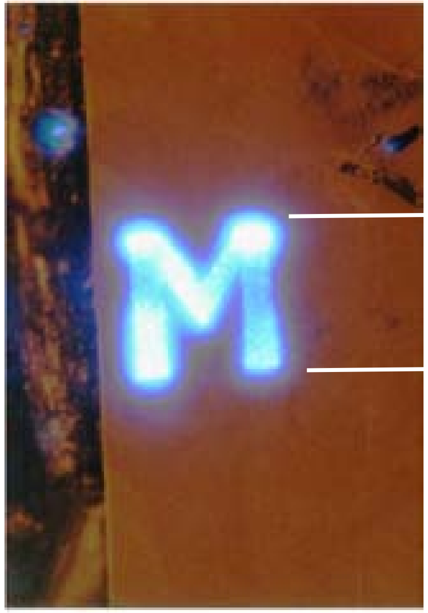
図9.11 GaPの単原子アクセプターの結合エネルギーに対する中心殻補正．P副格子上に置換したⅣ列不純物とGe副格子上に置換したⅡ列不純物との間の傾斜についての4倍の差に注目［データおよび有効質量エネルギー E_{EM} はP.J.Dean達による．*J. Appl. Phys.* 41 3474 (1970)］

J. C. Phillips,

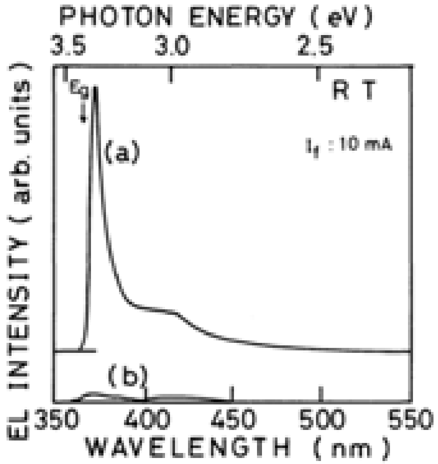
“Bonds and Bands in Semiconductors”

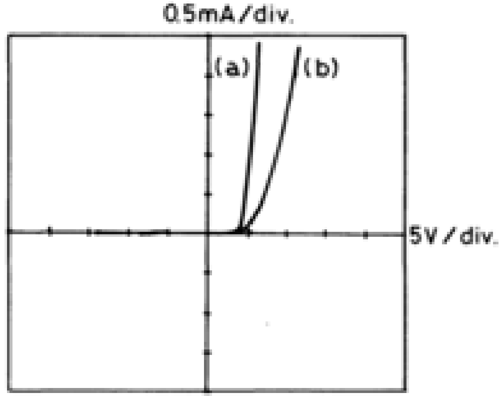
P-type GaN:Mg by LEEBI "Flowering"

M. Kito



50μm



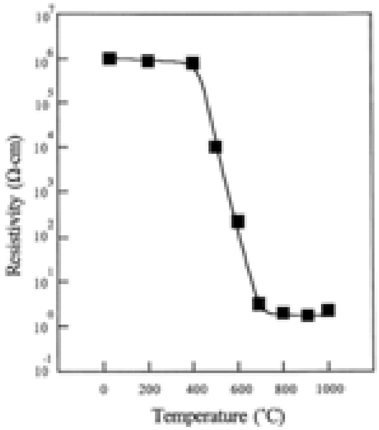


(a) w LEEBI
(b) wo LEEBI

H. Amano et al., Jpn. J. Appl. Phys. 28 (1989) L2112.

Thermal annealing and the mechanism

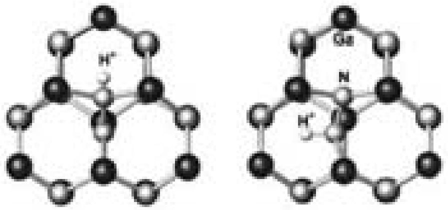
1992 Thermal annealing
S. Nakamura et al. Jpn. J. Appl. Phys. 31(1992)1258.



Thermal annealing

S. Nakamura et al, Jpn. J. Appl. Phys. 31 (1992) L139.
Van Vechten et al., Jpn. J. Appl. Phys. 31 (1992) 3662.

Hydrogen passivation

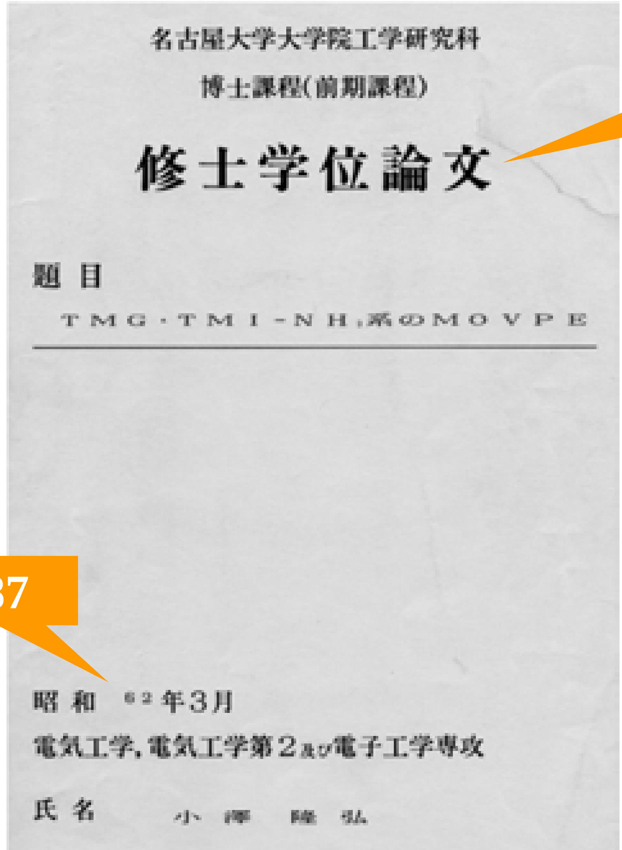


Lattice location of hydrogen in Mg doped GaN

W. R. Wampler,[a] S. M. Myers, A. F. Wright, J. C. Barbour, C. H. Seager, and J. Han
Sandia National Laboratories, Albuquerque, New Mexico 87185-1056

J. Appl. Phys, 90(2001)108.

Good fortune that we missed -InGaN-


名古屋大学大学院工学研究科
博士課程(前期課程)

修士学位論文

題目
TMG・TMI－NH₃系のMOVPE

昭和 62年3月
電気工学，電気工学第2及び電子工学専攻
氏名 小 澤 隆 弘

1987 Master thesis
Nagoya University

1987

We used <u>**hydrogen**</u>
as the carrier gas.

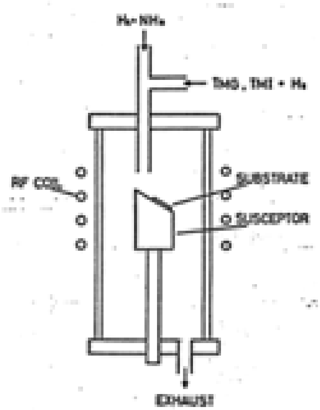


図2－1　成長炉概略図

表2－1　成長条件

－ AlNバッファ層 －	
TMA(15℃)	20cc/min
H_2	3 l/min
NH_3	2 l/min
成長温度	940℃
成長時間	25～40sec
－ InN層 －	
TMI(0～20℃)	100cc/min
H_2	2 l/min
NH_3	1.5 l/min
成長温度	500～1000℃
成長時間	20～60min

1989 International Conference on GaAs and Related Compounds

1989

(a) V /Ⅲ =16000 (b) V /Ⅲ =80000 (c) V /Ⅲ =165000

Inst. Phys. Conf. Ser. No 106 : Chapter 3
Paper Presented at Int. Symp. GaAs and Related Compounds, Karuizawa, Japan, 1989

Wide-gap semiconductor (In,Ga)N

T. Matsuoka, *H. Tanaka, T. Sasaki and A. Katsui

NTT OPTO-ELECTRONICS LABORATPRIES Tokai, Ibaraki, 319-11 JAPAN
*NTT APPLIED ELECTRONICS LAABOTATORIES Musashino, Tokyo, 180 JAPAN

2 CRYSTAL GROWTH

Films were grown by MOVPE in a vertical cold wall reactor. The source gases were trimethylindium (TMI), triethylgallium (TEG), trimethylaluminum (TMA) and purified ammonia. Both carrier and bubbling gases were purified nitrogen. The flow rate ratio of ammonia to the sum of group III sources was varied from 2,000 to 20,000, and the growth temperature was varied from 500 to 800° C. The reactor pressure was held at 76 Torr.

They used **nitrogen** as the carrier gas.

Blue luminescence at room temperature

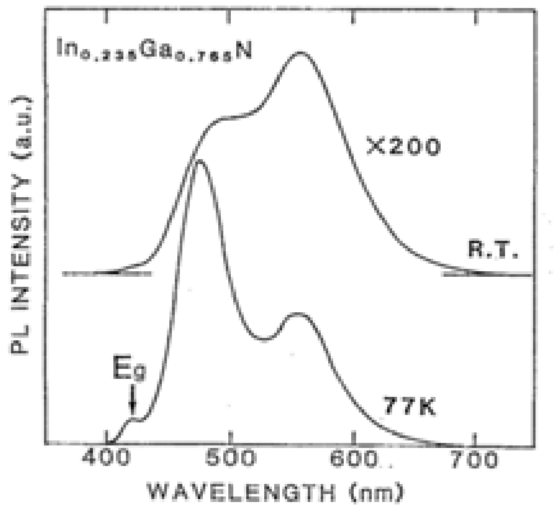


FIG. 3. Photoluminescence spectra of $In_{0.235}Ga_{0.765}N$.

N. Yoshimoto et al.,
Appl. Phys. Lett., 59(1991)2251.

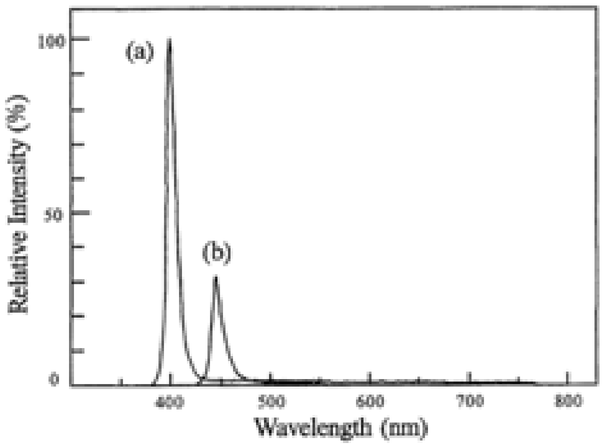
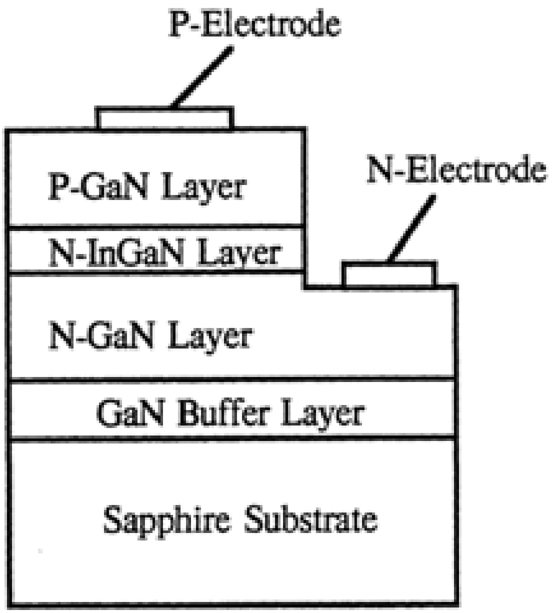


Fig. 3. Room-temperature PL spectra of the InGaN films grown on GaN films under the same growth conditions except for the InGaN growth temperature. The growth temperatures of InGaN were (a) 830°C and (b) 780°C.

S. Nakamura and T. Mukai
Jpn. J. Appl. Phys., 31(1992)L1457.

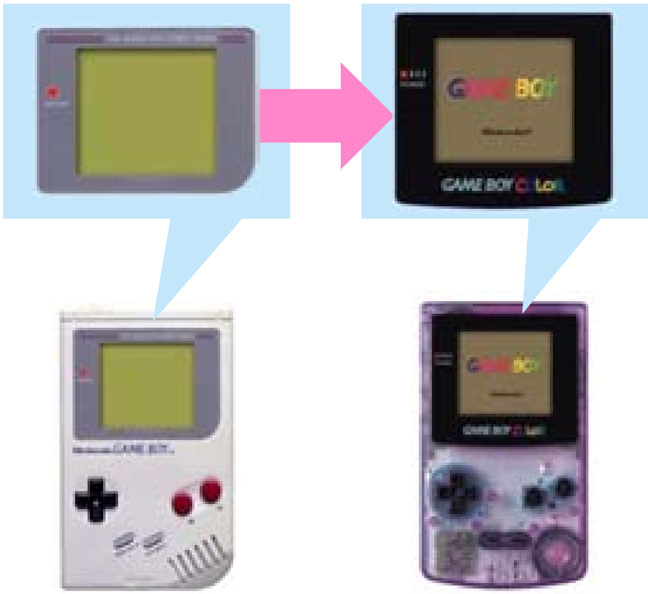
World's first commercialization "Fruition"



S. Nakamura et al., Jpn. J. Appl. Phys., 32 (1993) L8.

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
http://www.docomo-cs-tohoku.co.jp/museum/tanmatsu/p.html

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

Increase of smartphone addiction ?

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

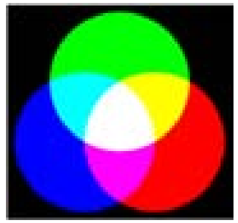
http://blogs.yahoo.co.jp/fpdxw092/61943354.html

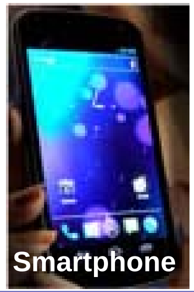
http://dankai-hiroba.cocolog-nifty.com/blog/2007/07/post_5274.html

White LEDs "Contribution to society"

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

Shuji Nakamiura
(Nichia, now UCSB)





Three primary colors

Wide-gap GaN
Blue LED

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

Nichia

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

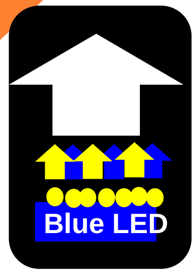
1987 JST
1995 Commercialization

Toyoda Gosei

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

Nichia

1996：White LED

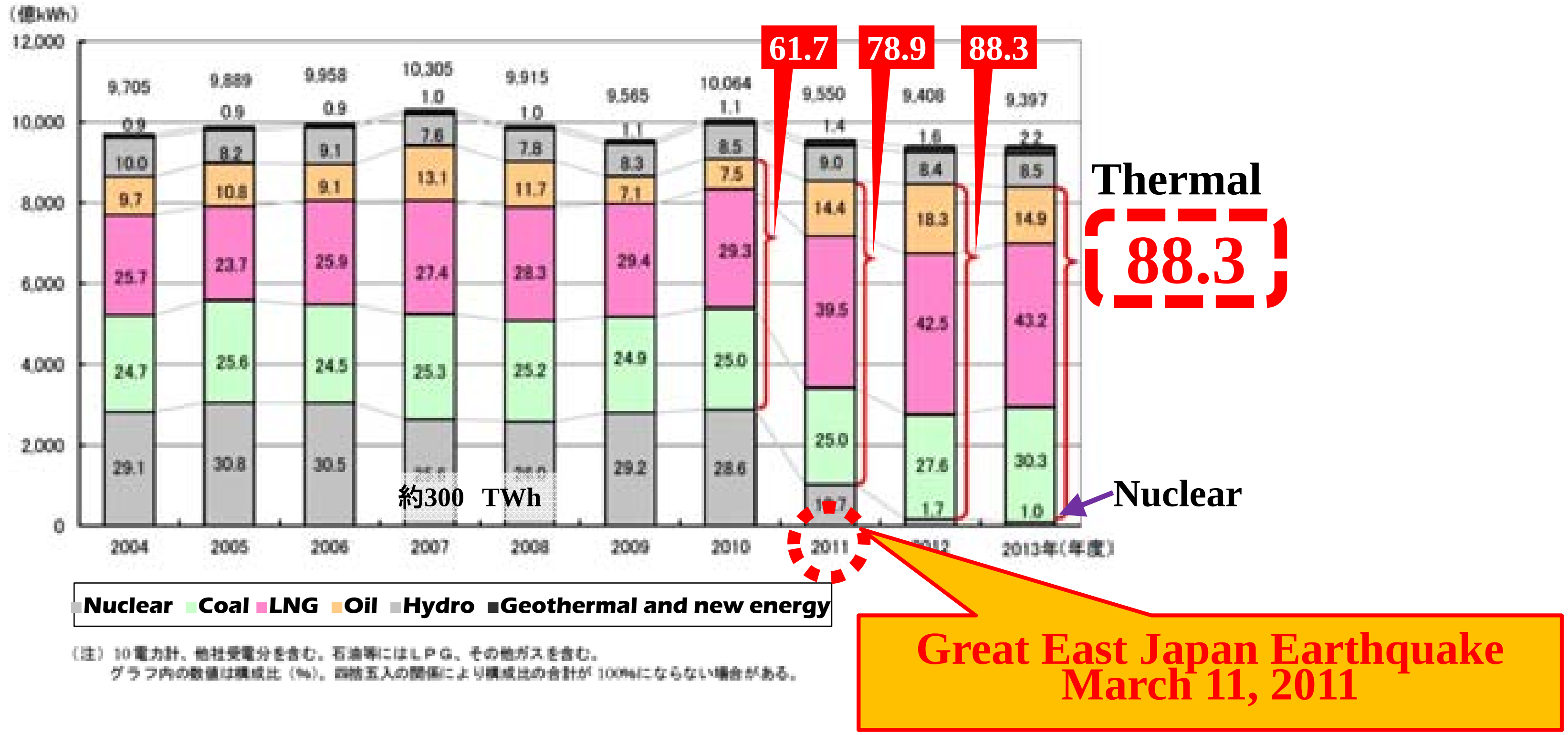


Yellow Phosphor

How InGaN LEDs contribute to saving energy

Electricity generation in Japan

2014.5.23
The Federation of Electric Power Companies of Japan



How InGaN LEDs contribute to saving energy

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

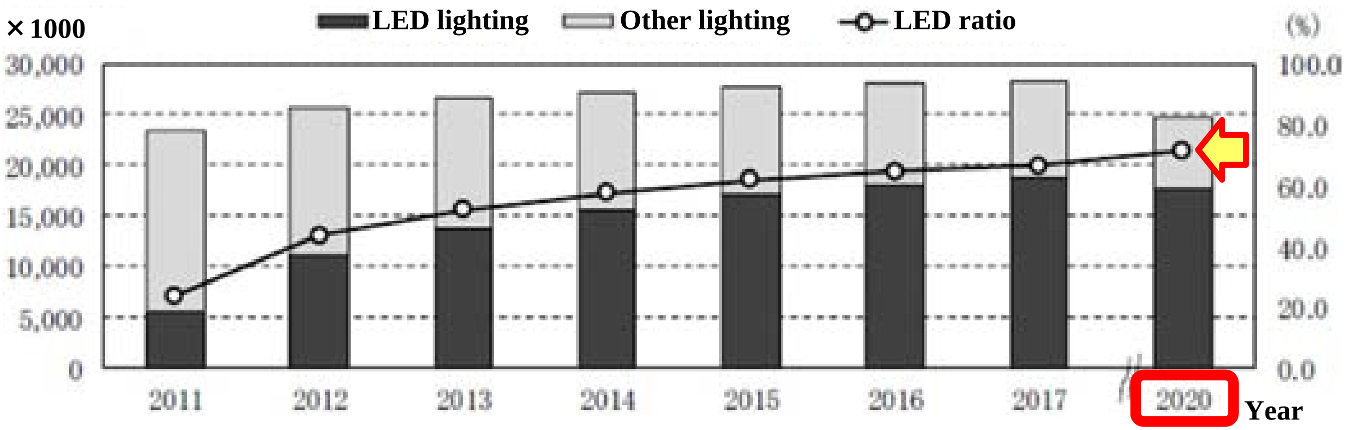
	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	**694**	**635**	**631**	**641**	**648**	**13,535**
Residential	173	142	138	146	153	3,105
Commercial	346	325	321	320	316	6,806
Industrial	58	49	44	41	38	947
Outdoor Stationary	116	119	128	135	141	2,676
LED market share (% of lm-hr)	**-**	**9.5%**	**35.8%**	**59.0%**	**73.7%**	**-**
Residential	-	8.1%	37.6%	60.7%	72.3%	-
Commercial	-	5.0%	27.8%	52.5%	70.4%	-
Industrial	-	8.8%	36.0%	59.2%	72.3%	-
Outdoor Stationary	-	29.0%	64.2%	81.6%	87.2%	-
Site electricity savings (TWh)	**-**	**21**	**122**	**217**	**297**	**2,672**
Residential	-	7	51	82	102	1,009
Commercial	-	6	38	73	111	902
Industrial	-	0	3	8	11	88
Outdoor Stationary	-	7	30	54	73	673
Site electricity savings (%)	**-**	**3.3%**	**19.4%**	**33.9%**	**45.8%**	**19.7%**
Residential	-	5.1%	37.3%	56.7%	66.9%	32.5%
Commercial	-	1.9%	11.7%	22.9%	35.0%	13.3%
Industrial	-	0.8%	7.4%	18.3%	29.4%	9.3%
Outdoor Stationary	-	6.2%	23.7%	40.2%	51.7%	25.2%

U.S. DOE Energy Savings Potential of Solid-State Lighting in General Illumination Applications, Jan.2012

Total consumption 4273 TWh

297/4273～7%

Forecast of ratio of LED lighting in Japan



Data from Fuji Chimera Research Institute, Inc.,
2014 LED Related Market Survey

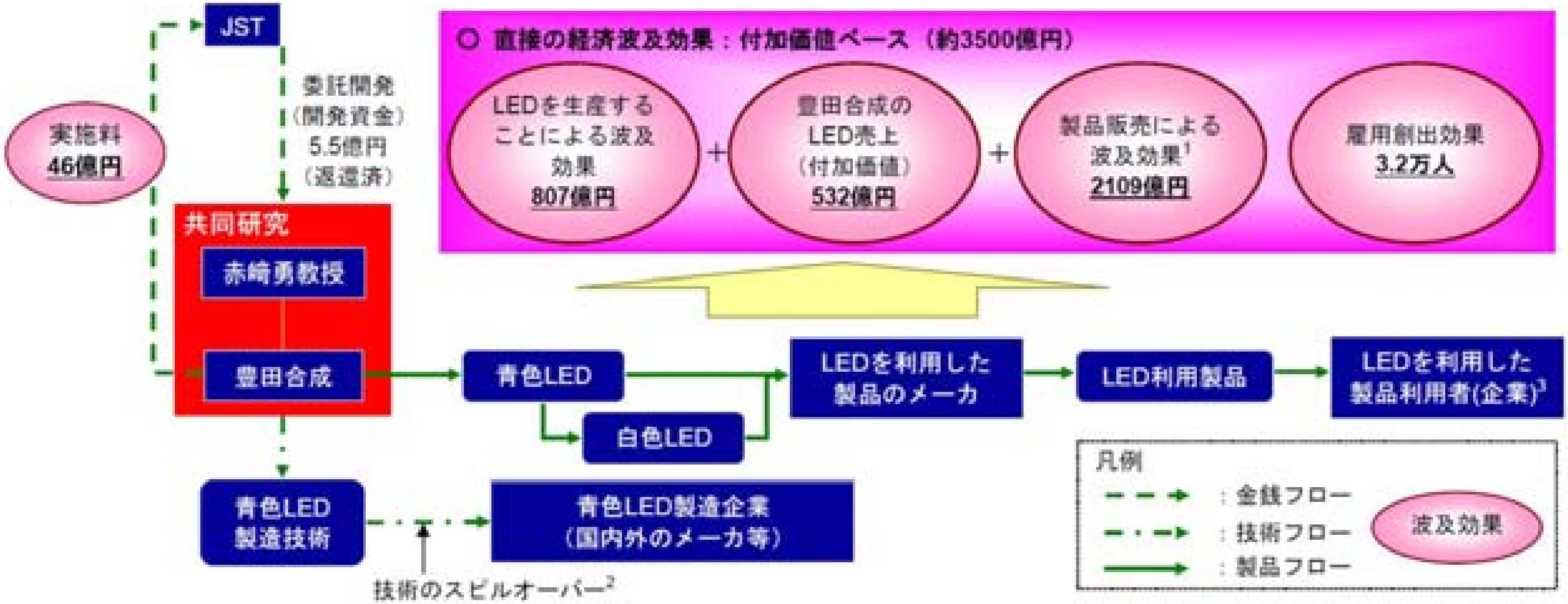
In Japan, we can reduce total electricity consumption by about 7% （=1T JP Yen） by 2020.

For the children living on Earth


"Mongolia Ger" by Japanese Wikipedia


Mr.Luvsannyam Gantumur,
Minister for Education and Science of Mongolia

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：赤﨑勇 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

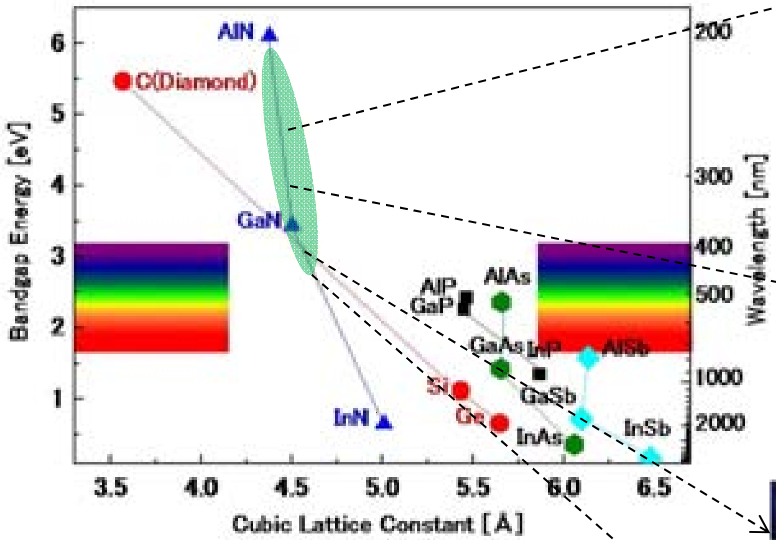


http://www.jst.go.jp/itaku/result/ef-1.pdf

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

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

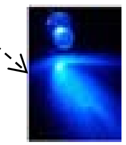


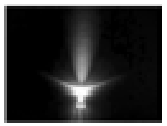
http://blogs.unicef.org/2014/03/20/world-water-day-2014-the-forgotten-768-million/

High frequency and high power HEMT

http://www.sei.co.jp/newsletter/2010/09/6a.html

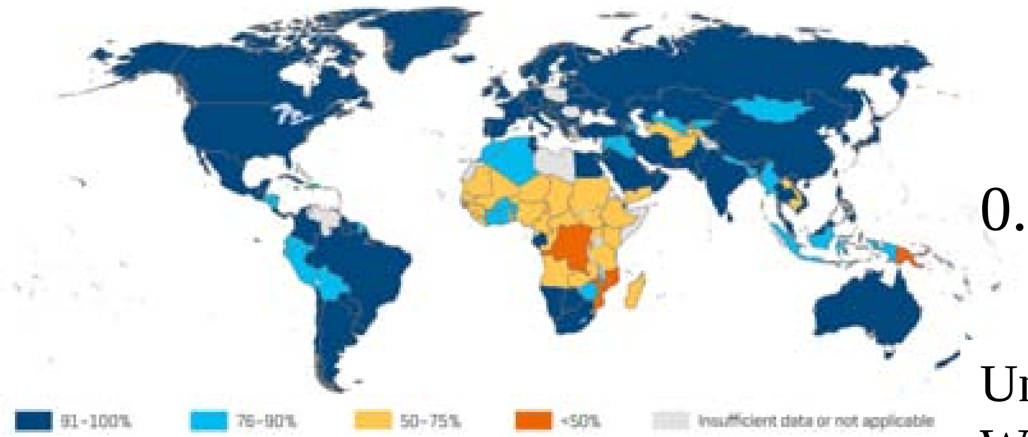
Violet LDs for Blu-ray Disc



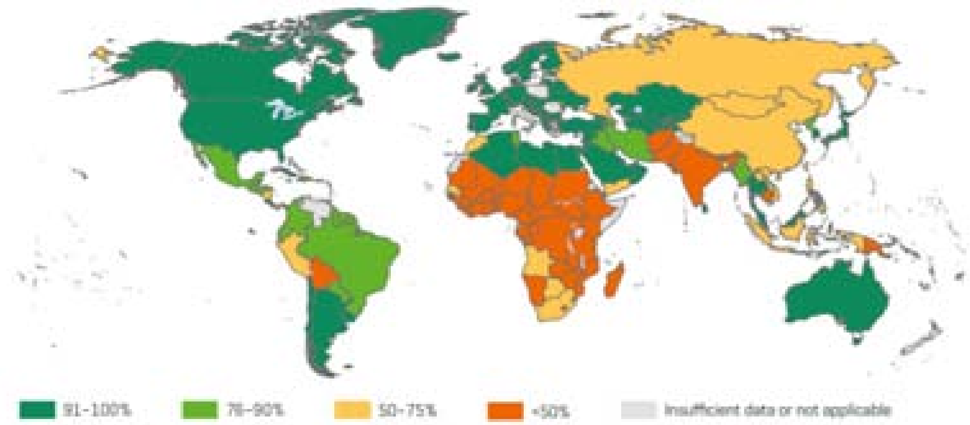


Blue LEDs, White LEDs

People who cannot access to safe water



Drinking water coverage 2012



Sanitation facility coverage 2012

0.77 Billion people

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

2.6 Billion people

http://www.unicef.org/gambia/Progress_on_drinking_water_and_sanitation_2014_update.pdf

Our development of AlGaN based DUV LEDs

NEDO
Sep.1997-Mar.2000 with Osaka Gas:A. Hirano
Sep. 2001-Mar.2004 with ASU:F. Ponce, Univ. Bristol: D. Cherns
Sep.2002-Mar.2006 with Osaka Gas: A. Hirano, Kyosemi: H. Tomosawa
Sep.2004-Mar.2006

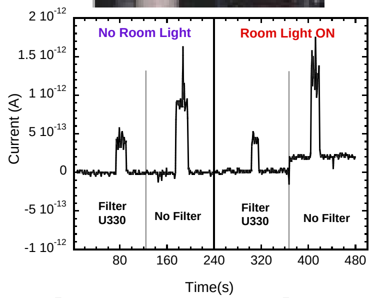
JSPS, MEXT
2003-2005 Grant-in-Aid for Scientific Research (A)
2006-2010 Grant-in-Aid for Scientific Research on Priority Area
2008-2012 Knowledge Cluster
2013-2015 Grant-in-Aid for Specially Promoted Area

1980 1990 2000 2010 2020

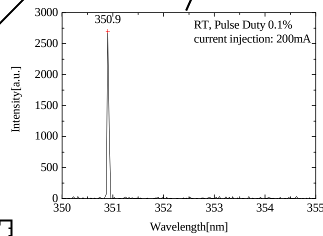
1986 1997 2006 2012 2015

AlGaN Growth by MOVPE

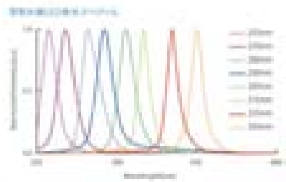
Nagoya Univ.
Dr. Koide



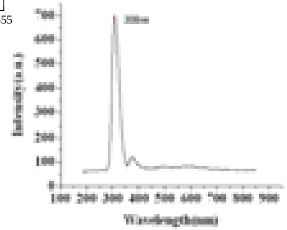
Flame sensor, Osaka Gas



UV LD
Meijo Univ.
Hamamatsu Photonics
ASU
Univ. Bristol



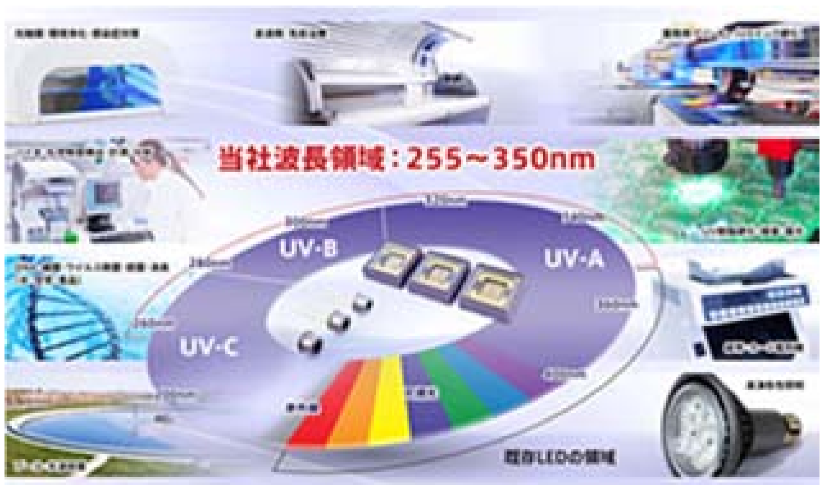
UV Craftry



DUV LED
Osaka Gas, Kyosemi

Nikkiso

Applications



Our development of AlGaN based DUV LEDs

DUV-LED Sterilization

DUV-LED array module

NIKKISO

Other applications of group III nitrides

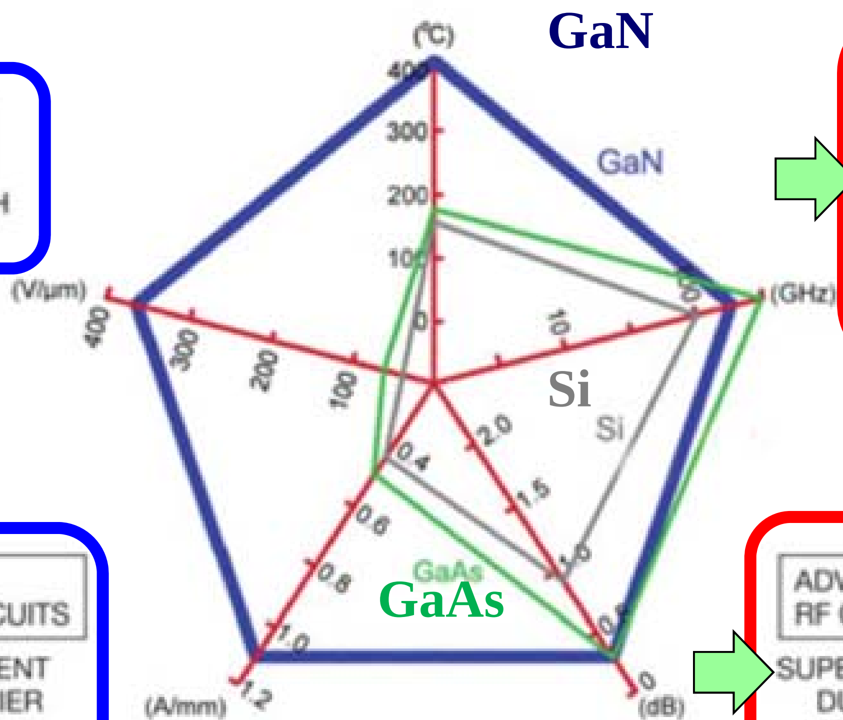
Why nitrides are so attractive for power device applications?

ADVANTAGEOUS IN POWER-SUPPLY CIRCUITS

HIGH OPERATING TEMPERATURE DUE TO LARGE BANDGAP AND HIGH POTENTIAL BARRIER

ADVANTAGEOUS IN POWER-SUPPLY CIRCUITS

HIGH BREAKDOWN STRENGTH DUE TO LARGE BANDGAP



ADVANTAGEOUS IN RF CIRCUITS

HIGH MAXIMUM OSCILLATION FREQUENCY DUE TO HIGH ELECTRIC FIELD SATURATION SPEED AND LOW PARASITIC CAPACITY

ADVANTAGEOUS IN POWER-SUPPLY CIRCUITS

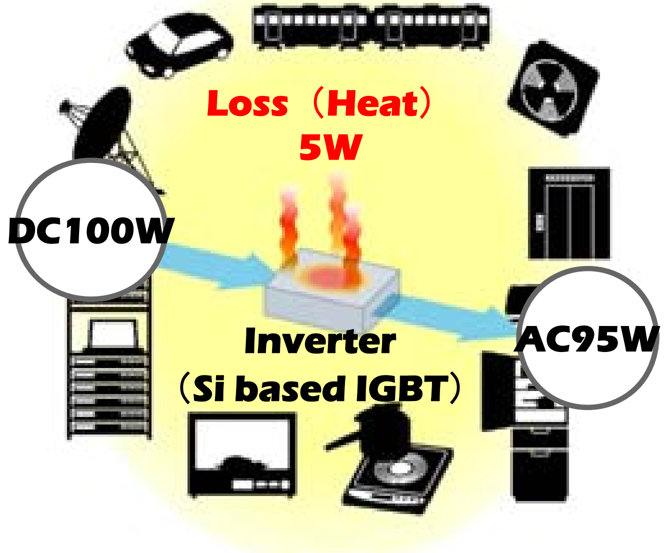
HIGH MAXIMUM CURRENT DUE TO HIGH CARRIER DENSITY AND HIGH ELECTRON MOBILITY

ADVANTAGEOUS IN RF CIRCUITS

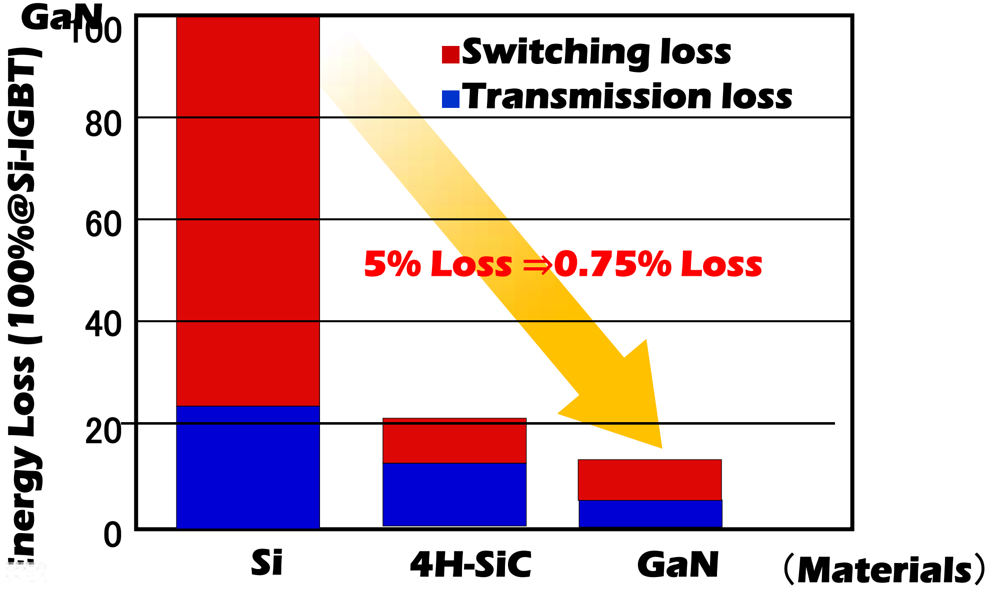
SUPERIOR NOISE FACTOR DUE TO LOW CARRIER SCATTERING AND LOW RF LOSSES

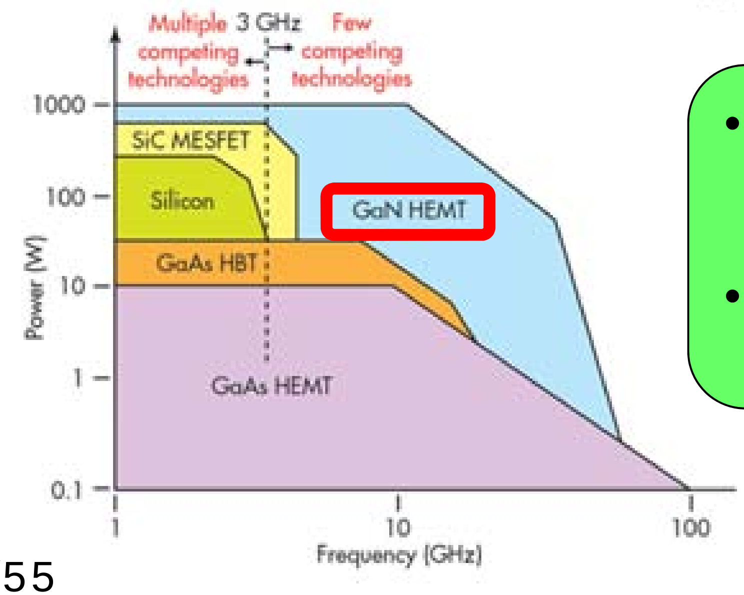
http://www.edn.com/Pdf/ViewPdf?contentItemId=4409627

Energy savings with GaN-based power devices



Highest efficiency power devices can be expected by using GaN



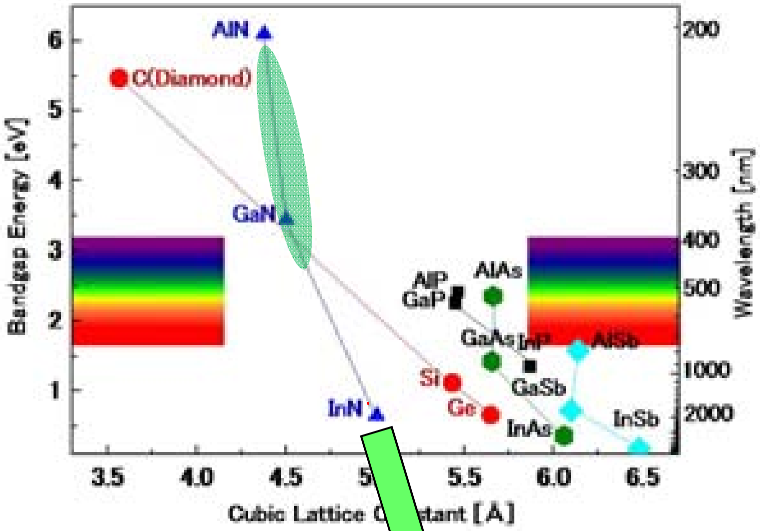


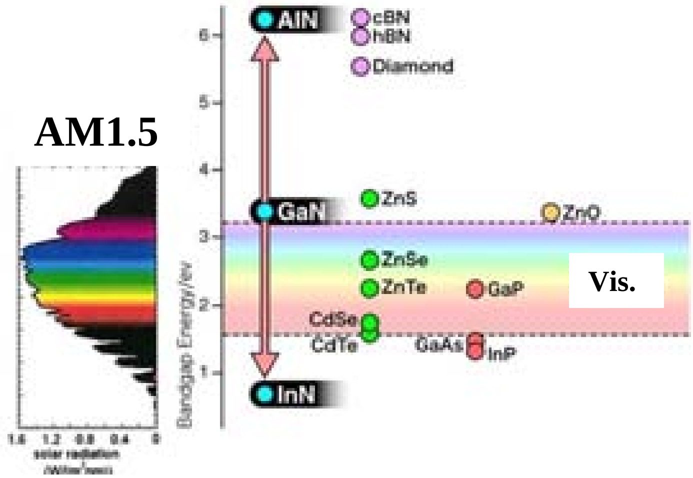
- By replacing Si-based IGBT to WBG devices, 9.8% of total electricity consumption can be saved.
- Super downsizing of power circuits is possible by using GaN-based devices.

http://electronicdesign.com/power/optimize-power-scheme-these-transient-times

Why nitrides are so attractive ? Energy harvesting

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



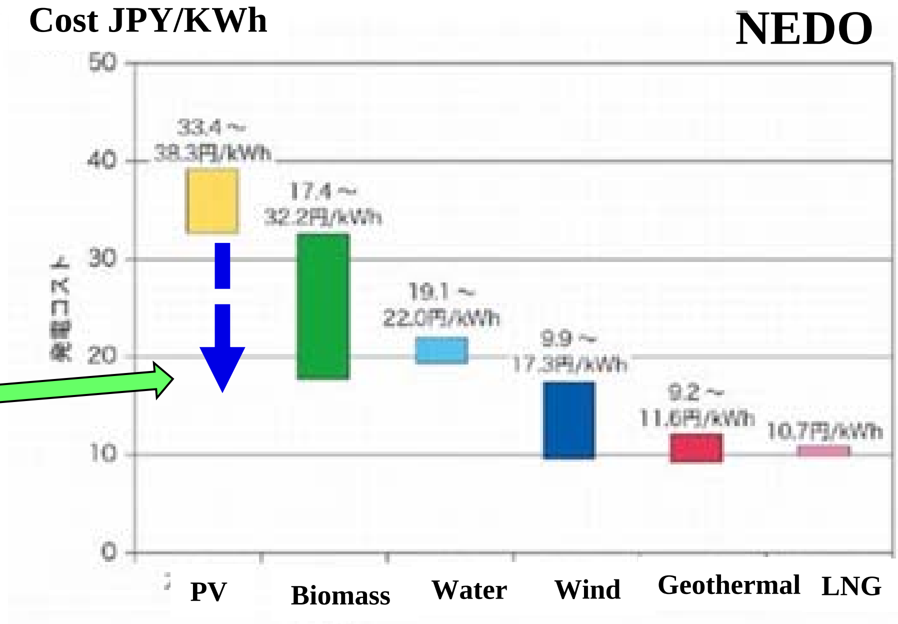


3 cells	InGaN top 4 cells	InGaN top 4 cells
	2.35eV (InGaN) (λ :527nm)	2.25eV (InGaN) (λ :551nm)
1.86eV	1.86eV	1.75eV
1.40eV	1.40eV	1.40eV
1.0 eV	1.0 eV	1.0 eV

3 cells
η : 36% (1sun)
: 45% (1000sun)

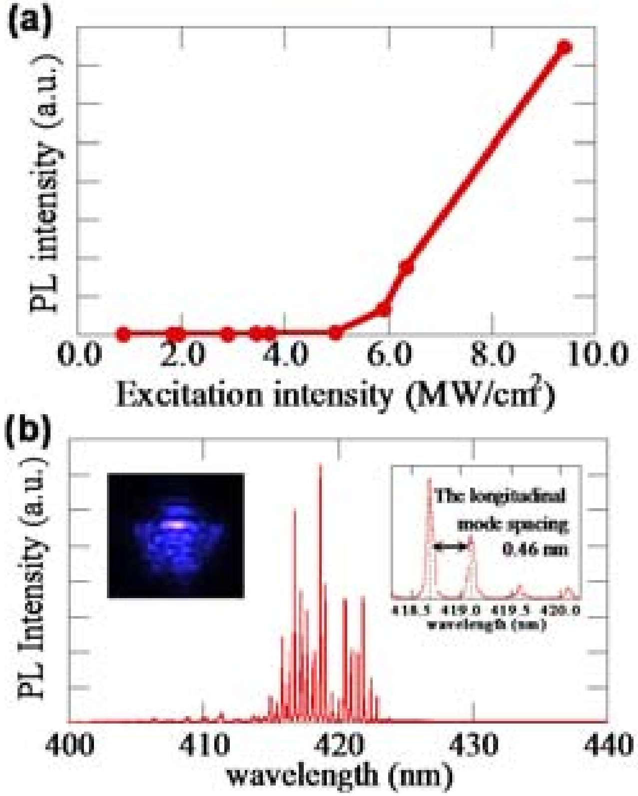
InGaN top 4 cells
η : 38.2% (1sun)
: 47.4% (1000sun)

InGaN top 4 cells
η : 43.5% (1sun)
: 53.3% (1000sun)

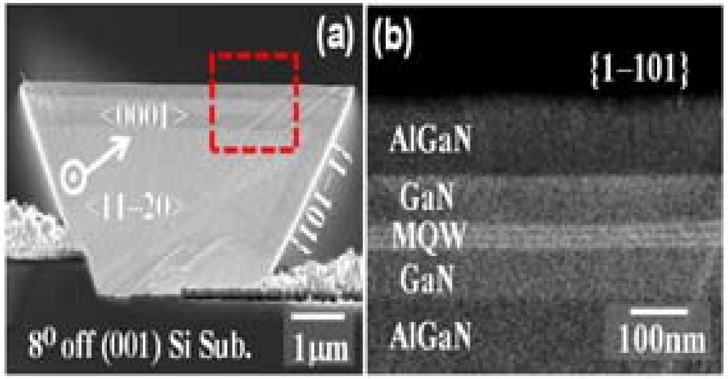


Achievements of our students

Semi polar (1-101) GaN on (001) Si



M. Kushimoto et al., Appl. Phys. Exp., 8 (2015) 022702.

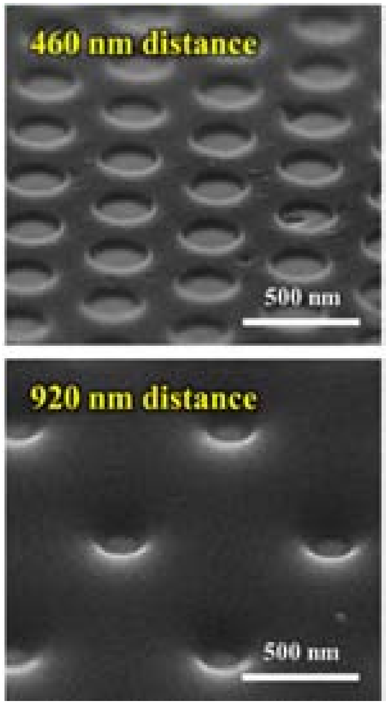


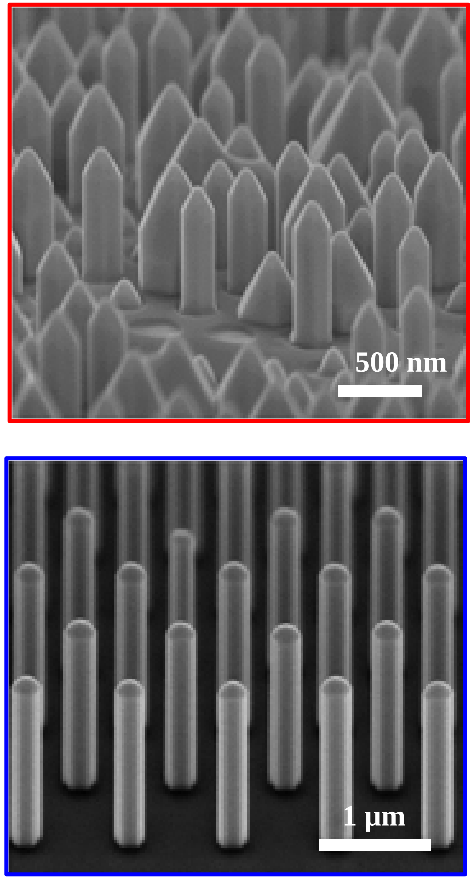
Maki Kushimoto

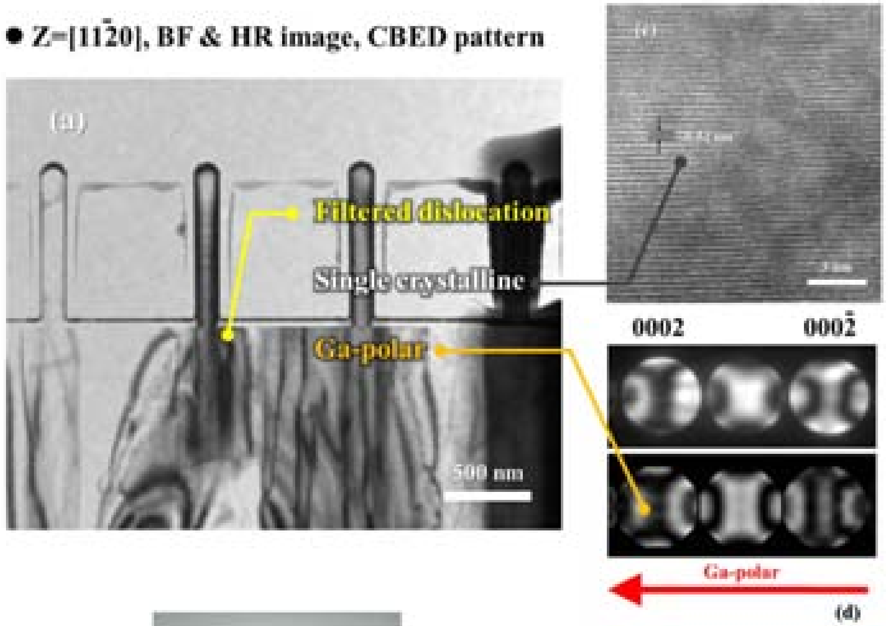
Laser on (001) Si

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

+c oriented GaN nanorod on (111) Si







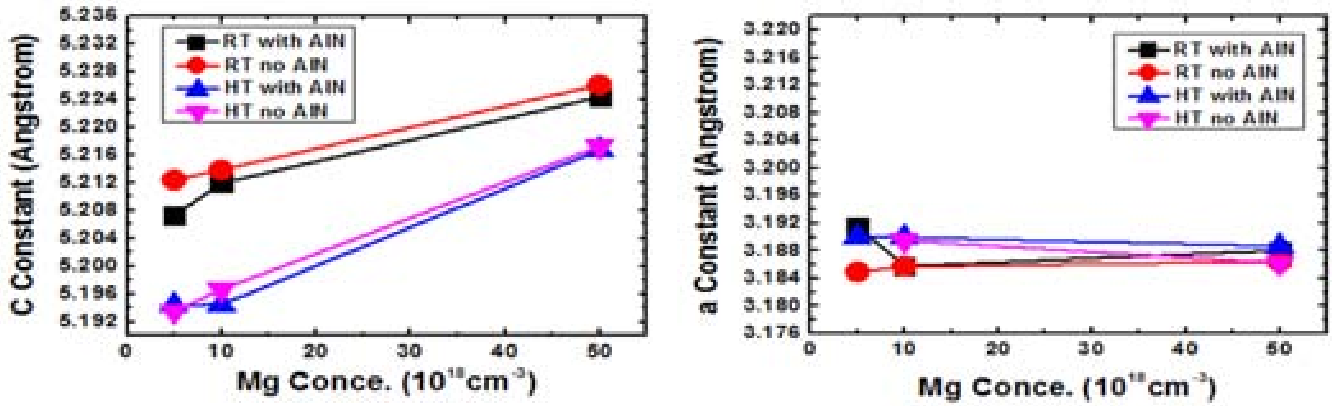
B. O. Jung et al., CrystEngComm., 16(2014)2014.

ByungOh Jung

- Solar cells
- Long wavelength light emitting devices
- Super junction vertical power devices

P-type GaN by Mg ion implantation

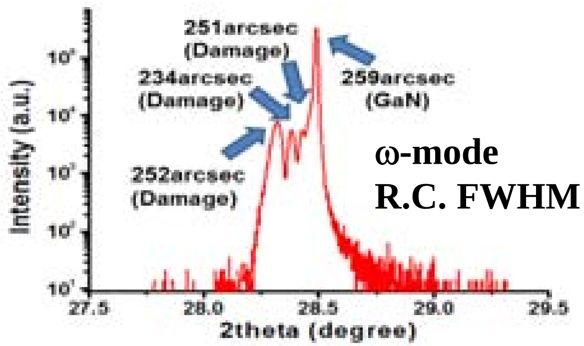
Damage Layer Lattice Constant



The c-constant linearly increased with increasing the Mg concentration.

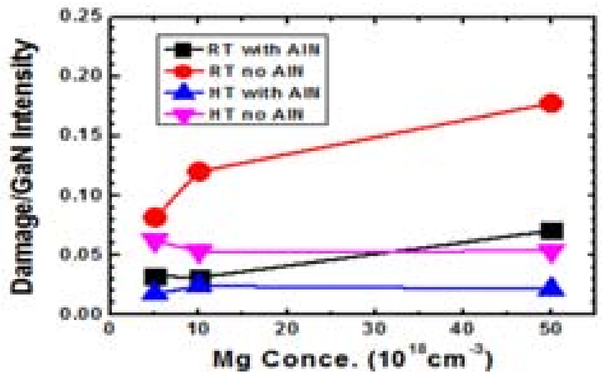
Damage Layer FWHM

HT-implan. (5×10^{19} cm^{-3})



ω-mode
R.C. FWHM

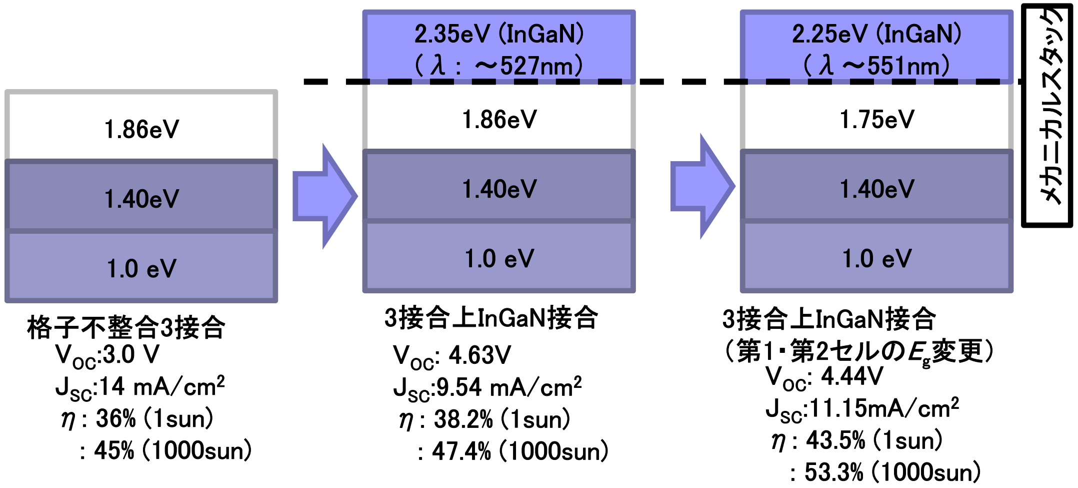
Damage Layer Intensity



Sun Zheng

Mechanical stack multi junction PV cell

Seunga Lee



Mechanical Stack PV cells

Non polar simulation

$In_{0.6}Ga_{0.4}N/GaN$ 100QWs

V_{oc}(V)	**1.83**
J_{sc} (mA/cm²)	24.27
CE (%)	**24.61**
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} (mA/cm²)	31.56
CE (%)	**29.82**
Fill factor (%)	90.48

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