October 2004

Temporal and spatial-resolved spectroscopy of InGaN/GaN

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collaborated with

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Motivation

Development of optical devises

Light emitting diode (LD), Laser diode (LD),
Optical Memory, Optical communication
Optical computing, 3D-hologram display

(1) Elucidation of the optical properties and function of several materials.

Compound Semiconductor (**GaN**, ZnSe, ZnO-based quantum well, dot, etc.)

Organic thin films (Polysilane Films, Alq_3-based EL , etc.)

Nana-particles of Metal, Semiconductor (Pt, Au, CdS, etc.)

Molecular organized system (solvation, micell, LB-layer, liquid crystal, etc.)

Biological living cell (Onion, Drosera capensis, Nerve cell of mouse, dopamine), **etc.**

(2) Development of the unique laser spectroscopy with time and spatial resolution

Time resolved micro photoluminescence spectroscopy (TR-μ-PL)

Scanning near-field optical microscopy (SNOM(=NSOM)) with i-c mode.

Third order nonlinear optical spectroscopy - Transient grating (TG) method , etc.

Bandgap of semiconductors

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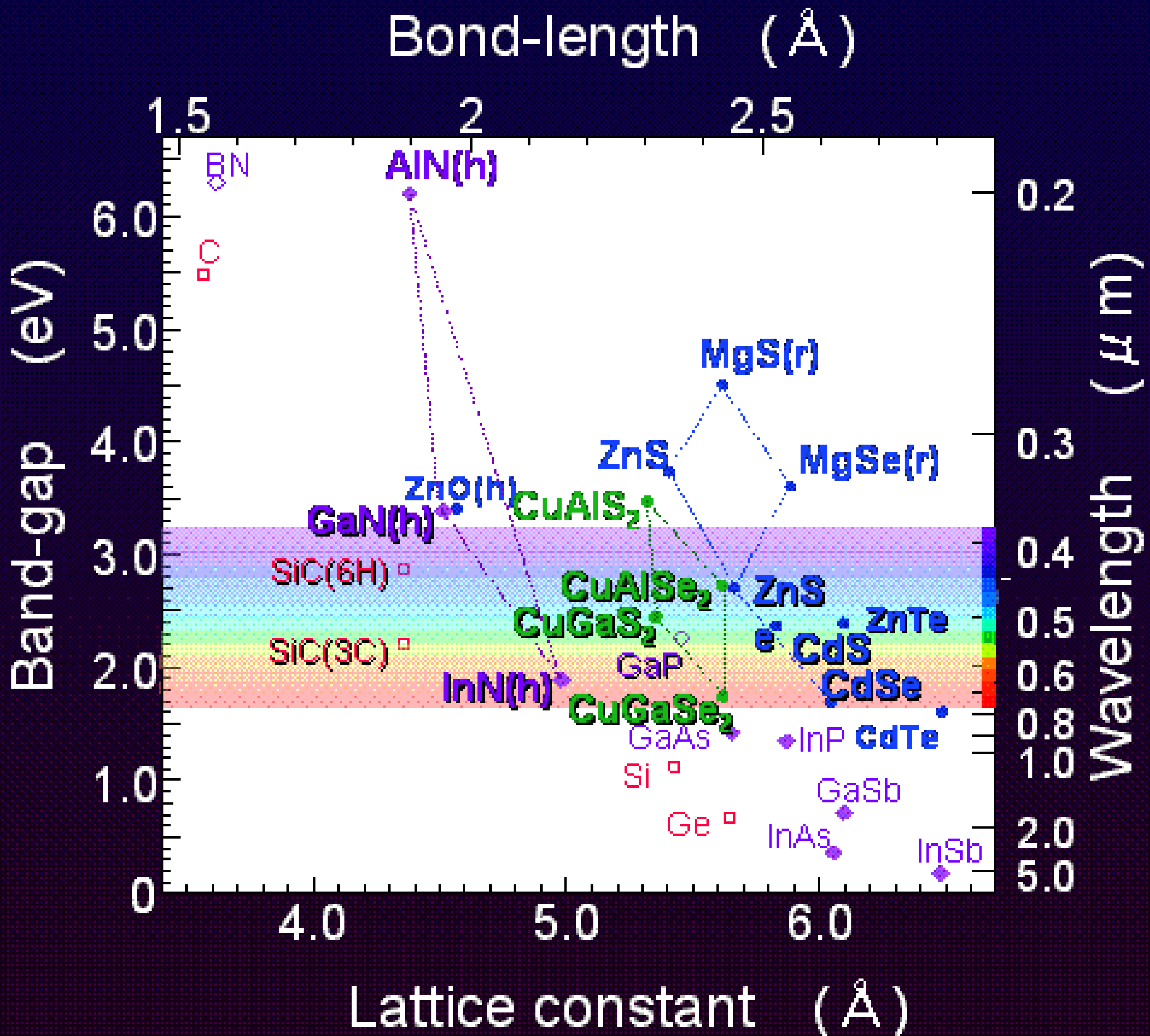
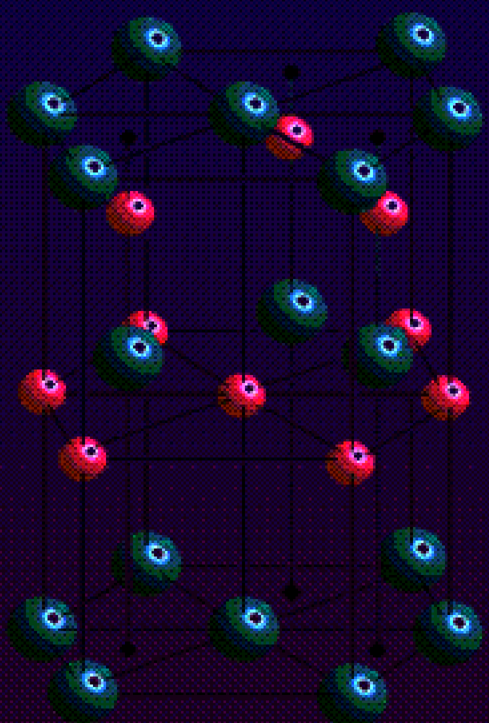


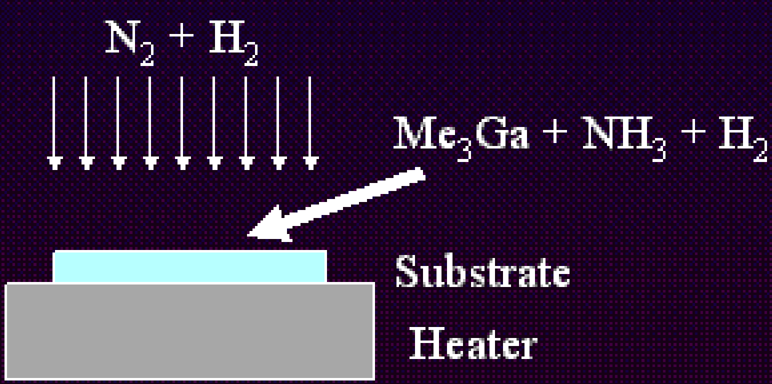
II	III	IV	V	VI
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

III-V Semiconductors

		GaN	AlN	InN	
Molecular weight:		83.72	40.98	128.82	
Density:		3.04	1.63	3.04	(gcm^{-3})
Lattice Constant	(a=)	3.19	3.11	3.54	(Å)
	(b=)	5.19	4.98	5.71	(Å)
Boiling point		1773, 2273	2673	1473	(ºC)
Band-gap		3.4	6.2	1.9	(eV)
		366	200	653	(nm)

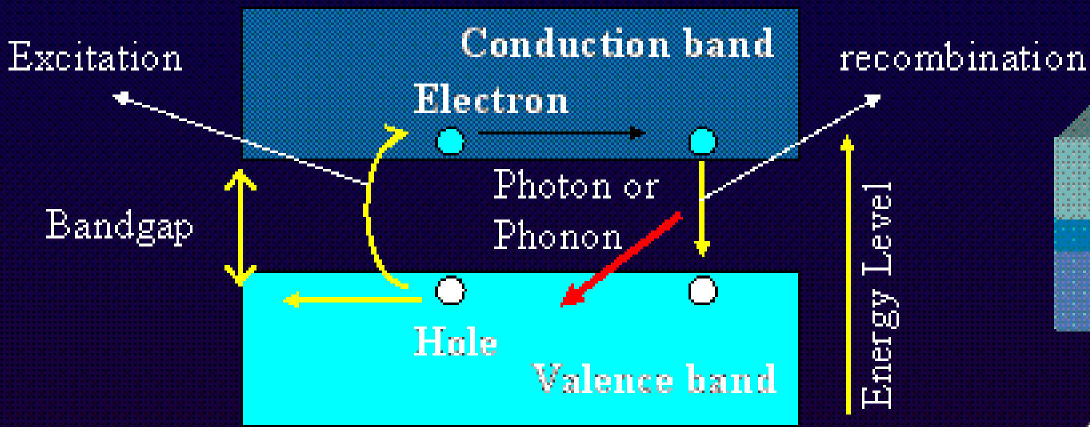


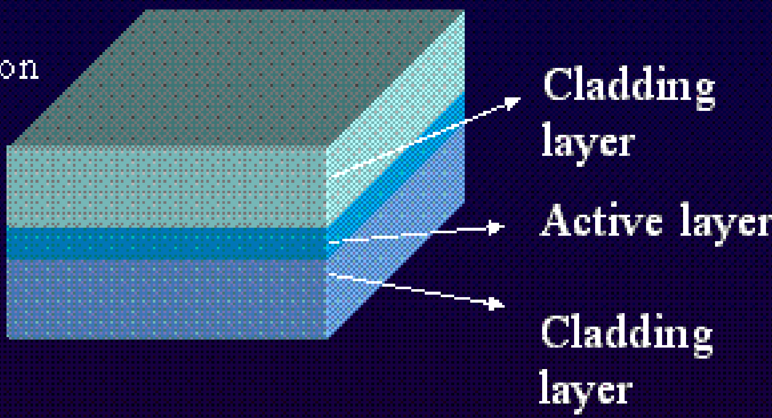
hexagonal wurtzite



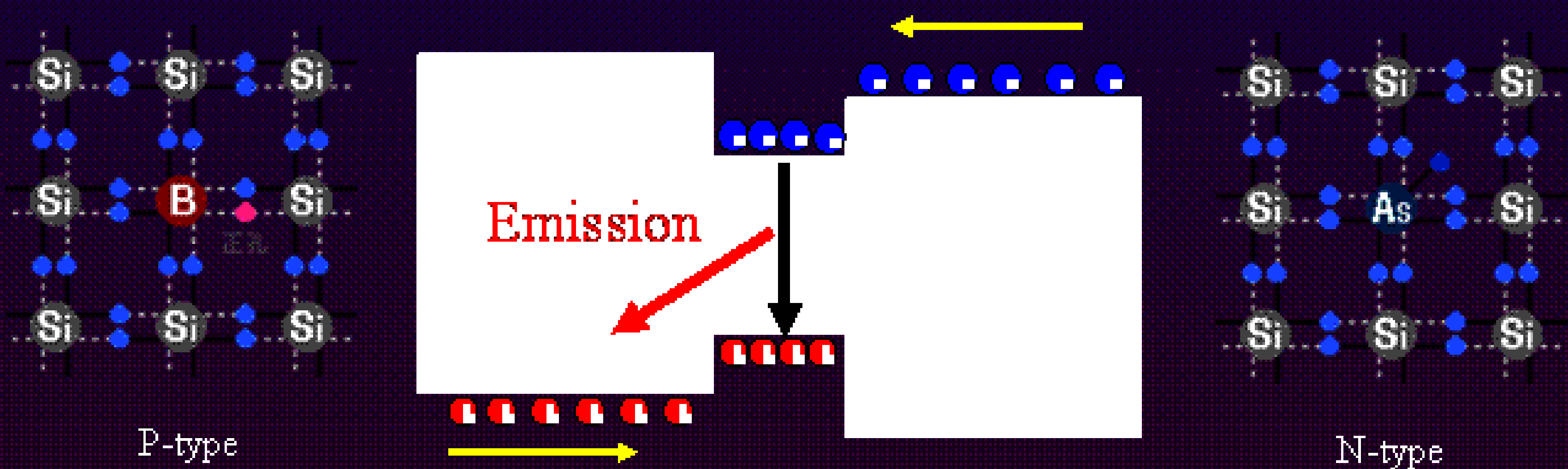
metalorganic chemical vapor deposition (MOCVD)

QW and LED



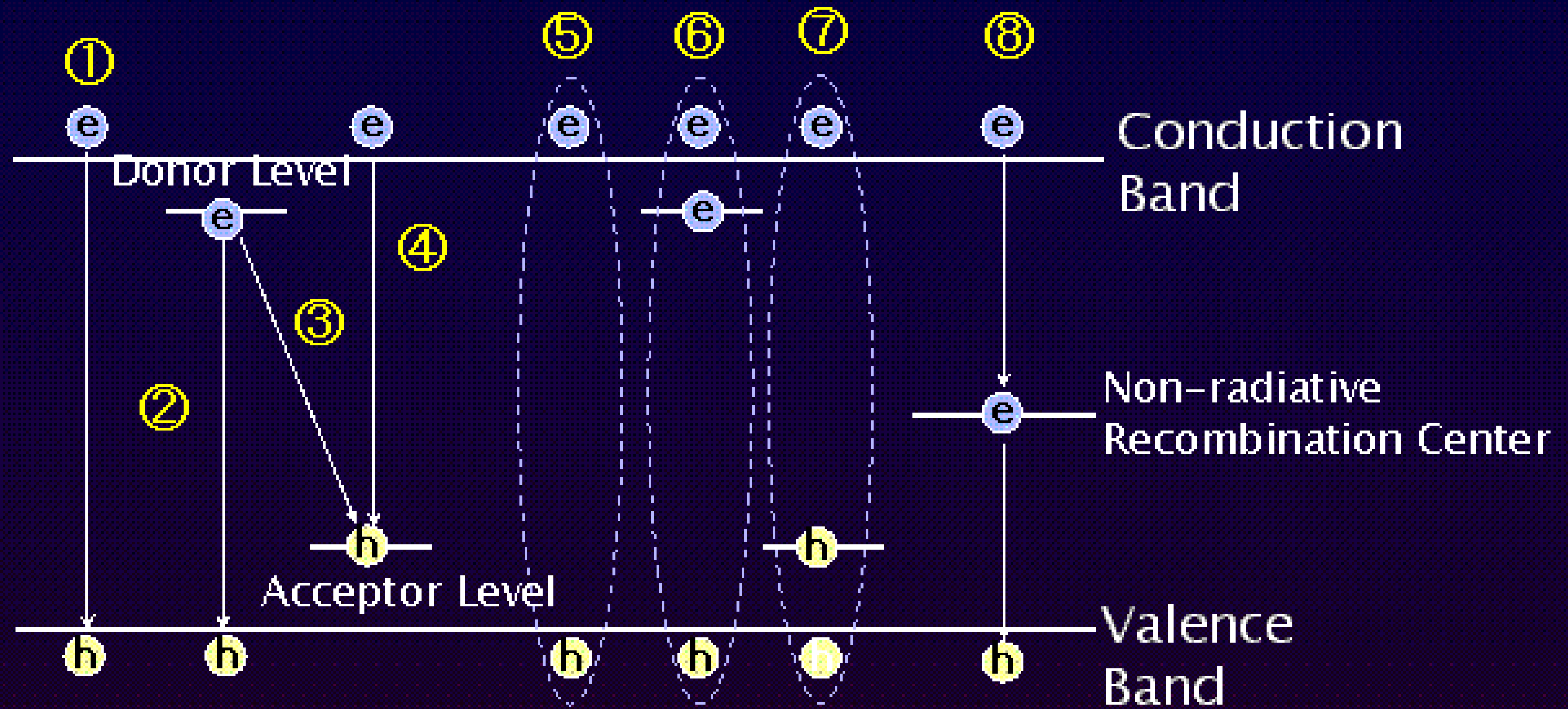


Quantum Well (QW)



Light-emitting diode (LED)

Electron-Hole recombinations



① Inter-band Emission
② BF (bound to free) Emission
③ Donor-Acceptor Emission
④ FB (free to bound) Emission
⑤ Free Exciton Emission
⑥ Donor bound Exciton Emission
⑦ Acceptor bound Exciton Emission
⑧ Non-Radiative Recombination

①〜⑦ : Radiative (Emission) Processes ⑧ : Non-Radiative

Historical Development of LEDs

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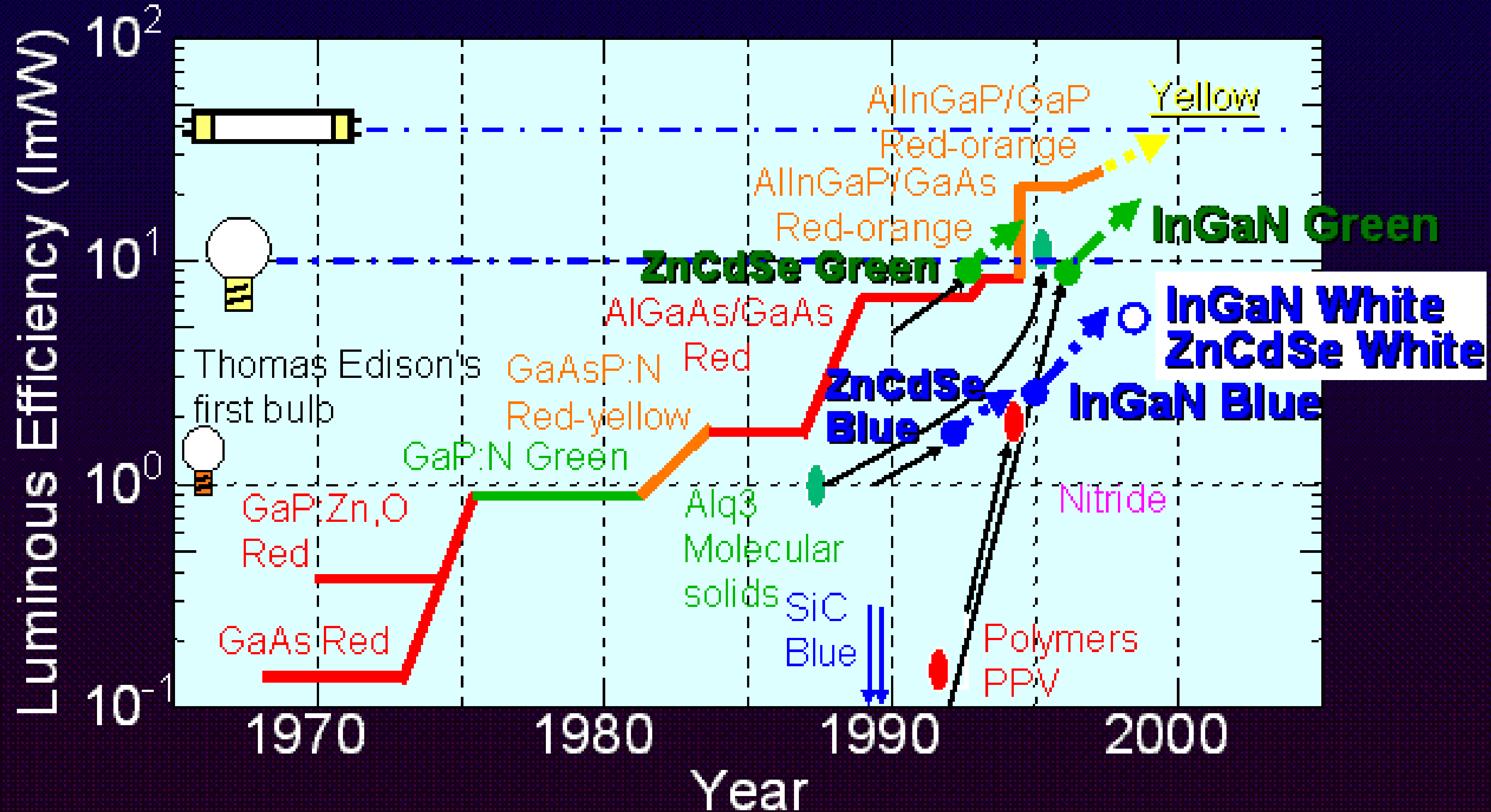


InGaN/GaN-based LEDs

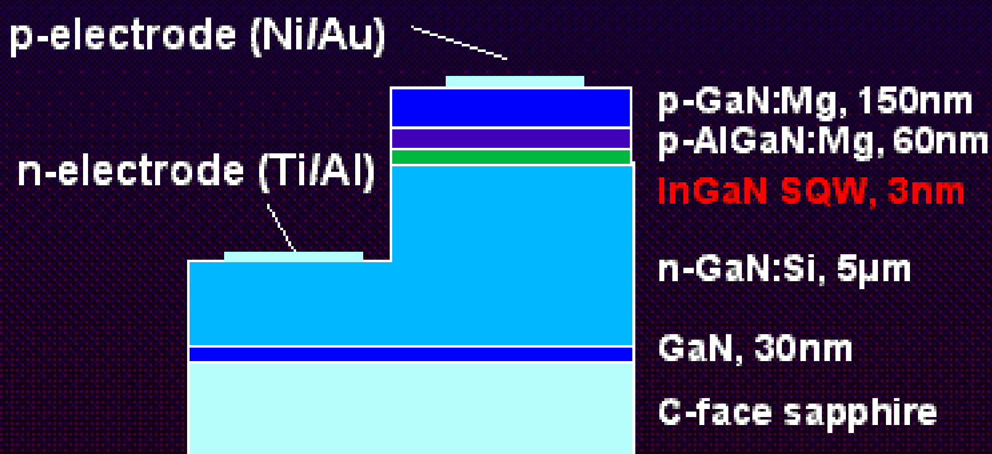
InGaN/GaN semiconductors

Very advantageous materials for light emitting diode (LED) and laser diode (LD).

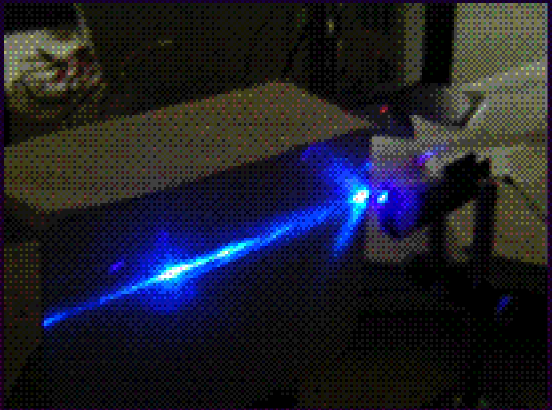
1993 GaN/InGaN based Blue-LED was developed by Shuji Nakamura in Nichia Co. (present; UCSB)

1995 GaN/InGaN based Blue-LD was also developed by Shuji Nakamura in Nichia Co.

Now: Cree, HP, Toyota gose, Omron, etc.



GaN/InGaN single quantum well structure of LEDs grown by two-flow metalorganic chemical vapor deposition (MOCVD)

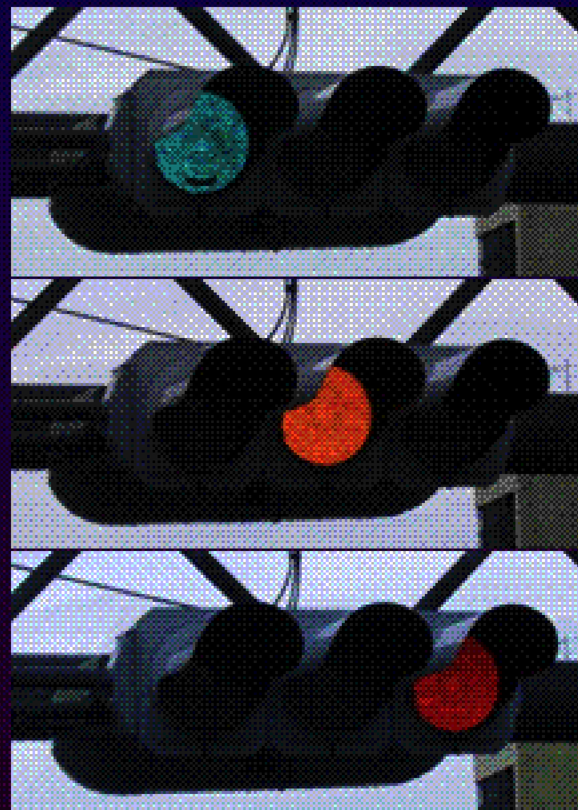


Super bright LEDs and LD of InGaN/GaN/AlGaN by Nichia

New Application of InGaN/GaN LED

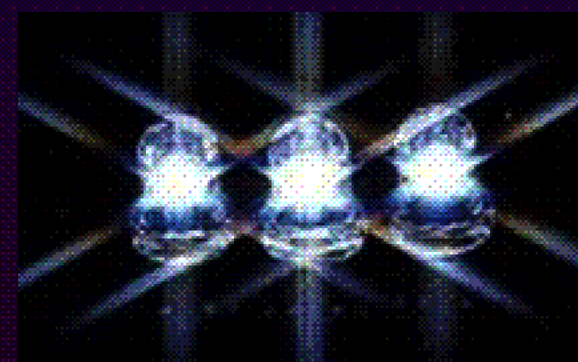
Primary color of light (RGB) were completed by LEDs

Full color LED display



LED Signal

Agriculture (Red and



White light LED
(blue LED and yellow fluorescent)

Application for Surgical Operation

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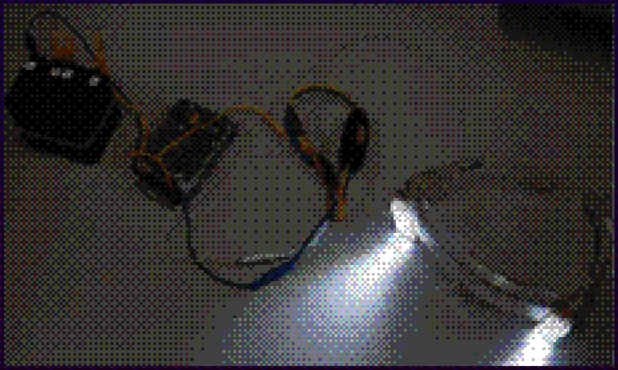
September 11, 2000 (Monday) in Kyoto, Japan

Operator Surgeon
Dr. J. Shimada (Kyoto Yoshanoumi Hosp.)
Associate Surgeon
Dr. H. Amachi (Kyoto Yoshanoumi Hosp.)
Nurse
Miss. Y. Shakamoto
Technical stuff
Dr. Y. Kawakami (Kyoto Univ.)
Dr. K. Okamoto (Kyoto Univ.)



This head-mounted light source uses **112** white LEDs to illuminated surgical operation.

Surgeons and scientists in Kyoto are collaborating on a head-mounted prototype white LED lighting system designed to provide directed illumination during surgical operations. The LEDs were mounted on simple lightweight goggles and made headlines in Japan recently following their use in a successful 2-hour forearm operation.

Optical Properties of InGaN/GaN

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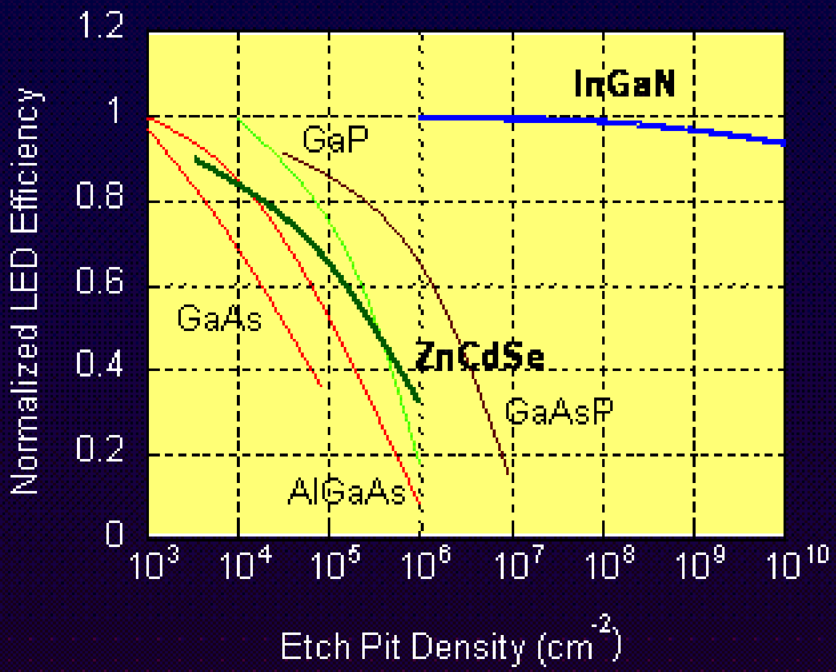

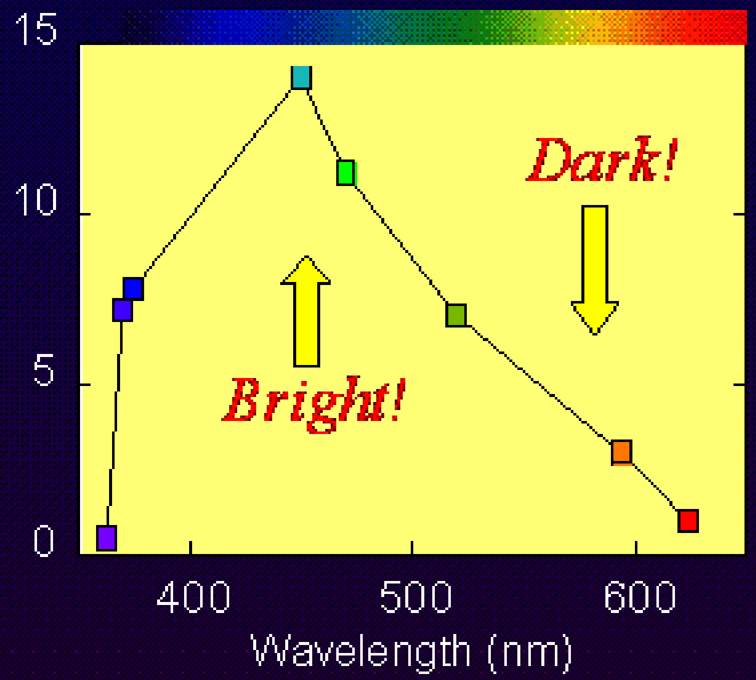

In spite of high threading dislocation density (10^8-10^{10} cm^{-2}), the external quantum effciency (η_{ext}) of emission are very high (10-15%) (20 % is now achieved in Lab.)

However, η_{ext} values are still lower for LEDs out of this blue spectral range.

Our Purpose

To elucidate the emission dynamics and optical properties

To obtain the way how to develop the emission efficiency

Carriers and Excitons Dynamics

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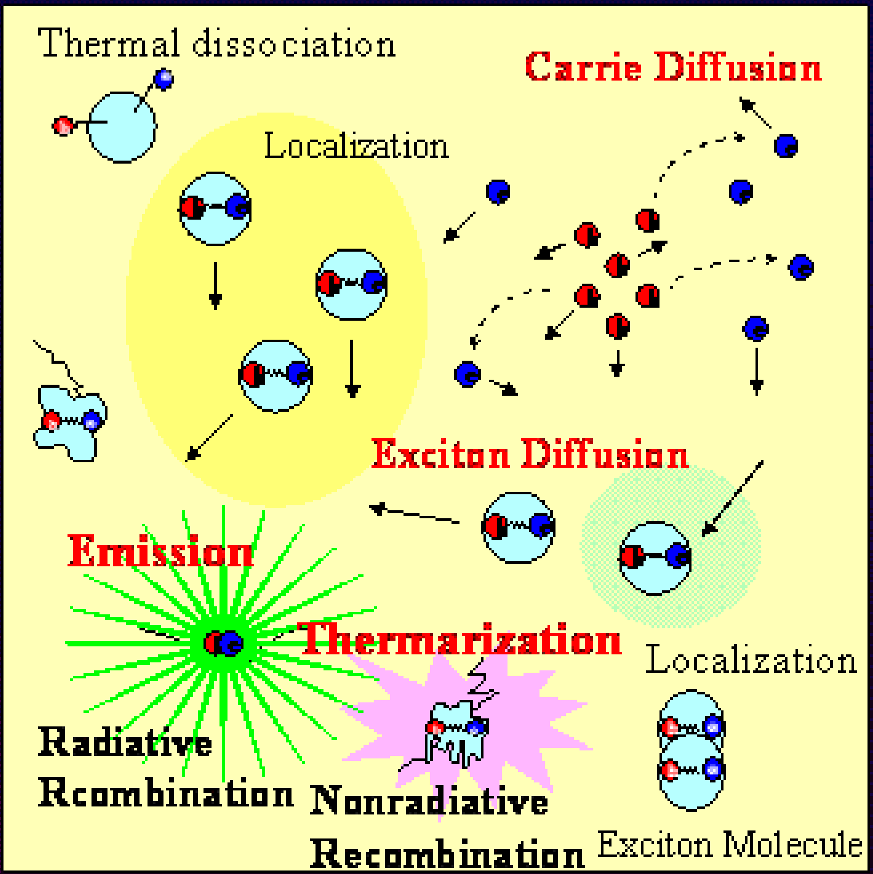
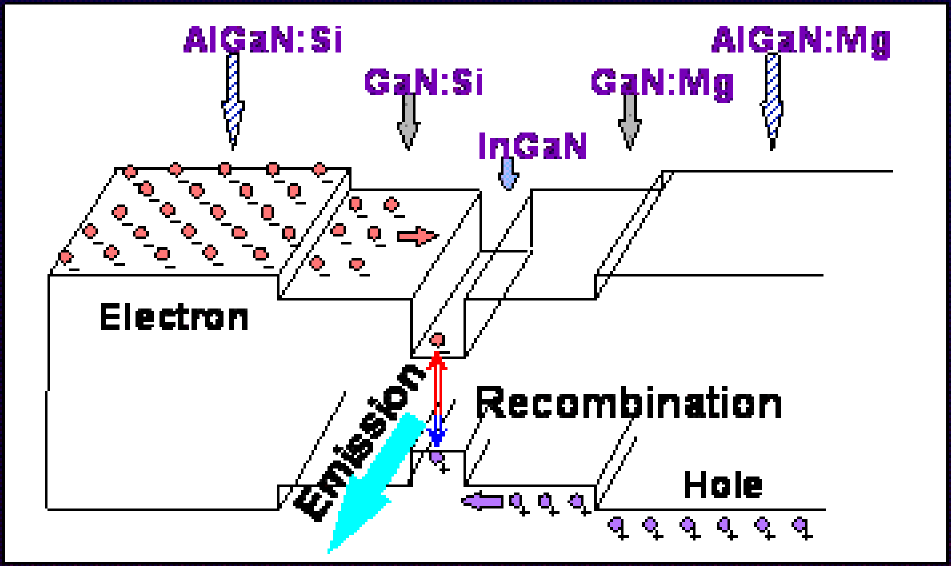
Optical properties are controlled by the **dynamics of carriers and/or excitons**





Until now, Photoluminecsence (PL) spectroscopy, time resolved PL, micro-PL, Electricluminecsence (EL), cathordoluminecsence (CL), etc.

We try to detect

(1) Time and spatial resolved PL

by time-resolved maicro-PL spectroscopy

(2) Nano-scale inhomogeneously of PL

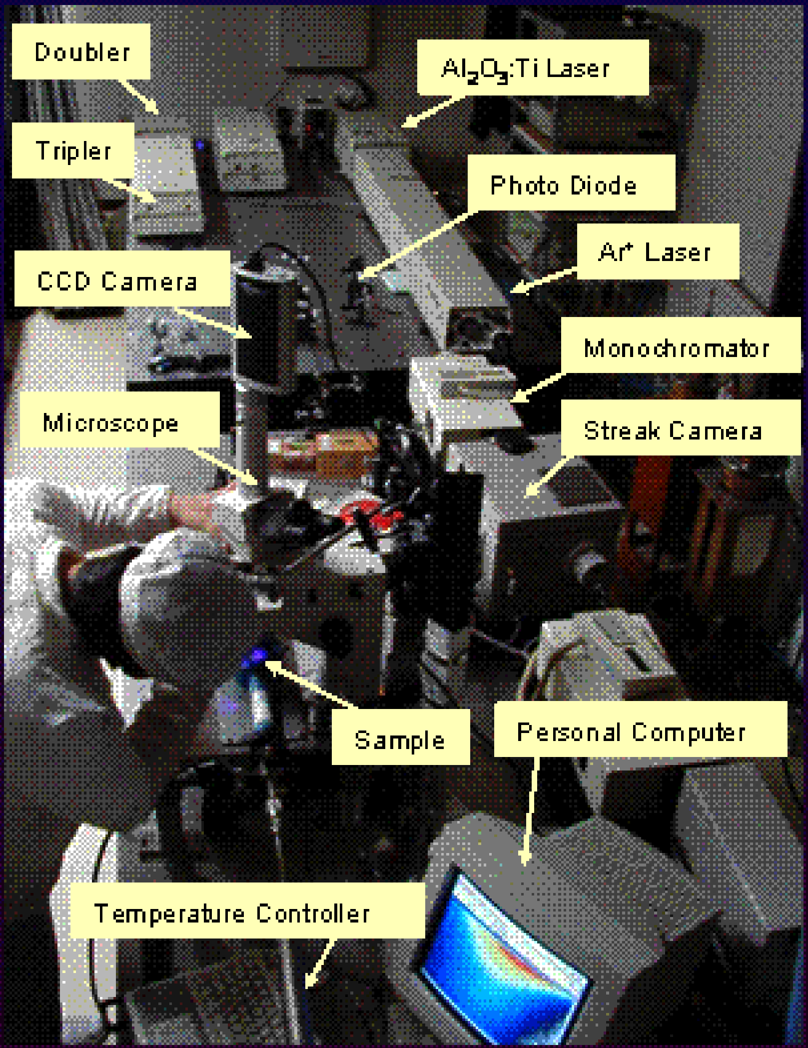
by SNOM(NSOM) with I-C mode

(3) Carrier diffusion and thermarization

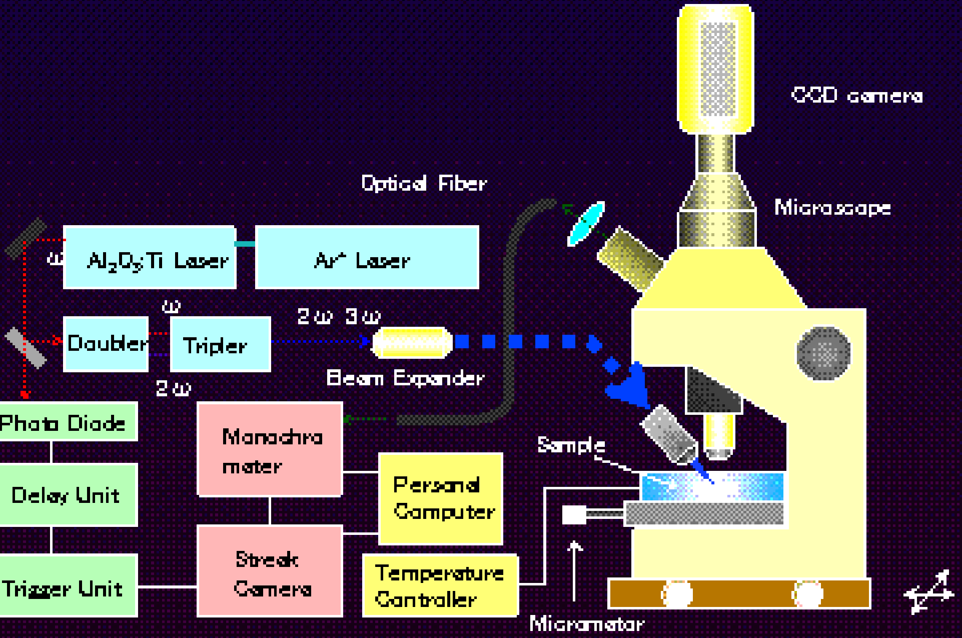
by third order nonlinear spectroscopy

Time Resolved Micro PL

K. Okamoto, et al, J. Crystal Growth, 214/215, 639 (2000).



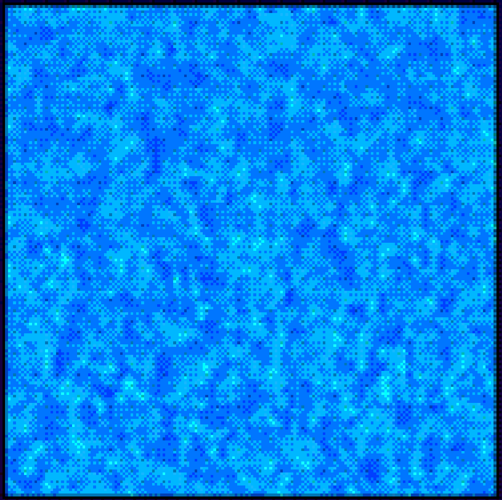
Mode locked Al_2O_3:Ti laser
(pumped by Ar^+ laser)
pulse width: 1.5 ps
wavelength: 400 nm
repetition rate: 80MHz
power density: 20μJ/cm^{-2}



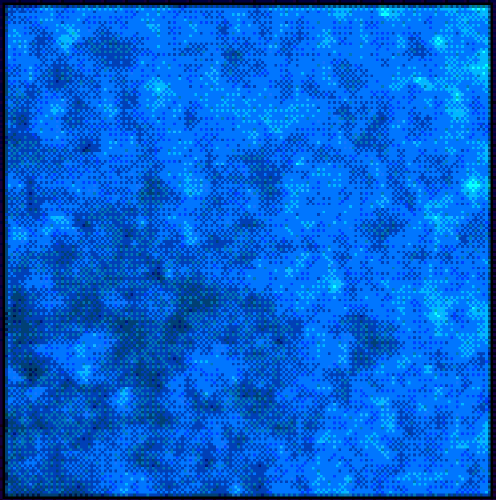
Microscopic Images

@R.T.

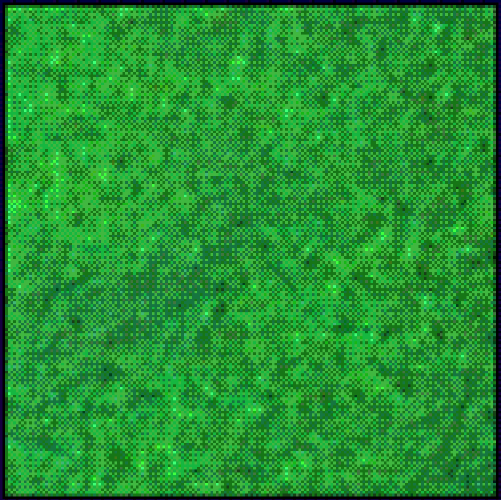
20 μm



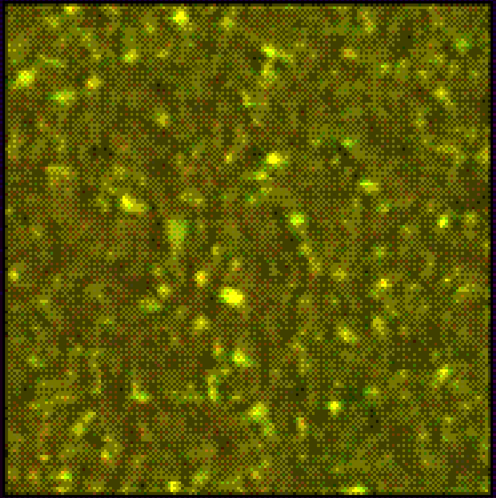
LED 460



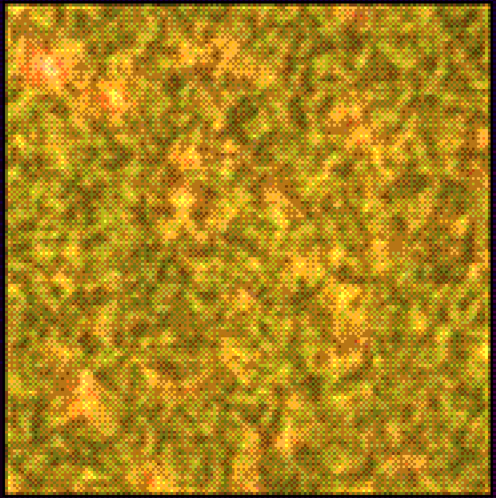
LED 470



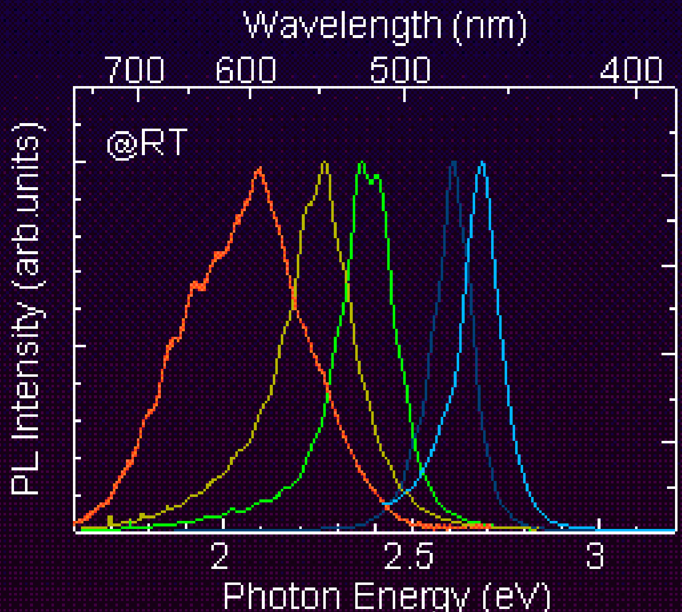
LED 510



LED 540

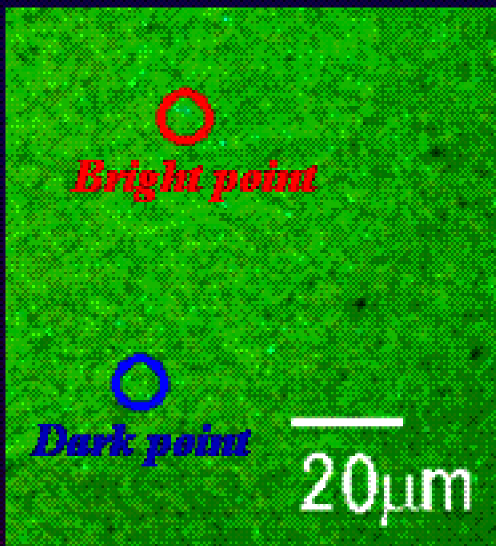


LED 600

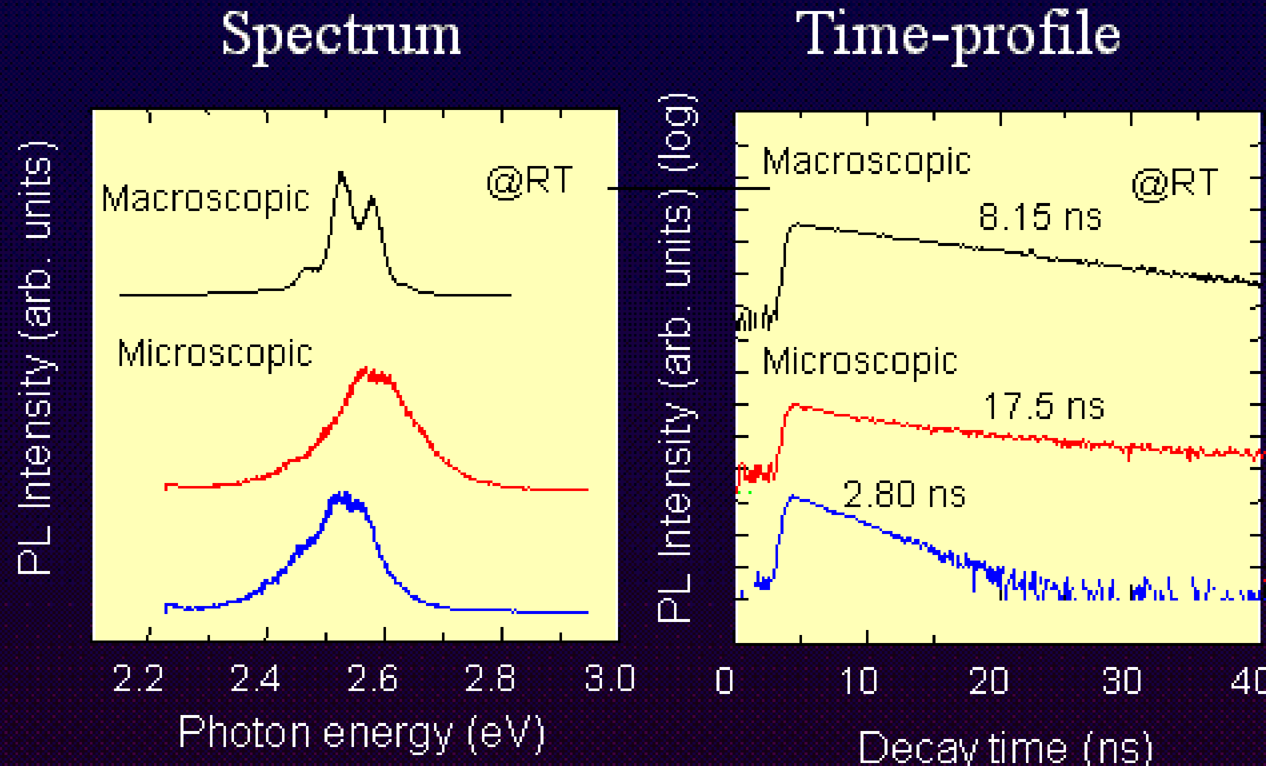


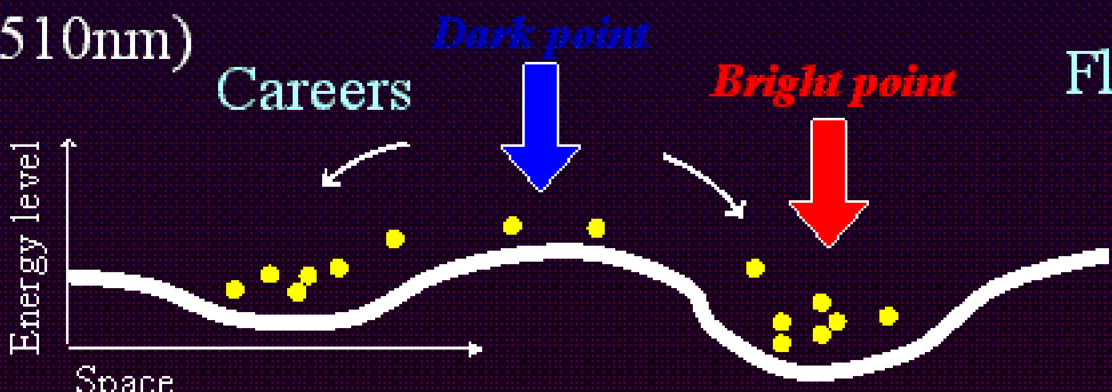
Results of the TRMPL

Spot Size (2µm×2µm)



Green LED (510nm)





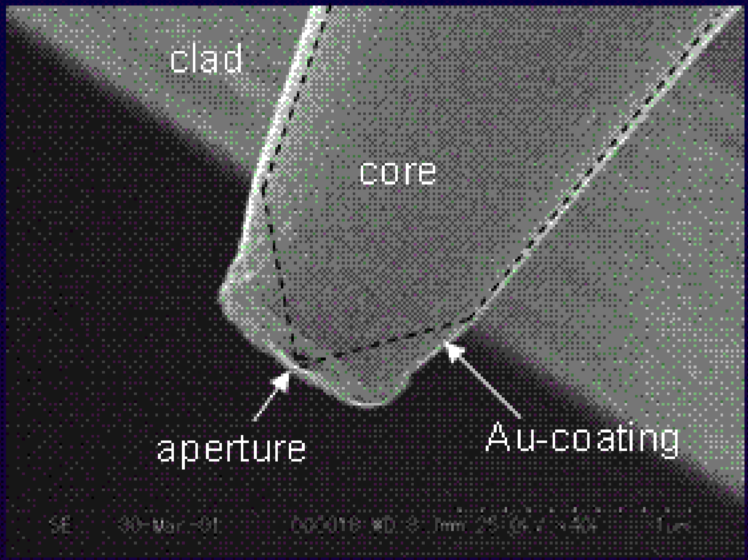
Fluctuation of Energy Level

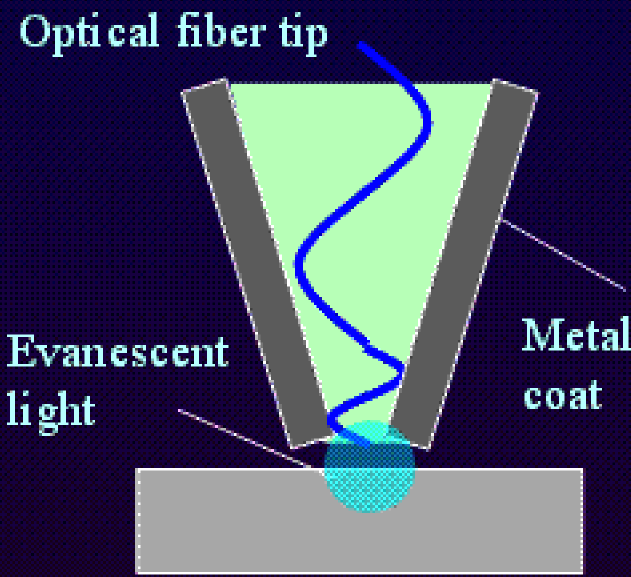
In Composition

quantum well width

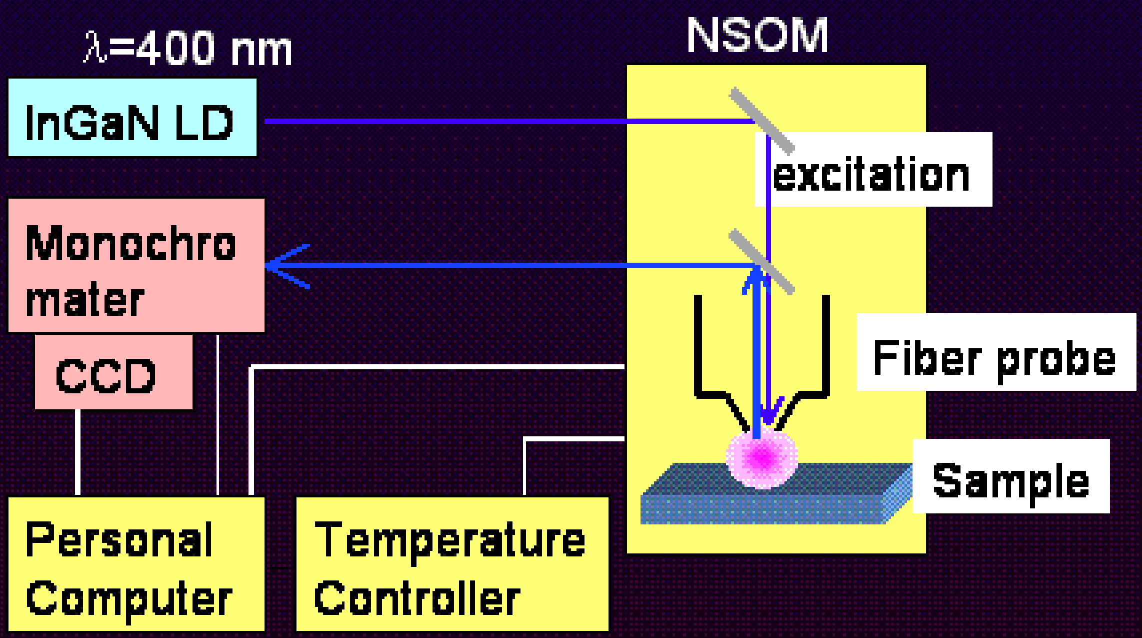
Piezoelectric field

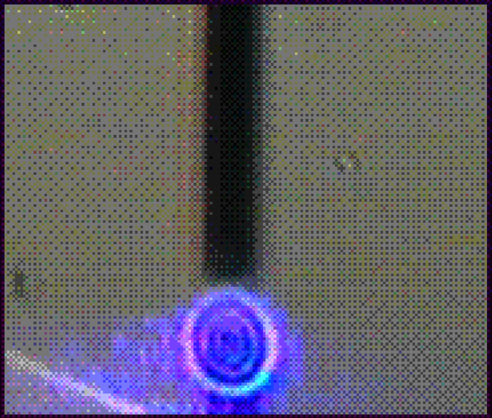
Near-field Scaning Optical Microscopy (NSOM)



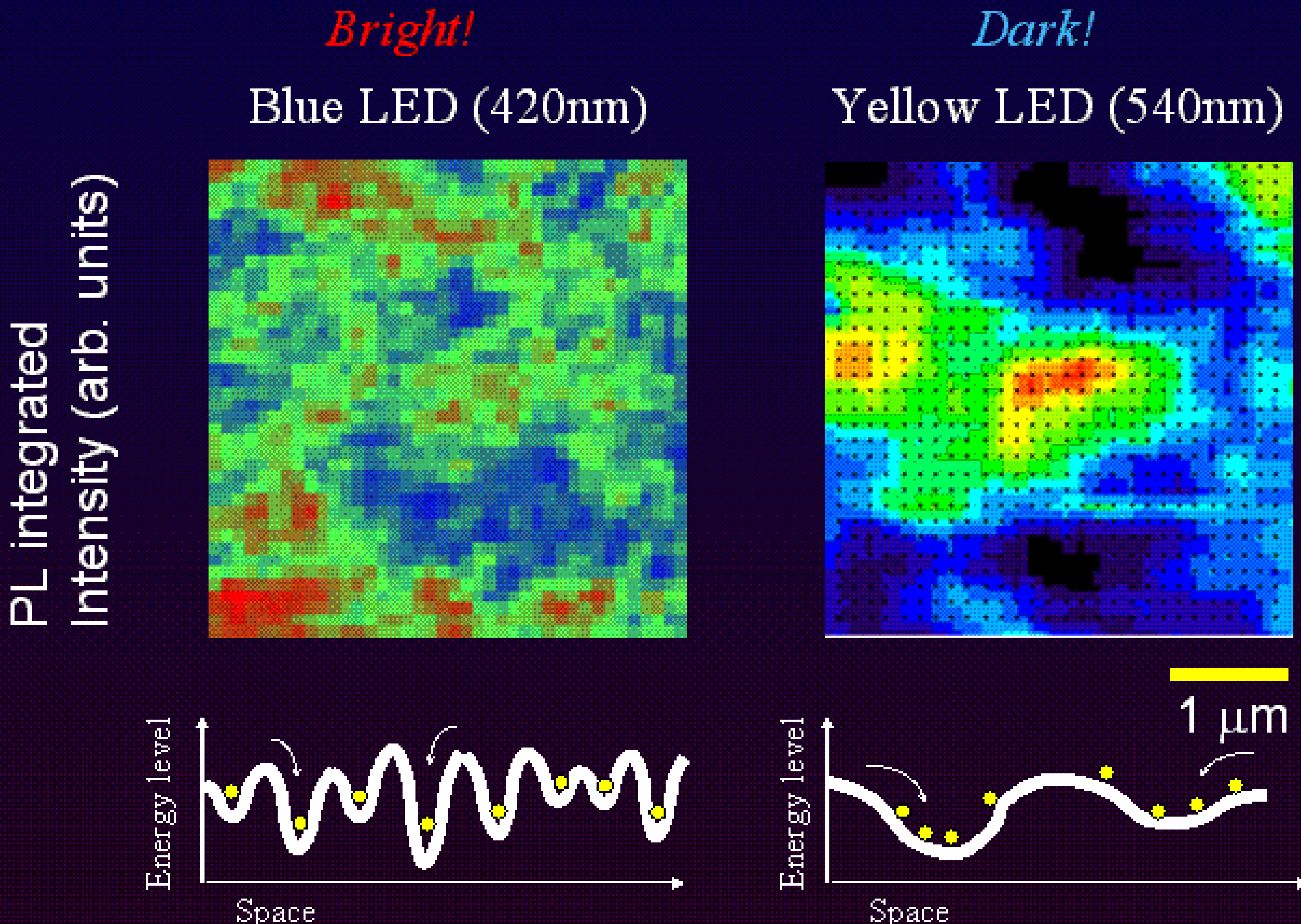


Aperture size: ~150 nm

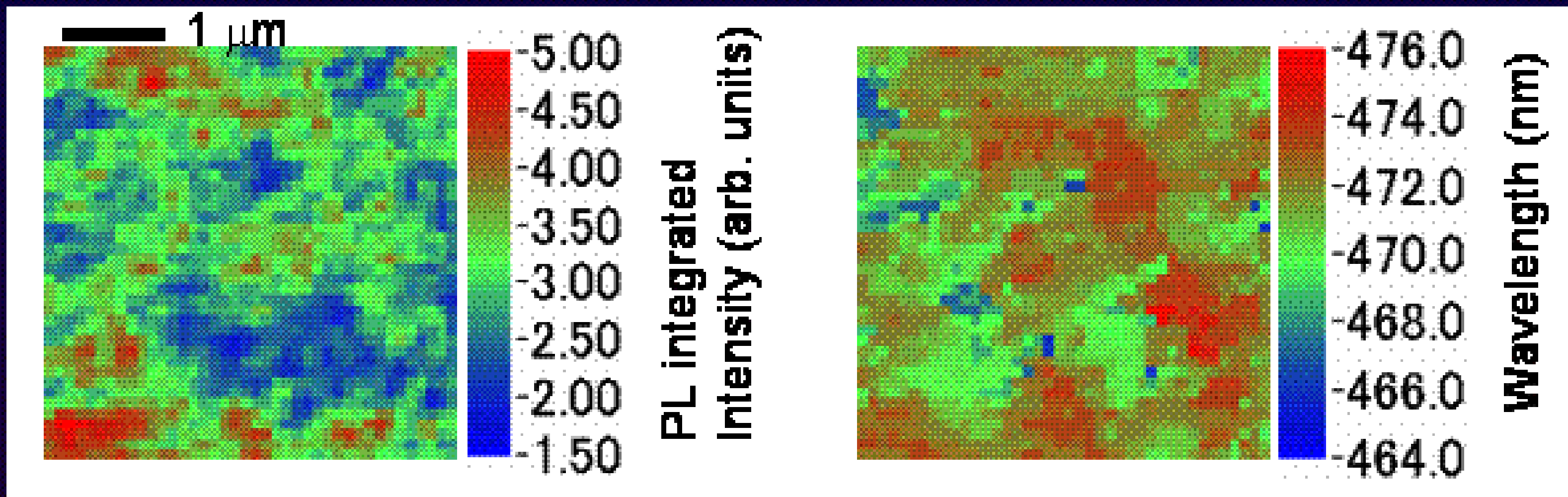


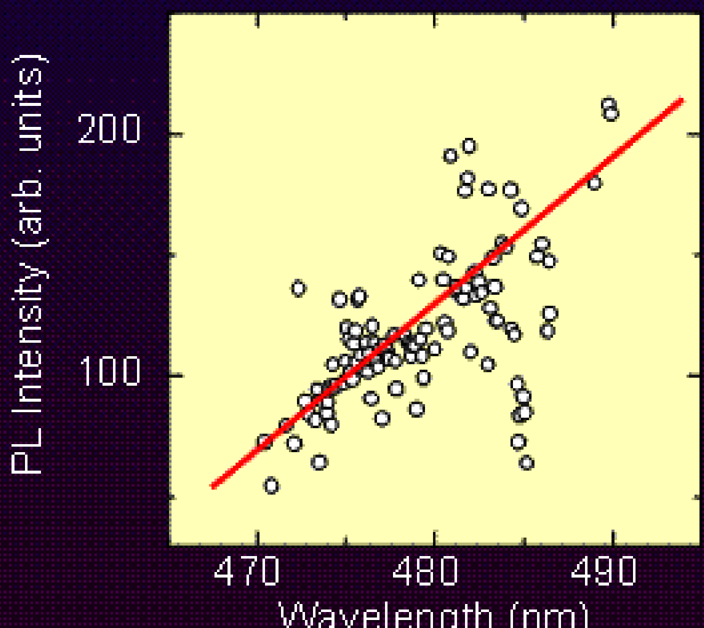


SNOM Images of LEDs



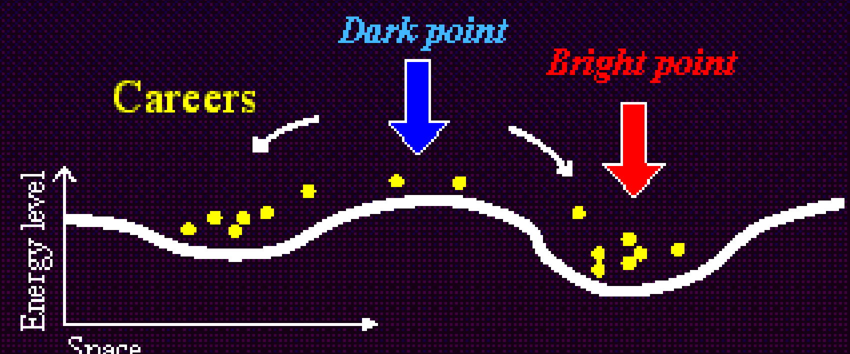
Correlation between PL intensity and peak wavelength





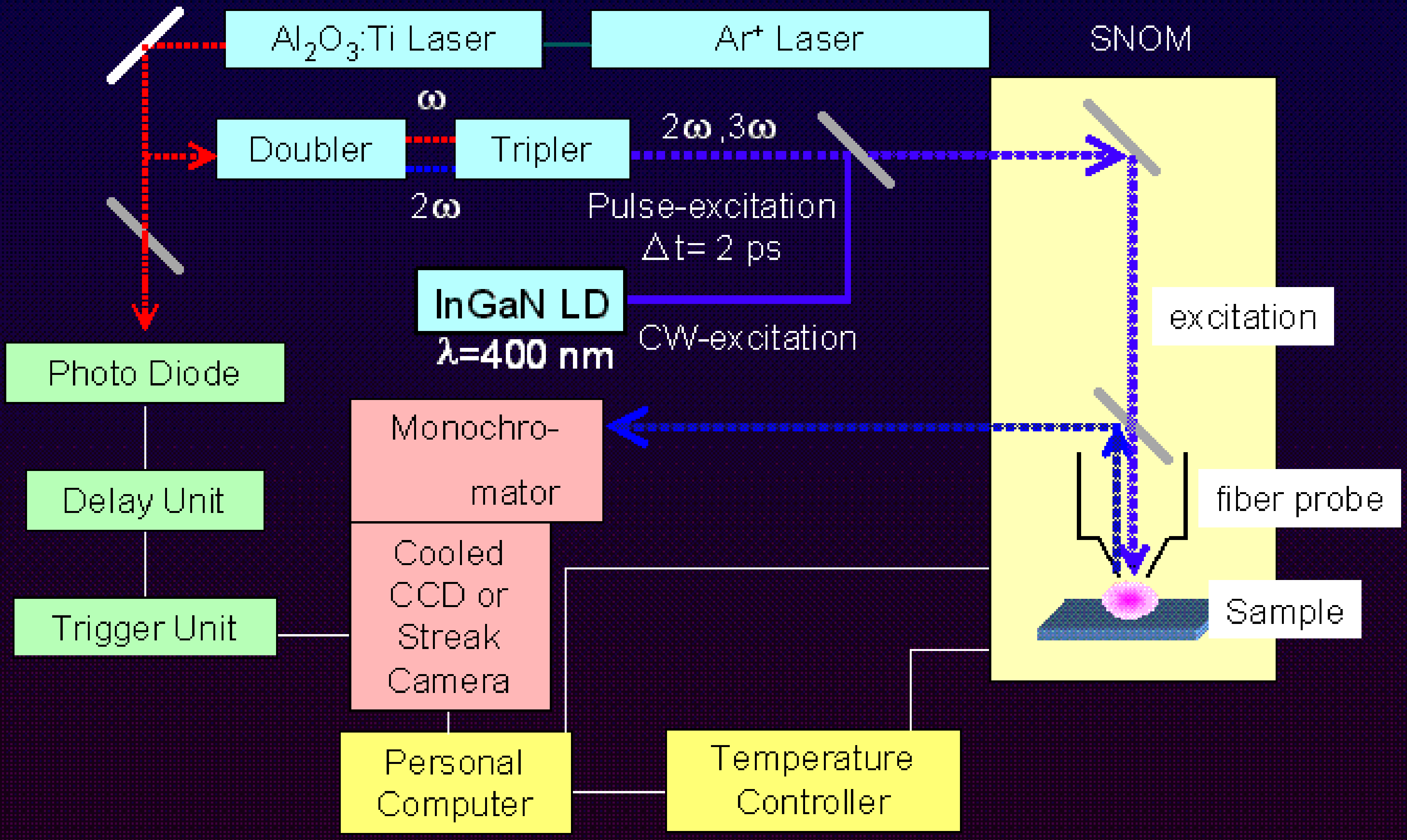
Strong PL region =

PL peak wavelength is longer



Time-resolved NSOM-PL

A. Kaneta, K. Okamoto, et al, Appl. Phys. Lett., 81, 4353 (2002)



NSOM PL image and PL lifetimes along the white bar

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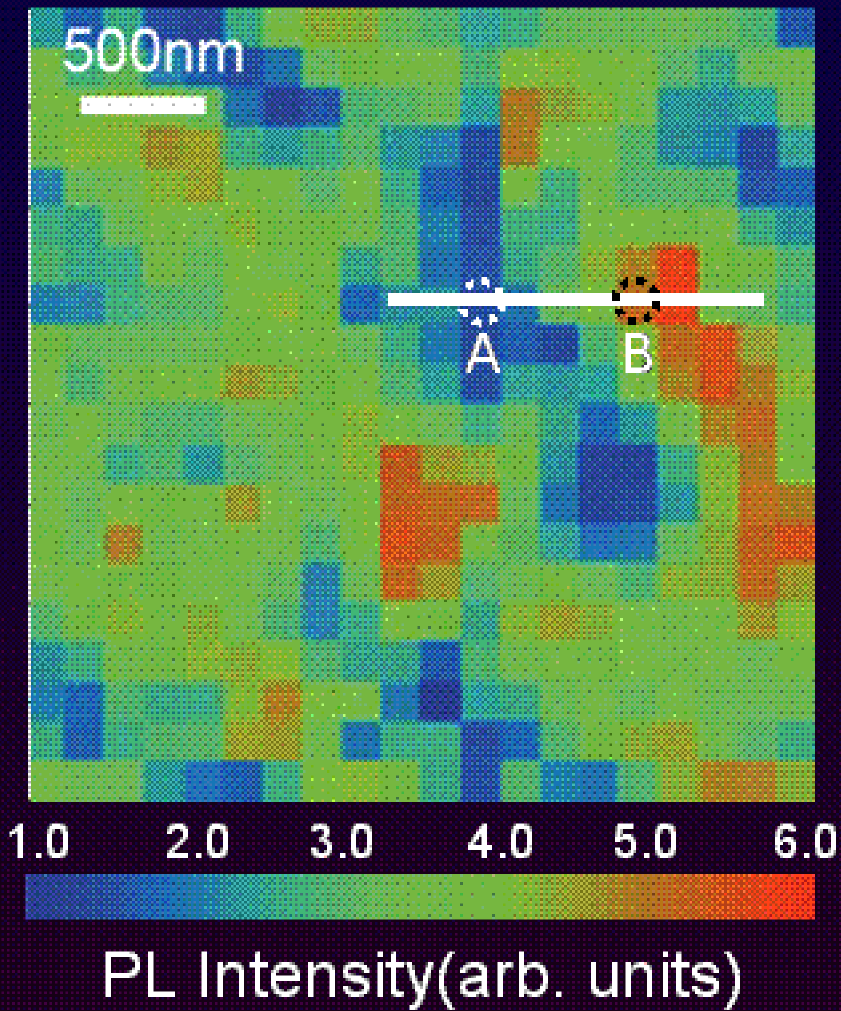
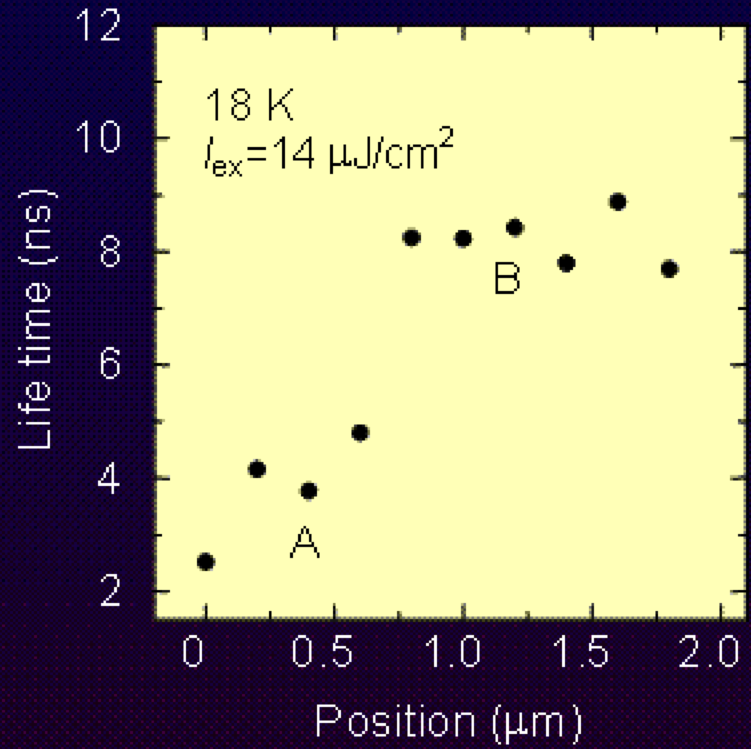
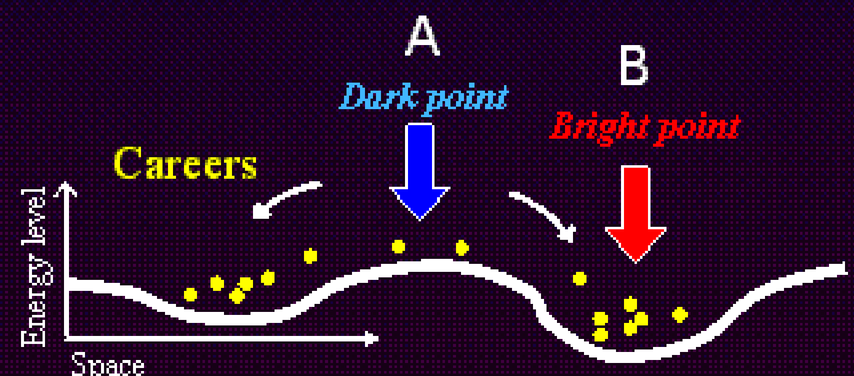
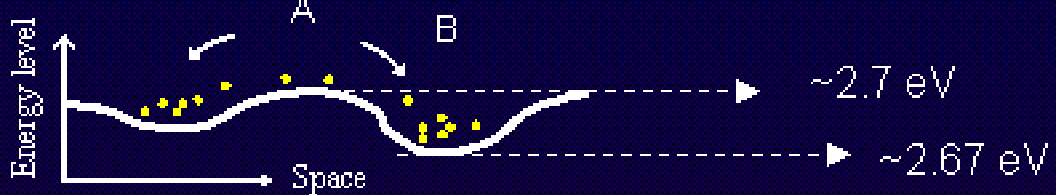
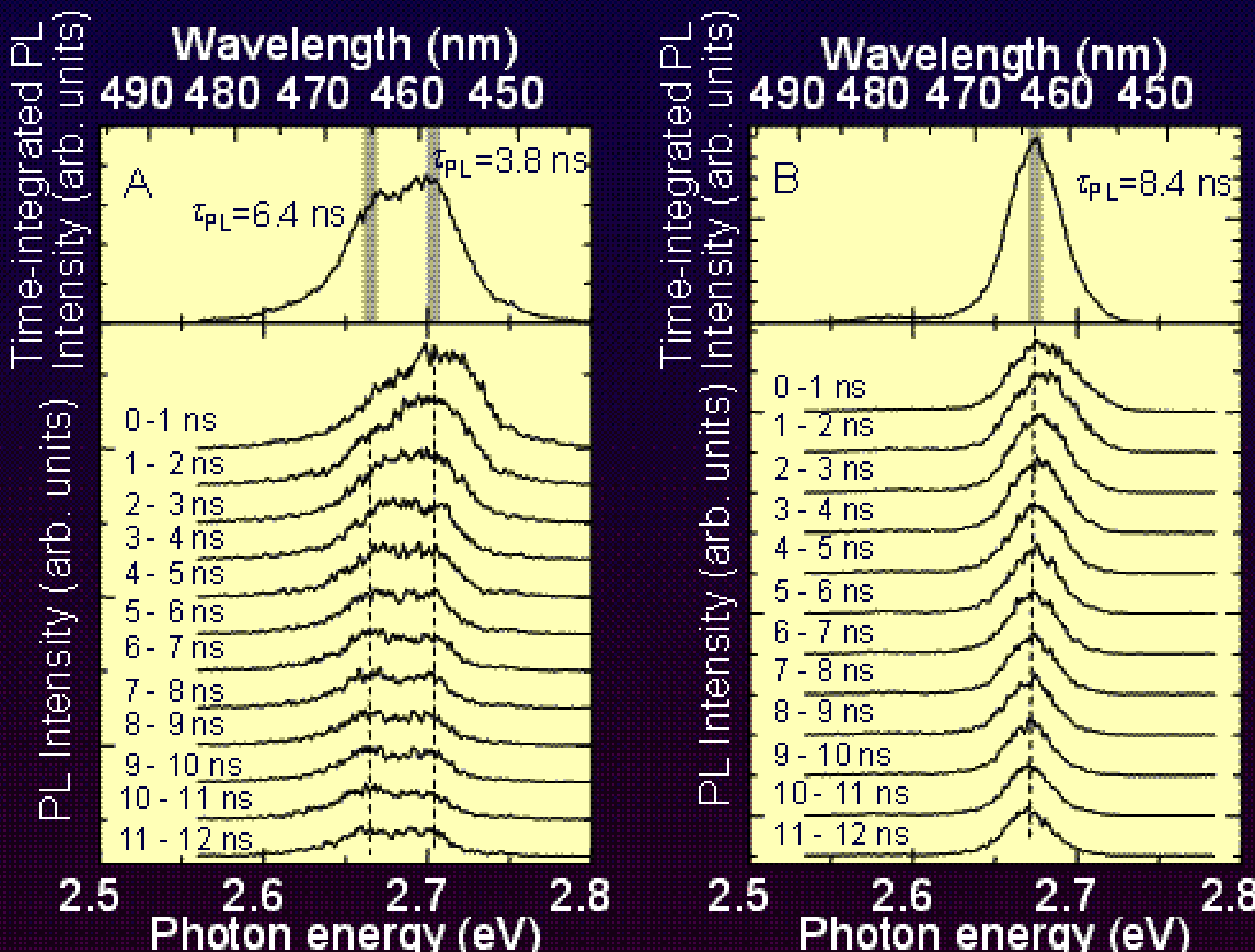






TR-PL spectra at A and B





Observation of nonradiative processes

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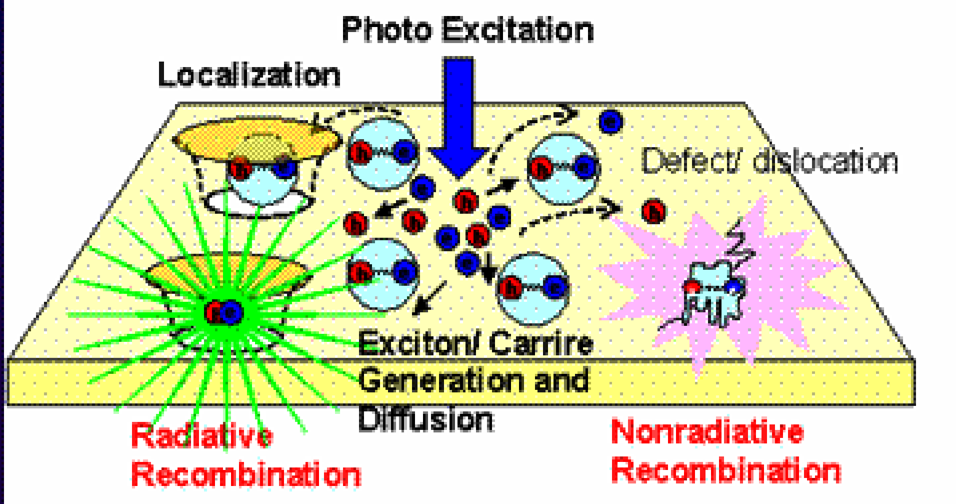


Radiative Processes

Well studied by

Photoluminescence (PL), Electricluminescence (EL), or Cathordoluminescence (CL)

Non-radiative Processes

Carrie dynamics, Therrnal dynamics

Also Important but very few studied

3rd order nonlinear optics

$$P / \varepsilon_o = \Sigma\, \chi_{ij}^{(1)} E_j + \Sigma\Sigma\, \chi_{ijk}^{(2)} E_j E_k + \underline{\Sigma\Sigma\Sigma\, \chi_{ijkl}^{(3)} E_j E_k} E_l + \ldots$$

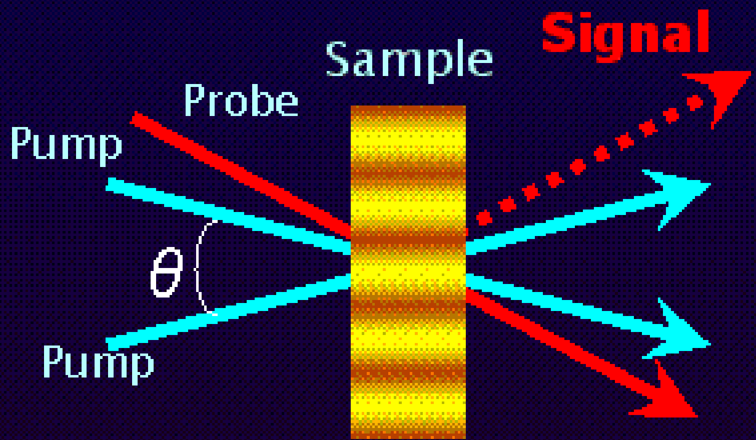
femto — pico — micro — mili — second — mint — hour → **Time**

Electronic polarization	Thermal dynamics	Clustering, Aggregation
Electron transfer	Volume, structure change	Molecular harmonic effect
Energy transfer	Density change	Nana particle growth
Carrier Dynamics	Ultrasonic, Acoustic wave	Crystal growth
Excitation Dynamics	Chemical reaction	Phase Transfer
Molecular vibration	Molecular translation	Metal diffusion

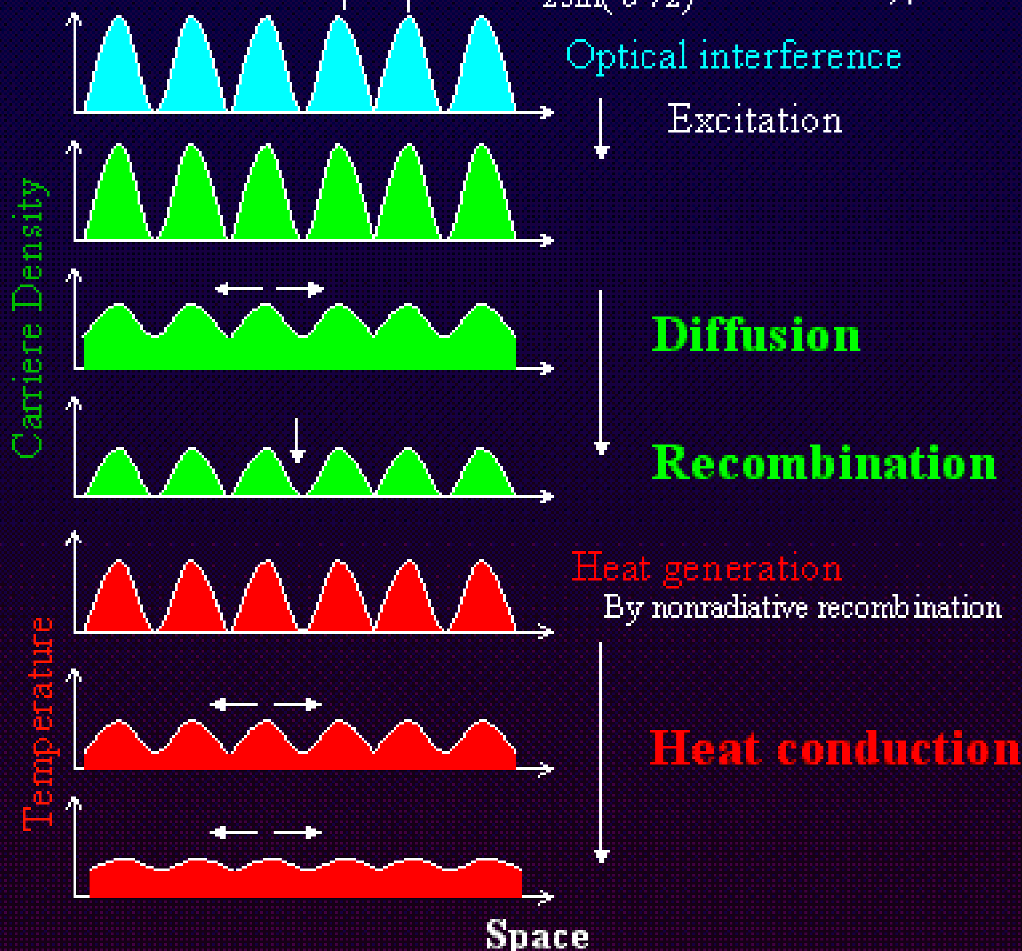
3rd order nonlinear spectroscopy

K. Okamoto, et al, Analytical Science, 17, s312 (2001).

Transient Grating (TG)



$$\Lambda = \frac{\lambda_e}{2\sin(\theta/2)} \qquad q = \frac{2\pi}{\Lambda}$$



Pump by the interference pattern created by crossing two beams

Create the grating (moderation of the carrire and/or exciton densities or temperature)

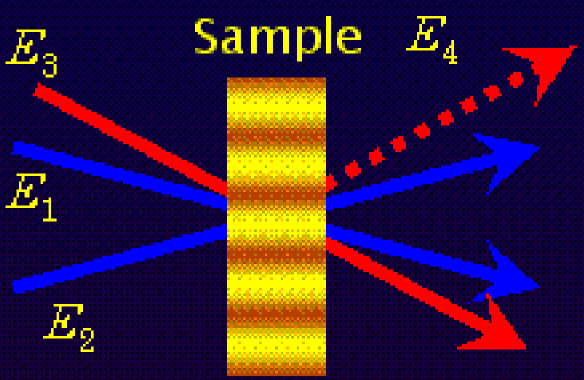
Probe by the diffracted beam

High sensitivities, high accuracy, high time resolution, and high spatial resolution

Application of TG method

© Koichi Okamoto

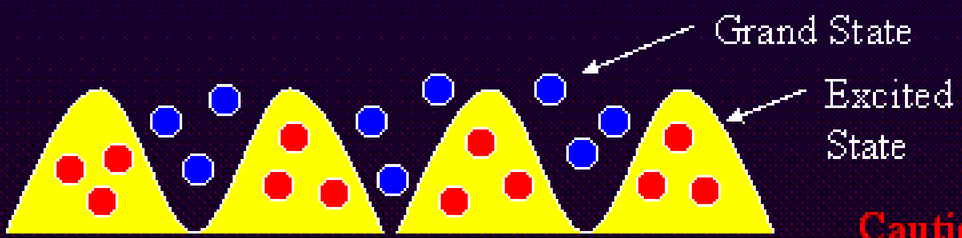
$$P / \varepsilon_o = \Sigma\ \chi_{ij}^{(1)} E_j + \Sigma\Sigma\ \chi_{ijk}^{(2)} E_j E_k + \underline{\Sigma\Sigma\Sigma\ \chi_{ijkl}^{(3)} E_j E_k E_l} + \ldots$$



femto	pico	micro	mili	second	mint	hour	Time

Electronic polarization	Thermal dynamics	Clustering, Aggregation
Electron transfer	Volume, structure change	Molecular harmonic effect
Energy transfer	Density change	Nana particle growth
Carrier Dynamics	Ultrasonic, Acoustic wave	Crystal growth
Excitation Dynamics	Chemical reaction	Phase Transfer
Molecular vibration	Molecular translation	Metal diffusion

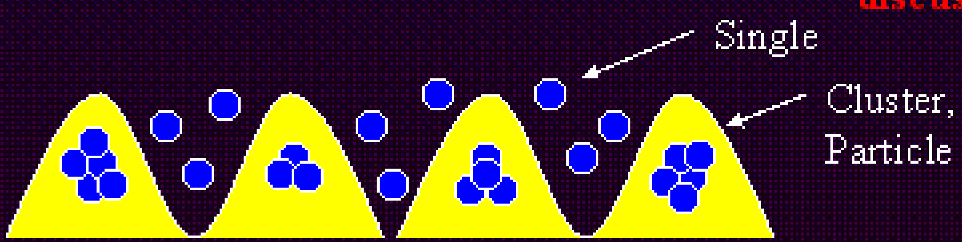
(For example) observation of molecular dynamics in solution



First time observation of diffusion of excited molecules

Both diffusions are quite different!!!

Caution!! Photochemical reaction should not be discusses based on only the hydrodynamic theory!!!



Real-time observation of molecular aggregation, ion clustering, metal particle growth

Experimental Setup of the TG method

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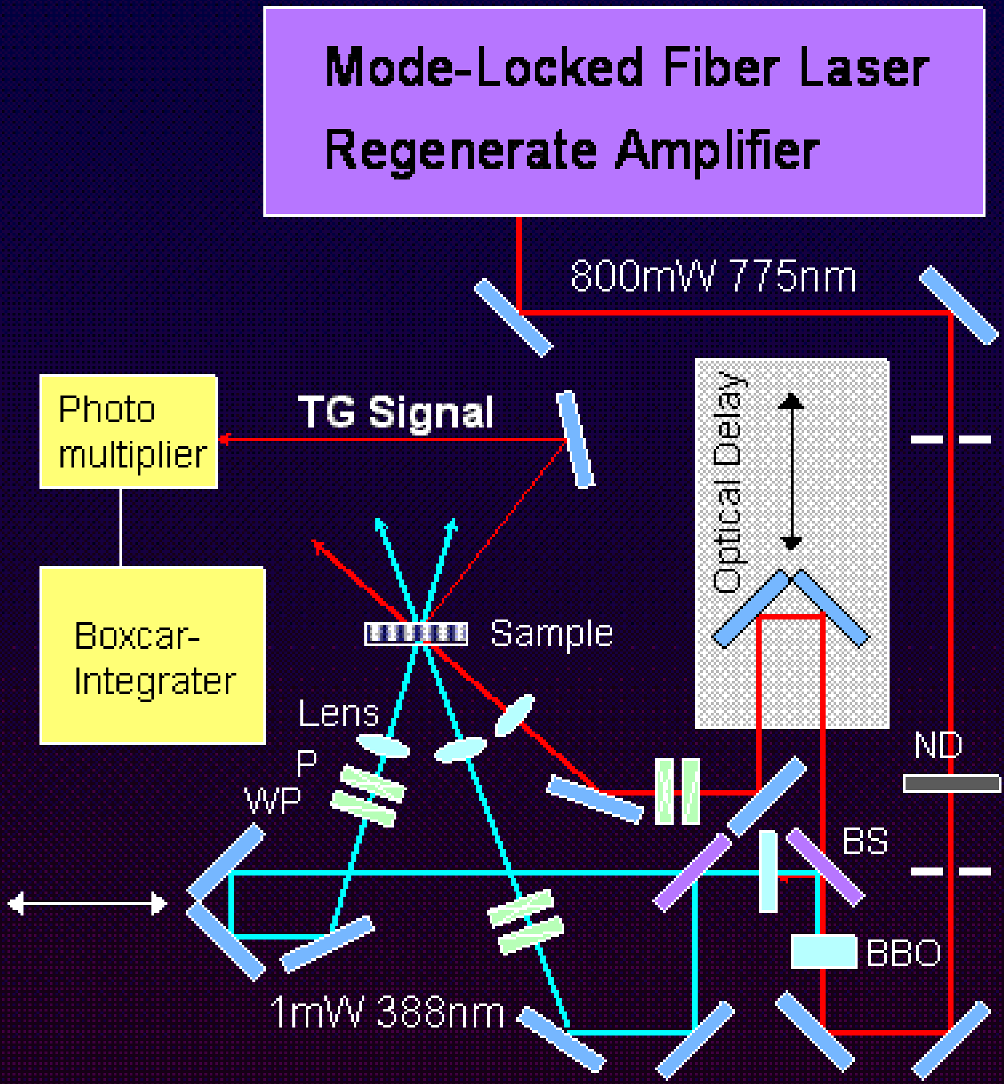
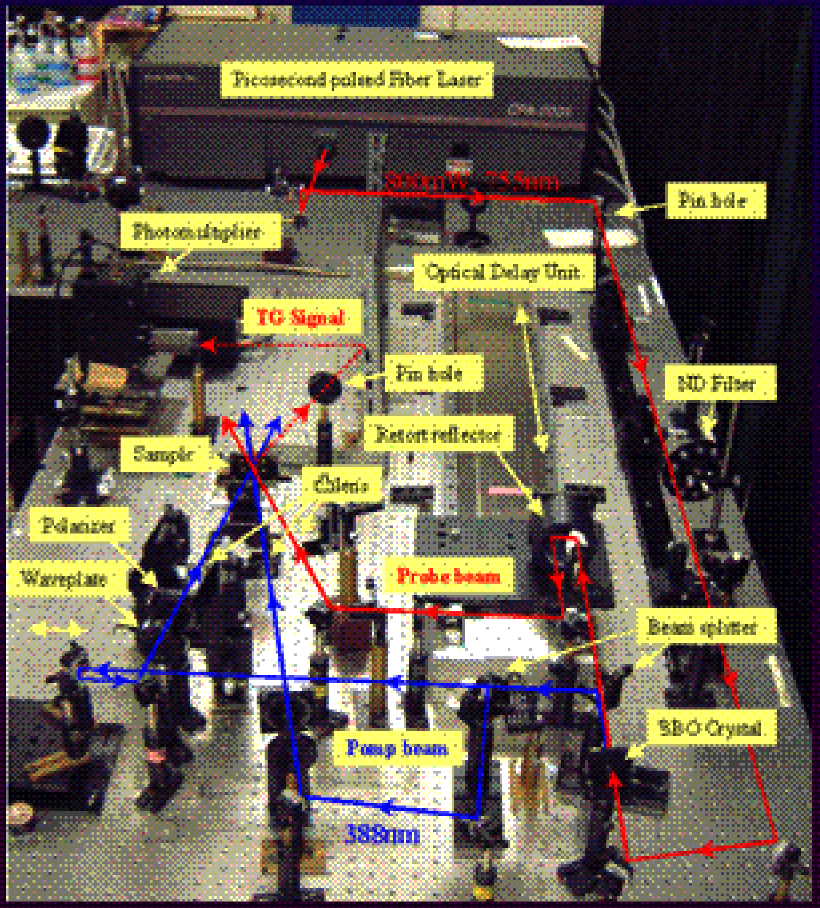
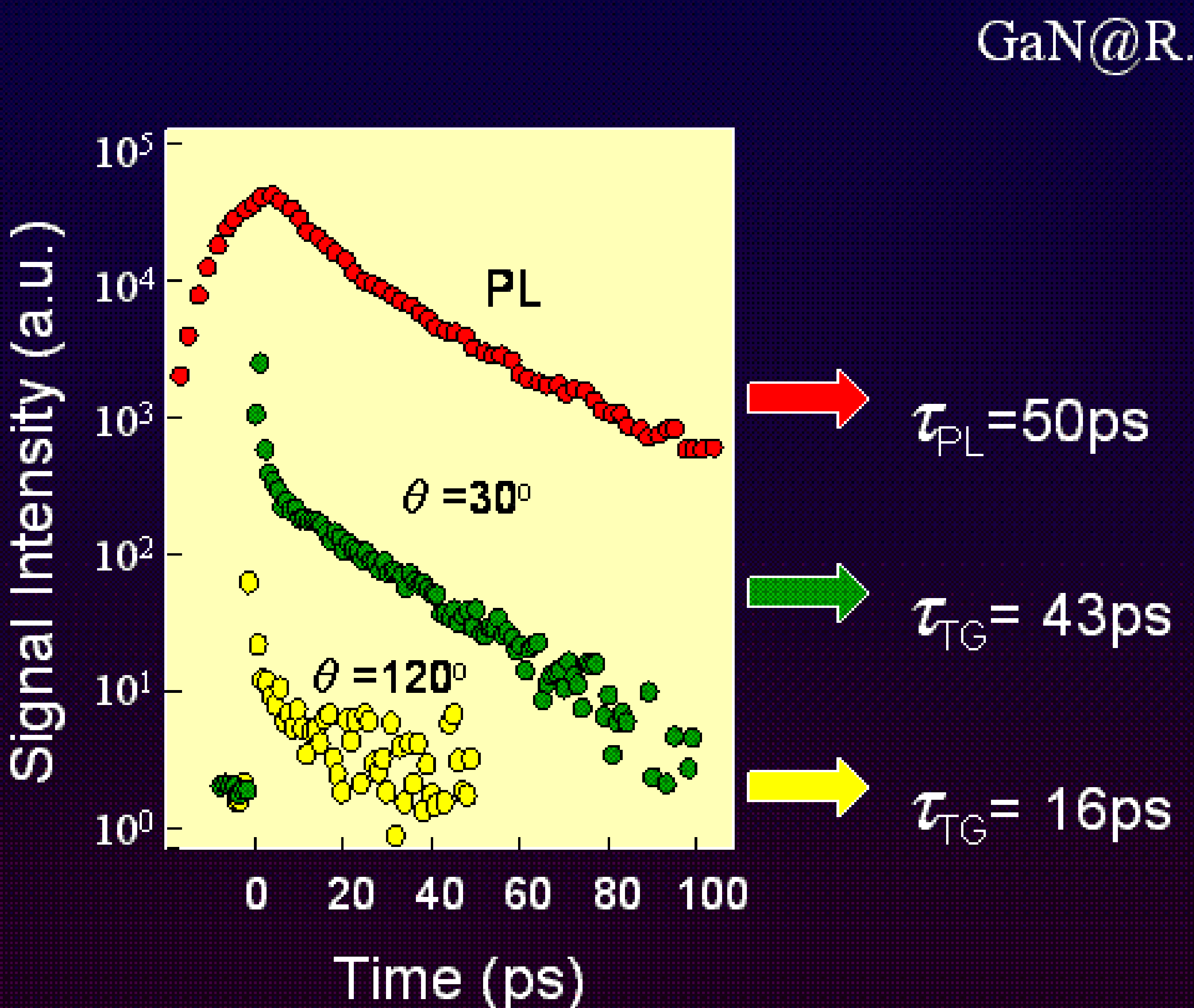


Picosecond time-scale

Mode locked Fiber laser
- frequency doubled beam
- pulse width: 500 fs
- wavelength: 388 nm
- repetition rate: 1 kHz
- power density: 0.5μJ/cm^2



Time-profile of the TG signals of GaN



Results and Analysis of the TG signal

The TG signal intensity is given by the refractive index change

$$I_{TG} / I_0 = \alpha \, \Delta n^2 + \beta \, \Delta k^2 \qquad \text{In this time, } I_{TG}^{1/2} \propto \Delta n$$

$\delta n\,(x, t)$ depend on the dynamics of carrier and/or exciton

$$\delta n(x,t) = \left(\frac{\partial n}{\partial N}\right)\delta N(x,t) + \left(\frac{\partial n}{\partial T}\right)\delta T(x,t) \qquad \left(\frac{\partial n}{\partial N}\right) < 0, \quad \left(\frac{\partial n}{\partial T}\right) > 0$$

The carrier dynamics can be written by

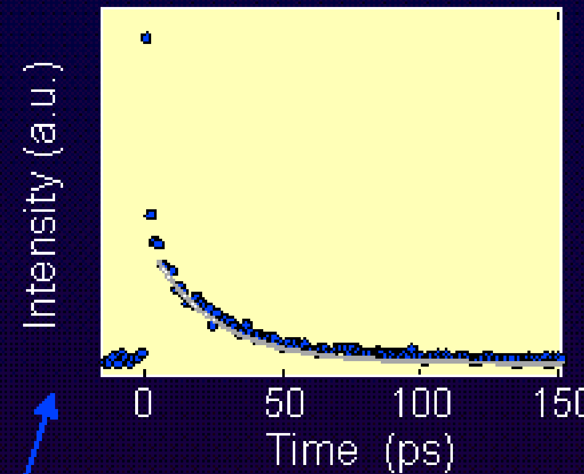
$$\frac{d\,\delta N(x,t)}{dt} = D\frac{\partial^2 \delta N(x,t)}{\partial x^2} - \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right)\delta N(x,t)$$

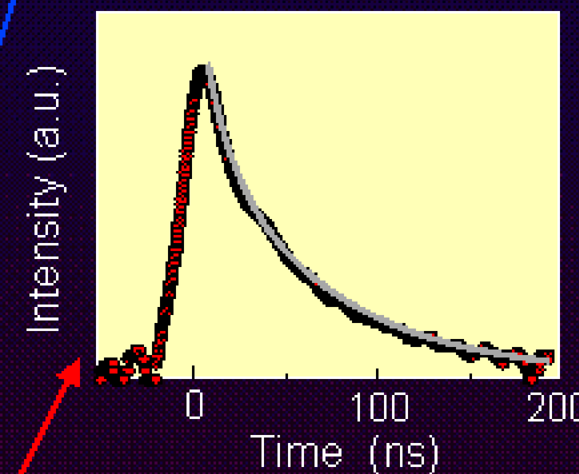
$$\frac{d\,\delta T(x,t)}{dt} = \frac{1}{\tau_{on-rad}}\frac{Q\,\delta N(x,t)}{\rho C p} + D_{th}\frac{\partial^2 \delta T(x,t)}{\partial t}$$

By solving, the time profile of the TG signal was given by

$$\delta\hat{n}(q,t) = \left(\frac{\partial n}{\partial N}\right)\delta\hat{N}(q,0)\exp\left[-\left(Dq^2 + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right)t\right]$$

$$+\left(\frac{\partial n}{\partial T}\right)\frac{\tau_{rad}}{\tau_{rad} + \tau_{non-rad} + \tau_{rad}\tau_{non-rad}Dq^2}\frac{Q\,\delta\hat{N}(q,0)}{\rho C_p}\left\{-\exp\left[-\left(Dq^2 + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right)t\right] + \exp\left(-D_{th}q^2 t\right)\right\}$$





Carrier diffusion and thermal conductivity

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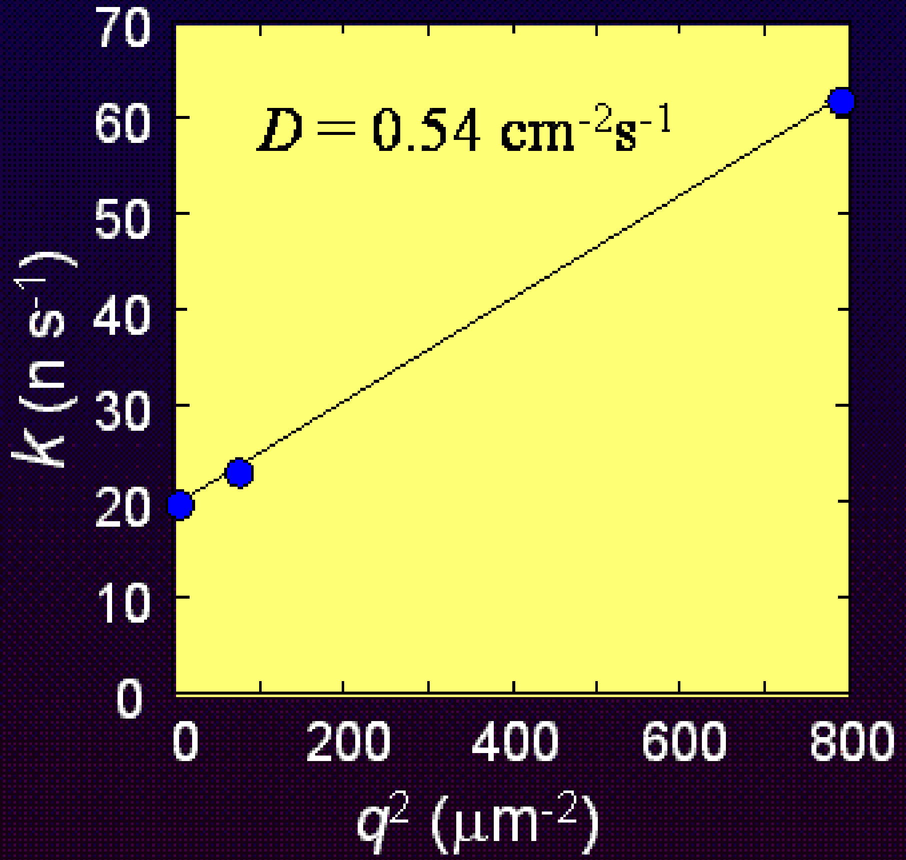
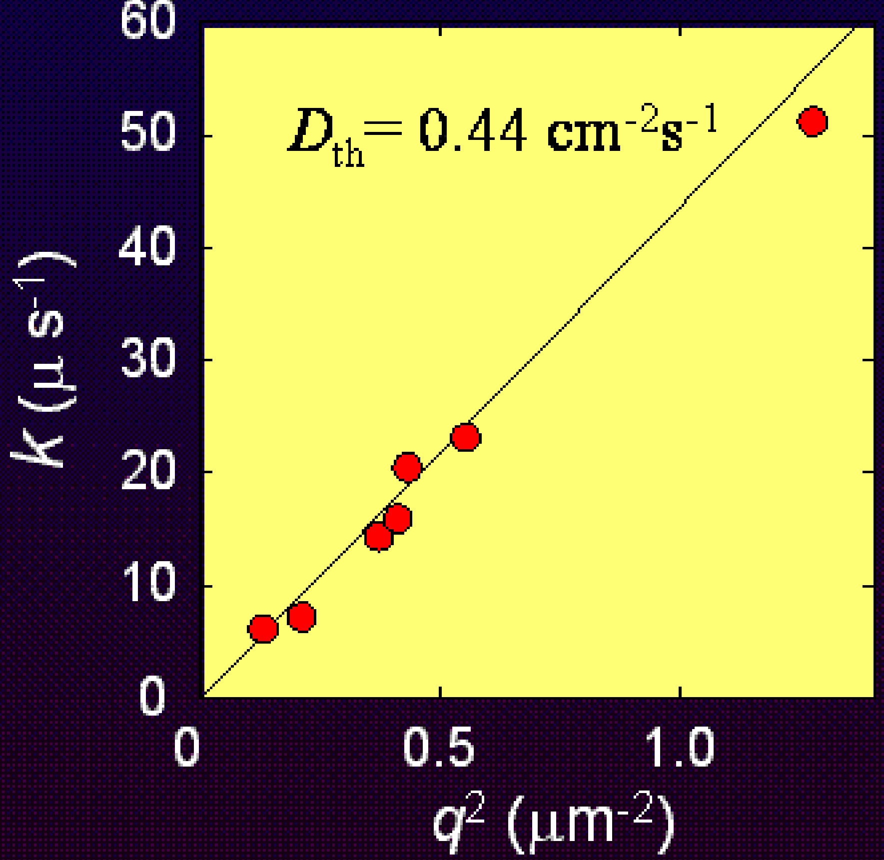
GaN@R.T.

Carrier density grating

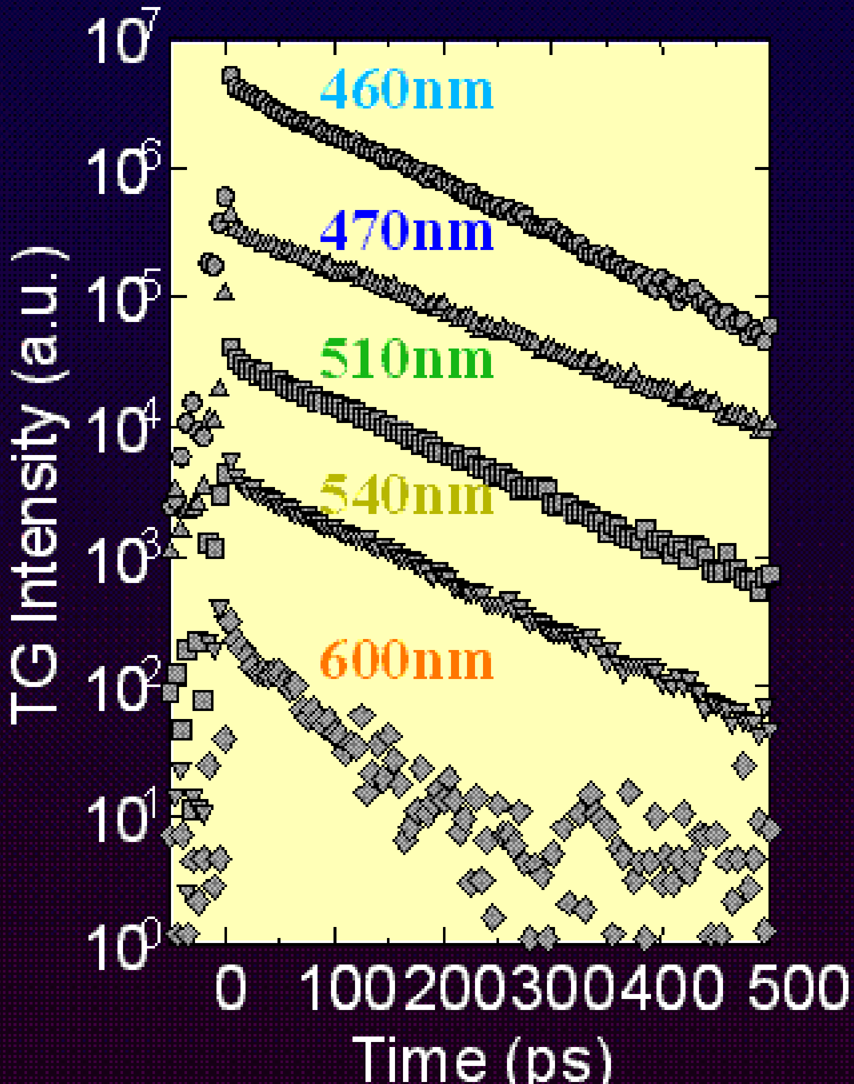


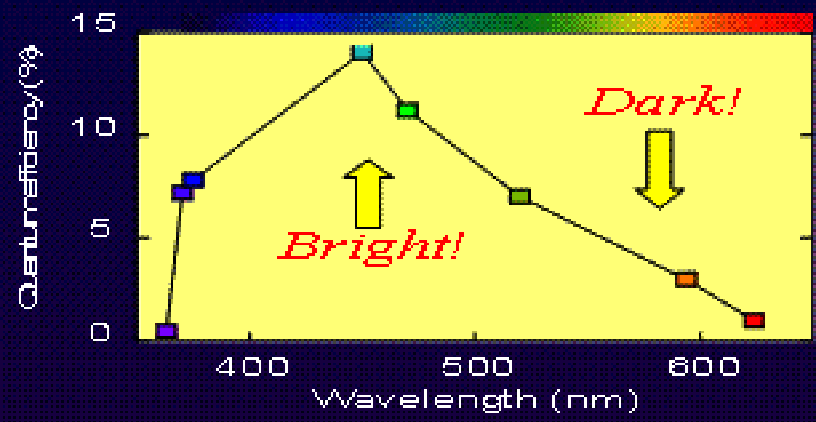
Thermal grating

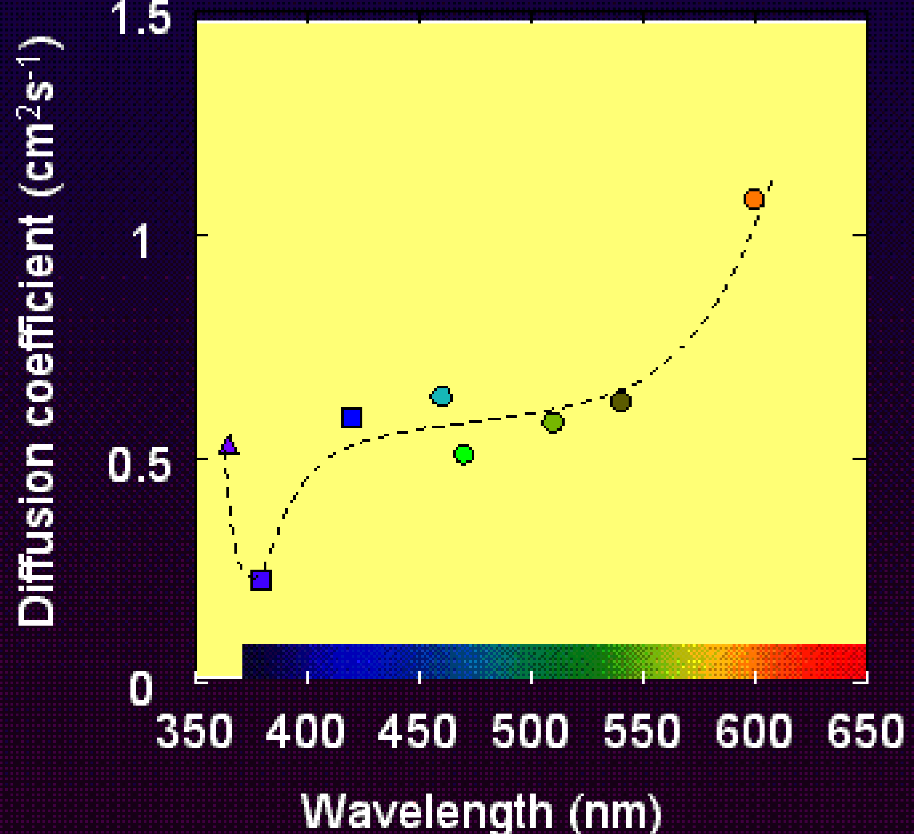


TG measurement for InGaN LEDs

K. Okamoto, et al
Physica Status Solidi B, 228, 81 (2001)

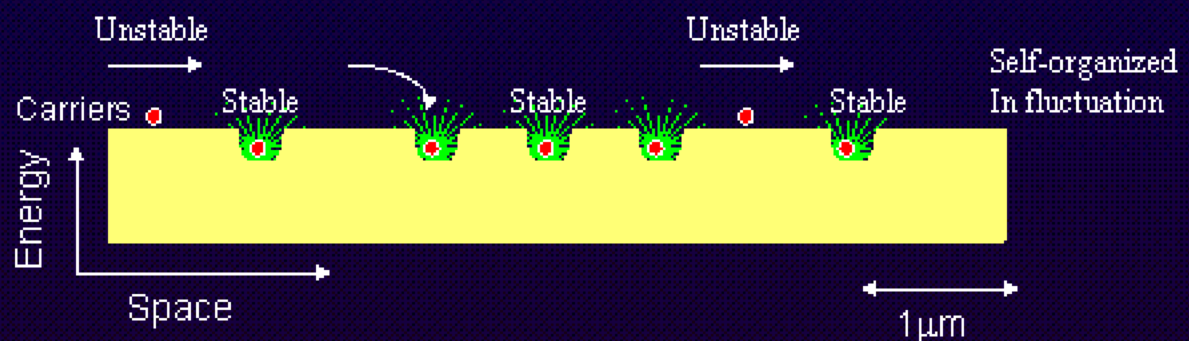






Carrier Diffusion and Localization

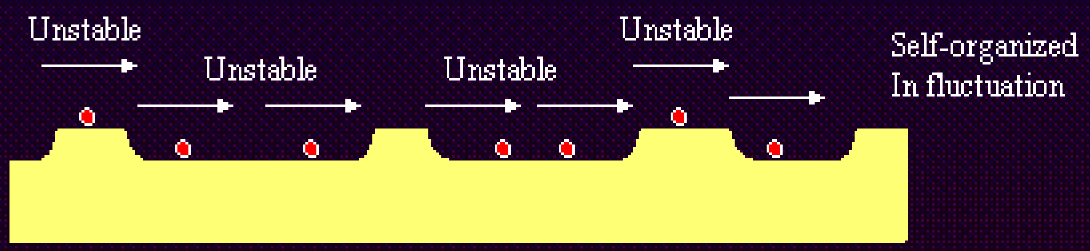
© Koichi Okamoto



Bright!

LED with blue-green

(low In doping)



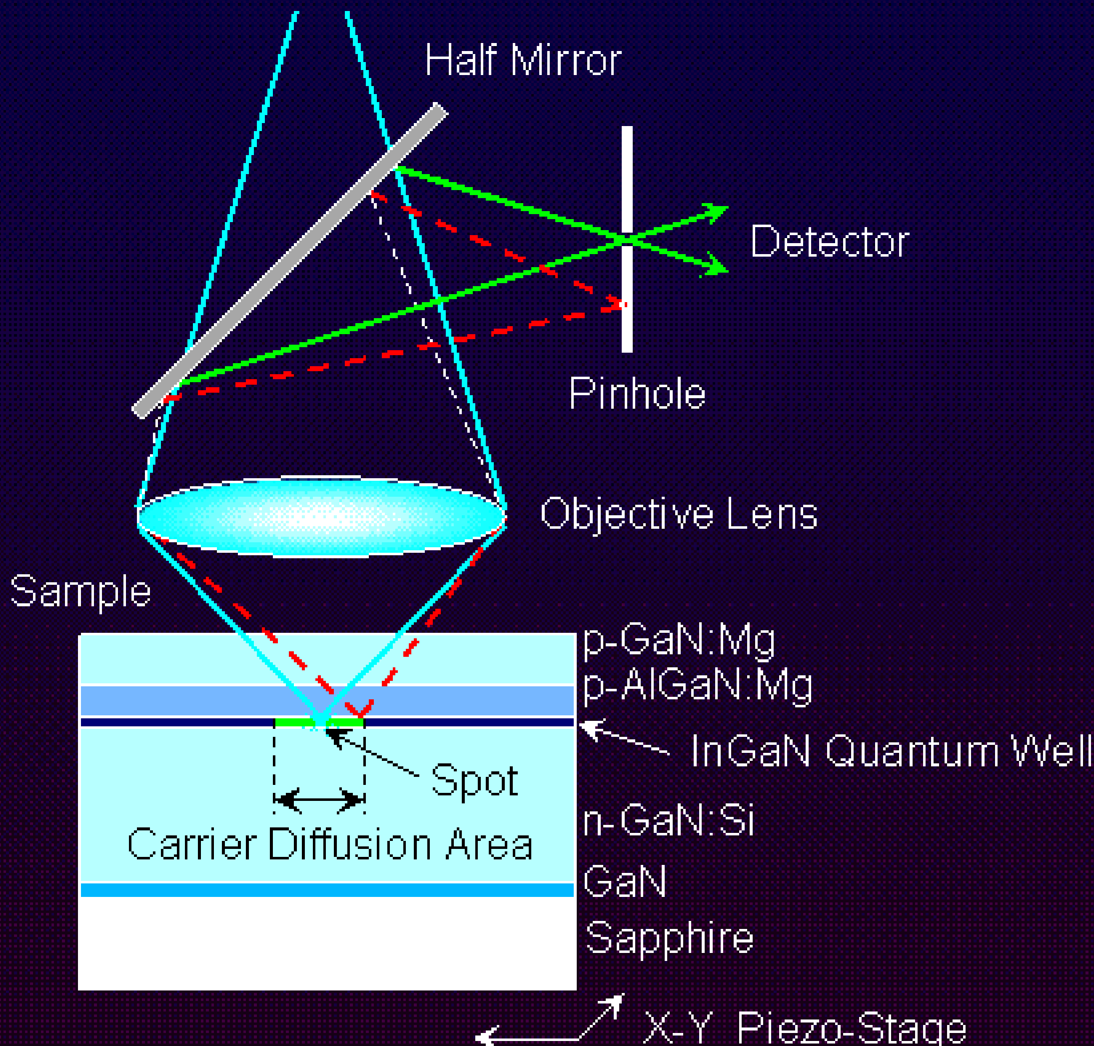
Dark!

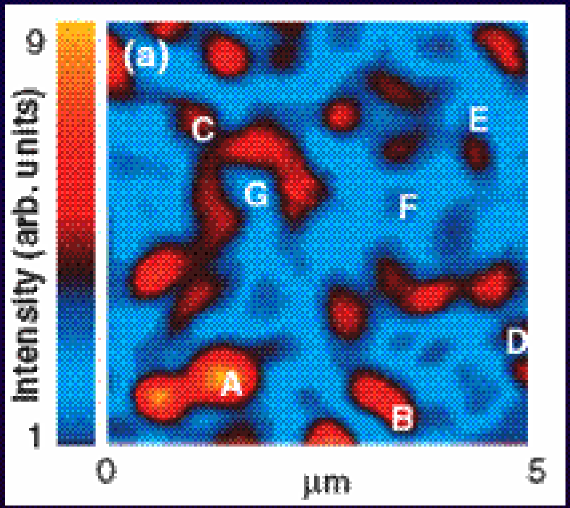
LED with yellow-red

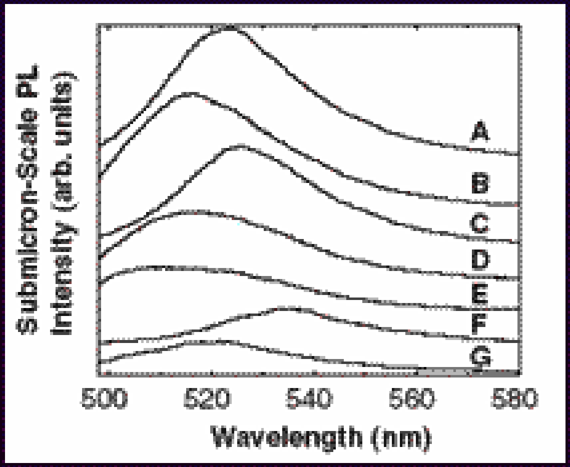
(high In doping)

Confocal Microscopy

K. Okamoto, et al., *Jpn. J. Appl. Phys.* 43, 839 (2004)

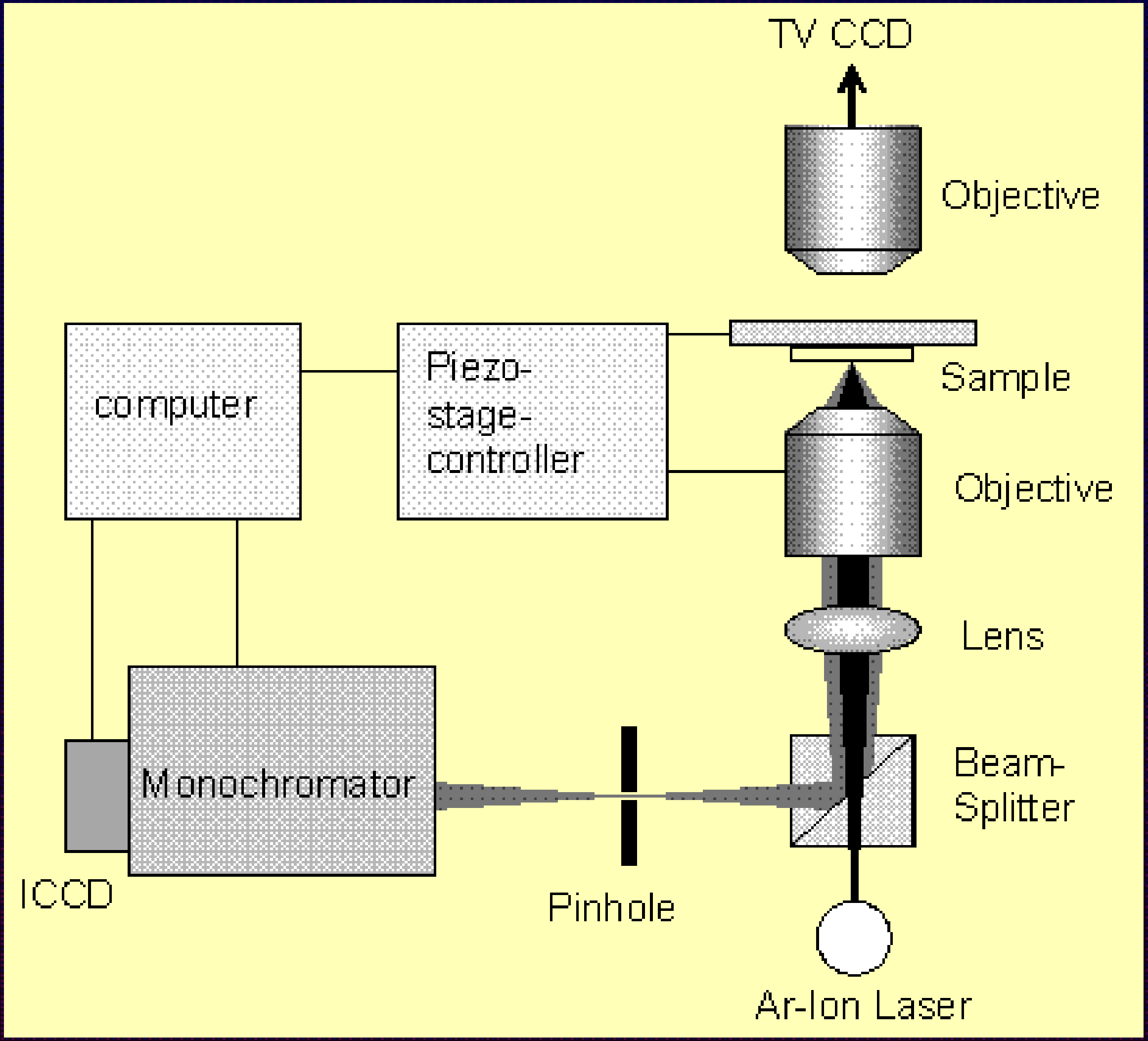






Experimental setup

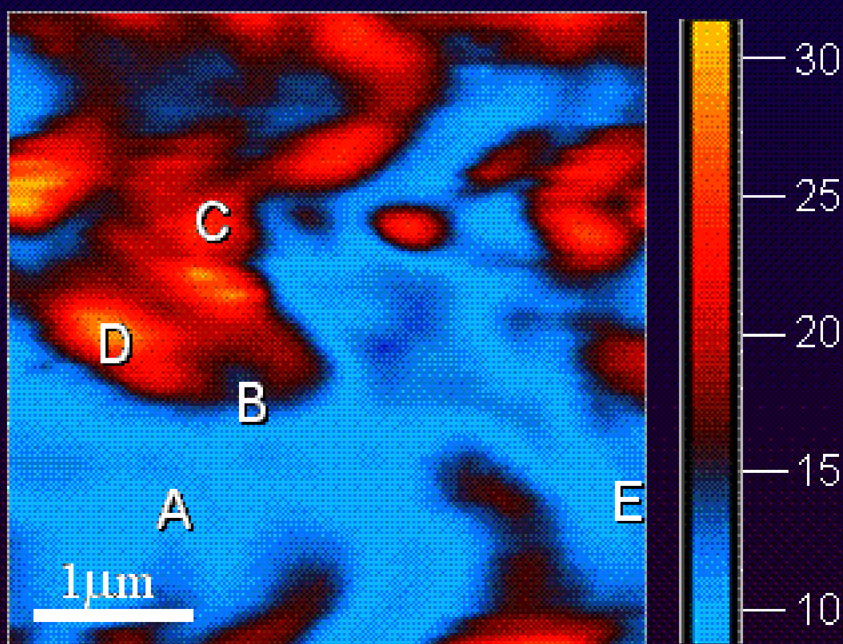
© Koichi Okamoto



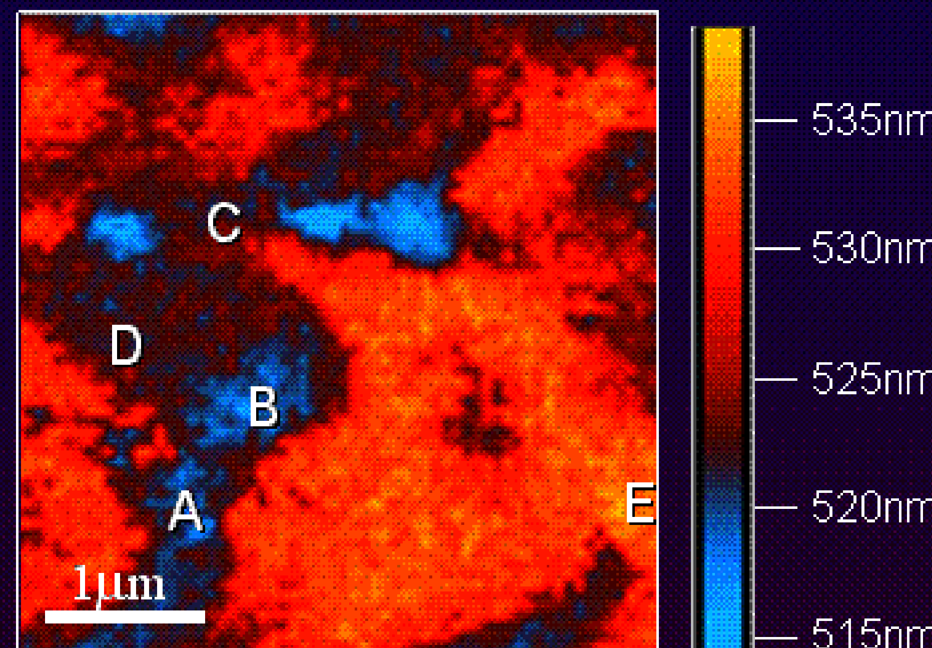
Confocal microscopic image

© Koichi Okamoto

InGaN/GaN LED 540nm @R.T.   Excitation: Ar laser (488nm)   4×4 μm



Peak Intensity Mapping (a.u.)

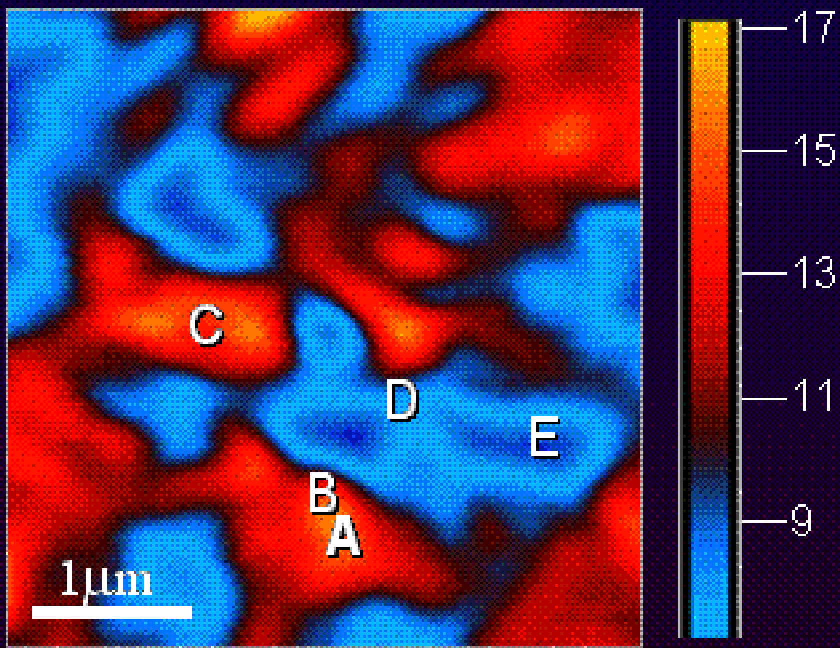


Peak Wavelength Mapping (nm)

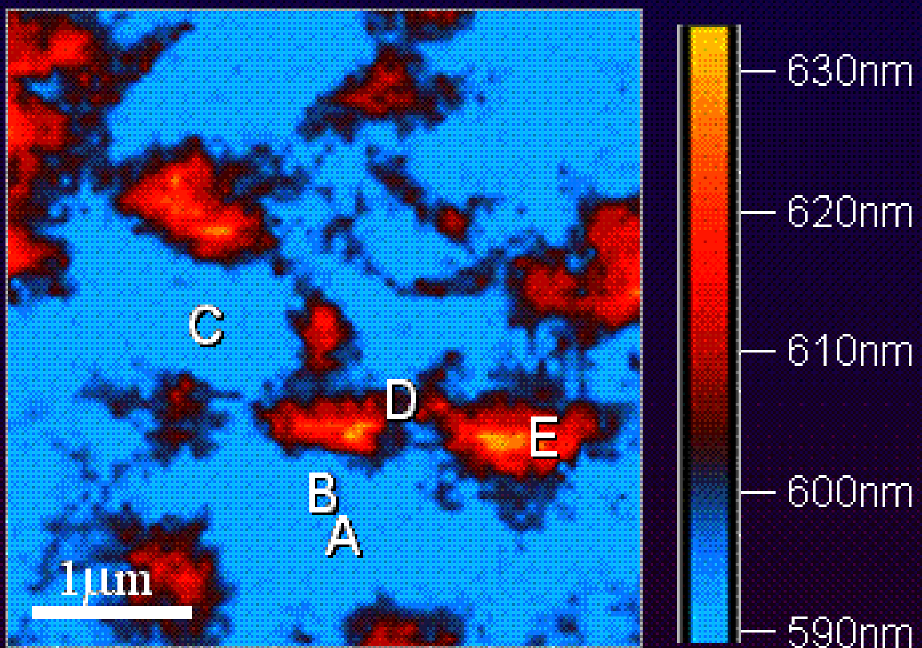
Confocal microscopic image

© Koichi Okamoto

InGaN/GaN LED 600nm @R.T. Excitation: Ar laser (488nm) $4 \times 4 \mu m$



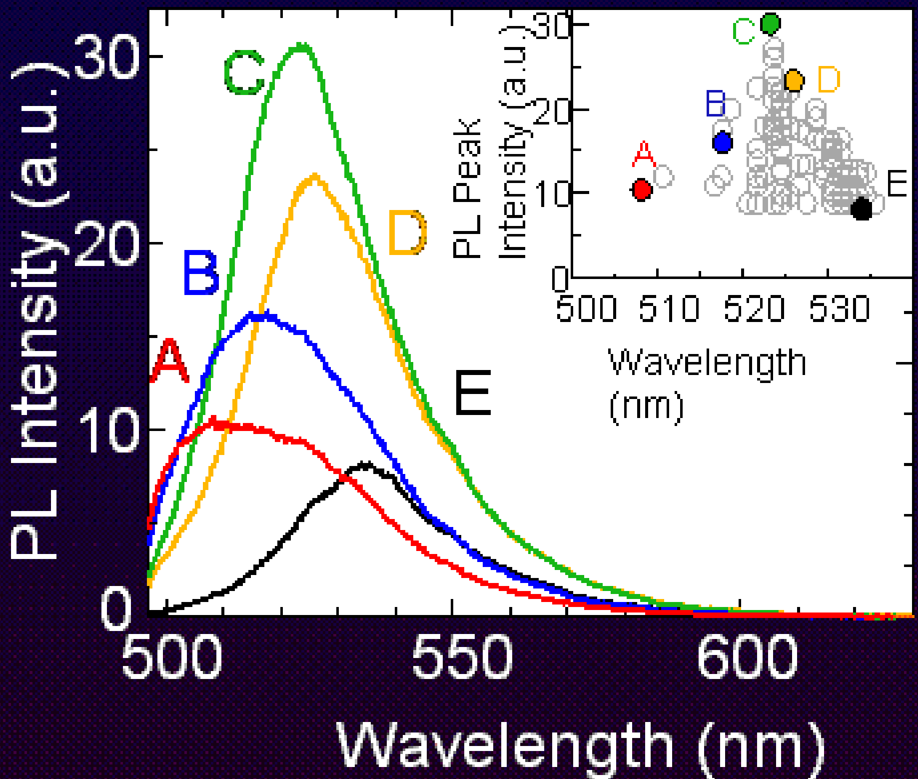
Peak Intensity Mapping (a.u.)

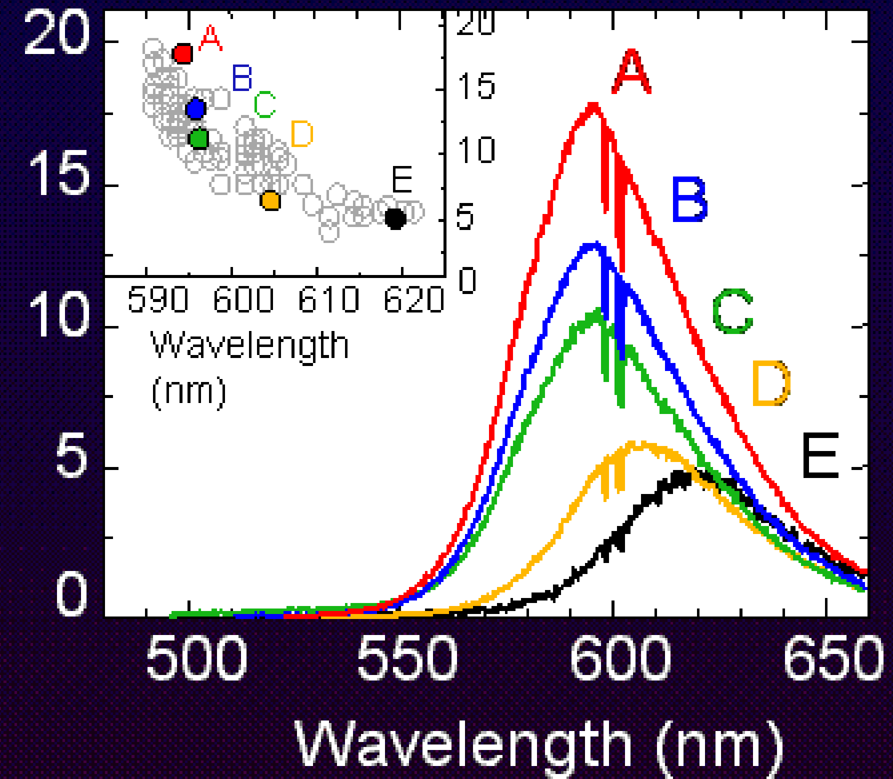


Peak Wavelength Mapping (nm)

Confocal microscopic PL spectra

© Koichi Okamoto





Band diagram fluctuation and exciton dynamics

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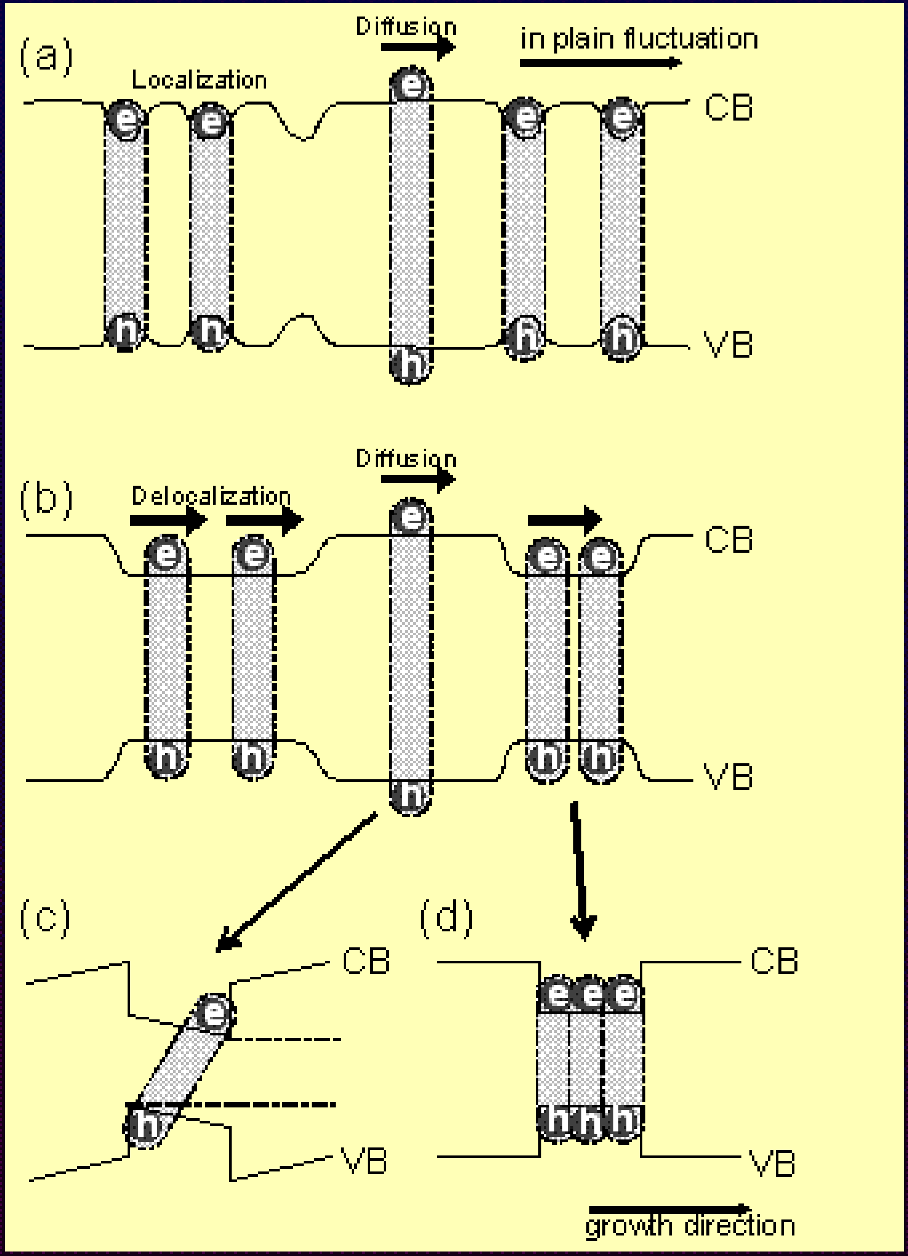


Schematic band diagrams of in-plain fluctuation and diffusion, localization, and recombination dynamics of electron-hole pairs in InGaN active layers which have

(a) low indium composition (blue or green emission)
(b) high indium composition (amber emission).

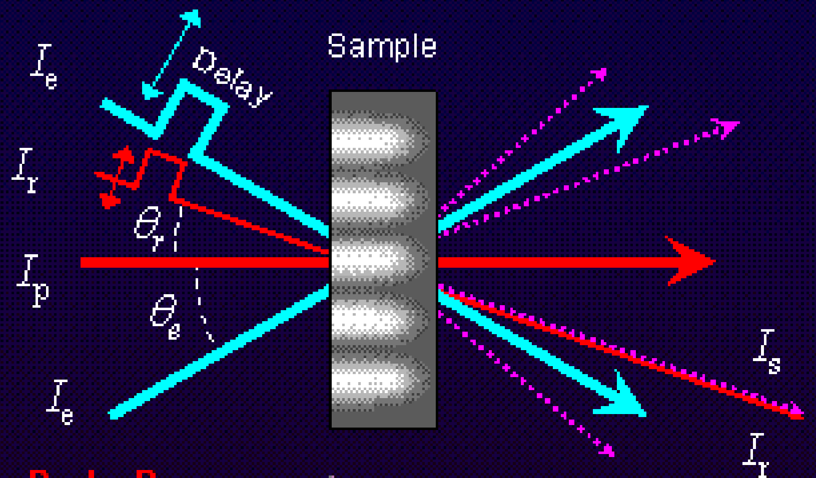
(c) Schematic band diagram strained by strong piezoelectric field along the growth direction.
(d) Partial reduction of QCSE by bond-filling at the high density regions of generated electron-hole pairs.

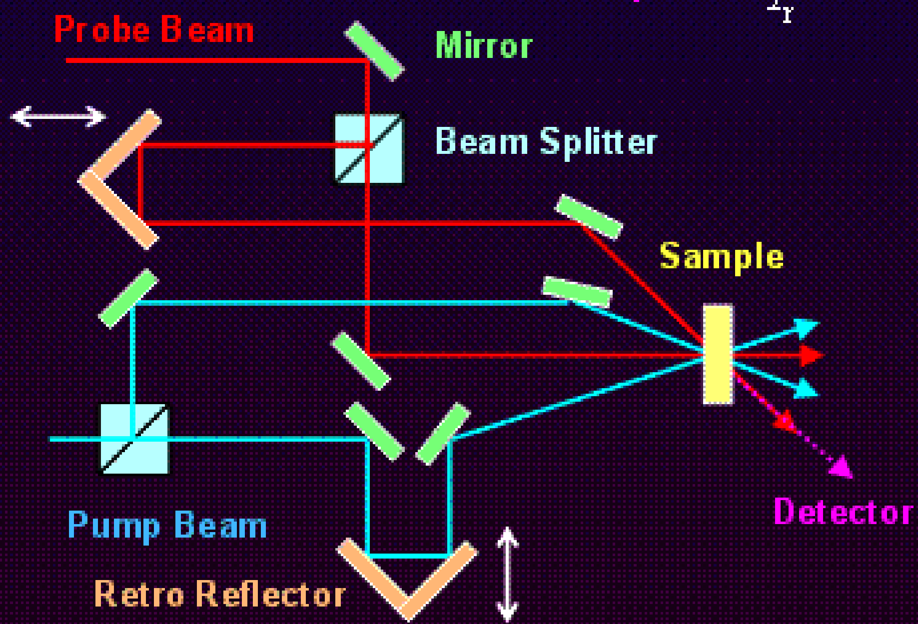
More advanced and simple technique

© Koichi Okamoto

K. Okamoto, et al, Appl. Phys. Lett., 85, 4842 (2004)

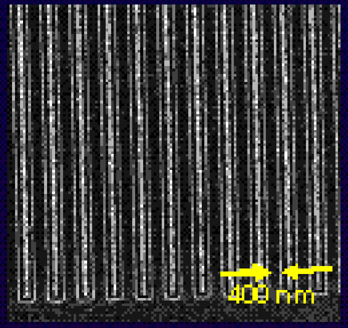
Optical Heterodyne detected TG

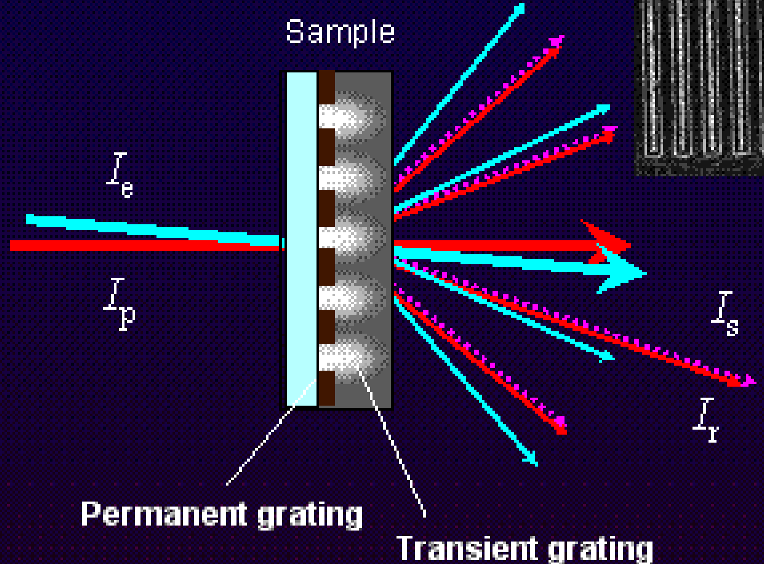


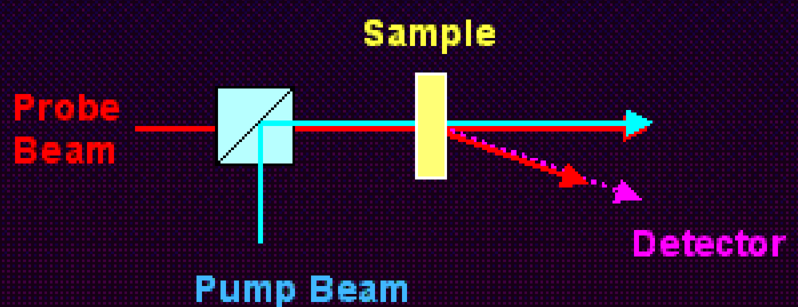


Our invented new method

Mask pattern transfer-TG (MPT-TG)



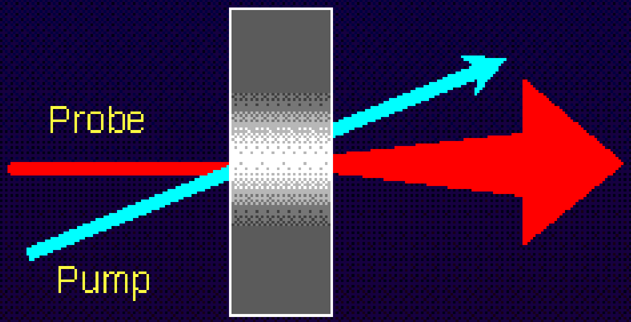


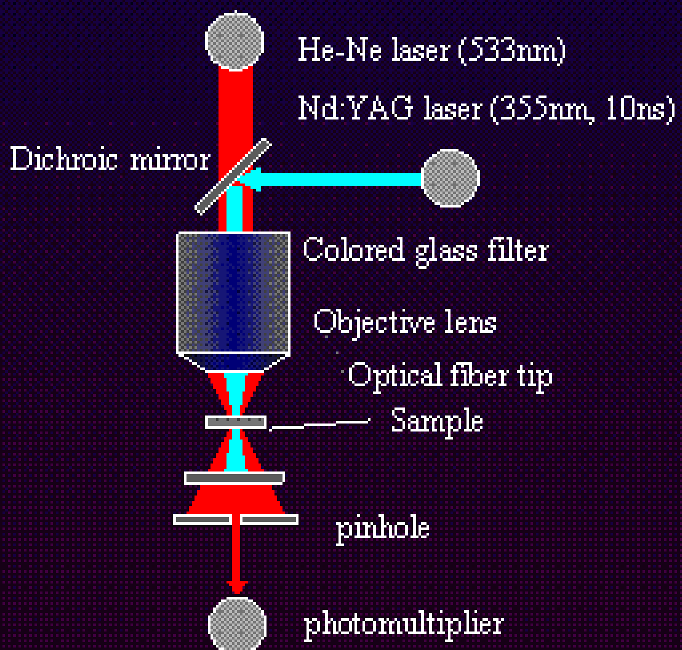


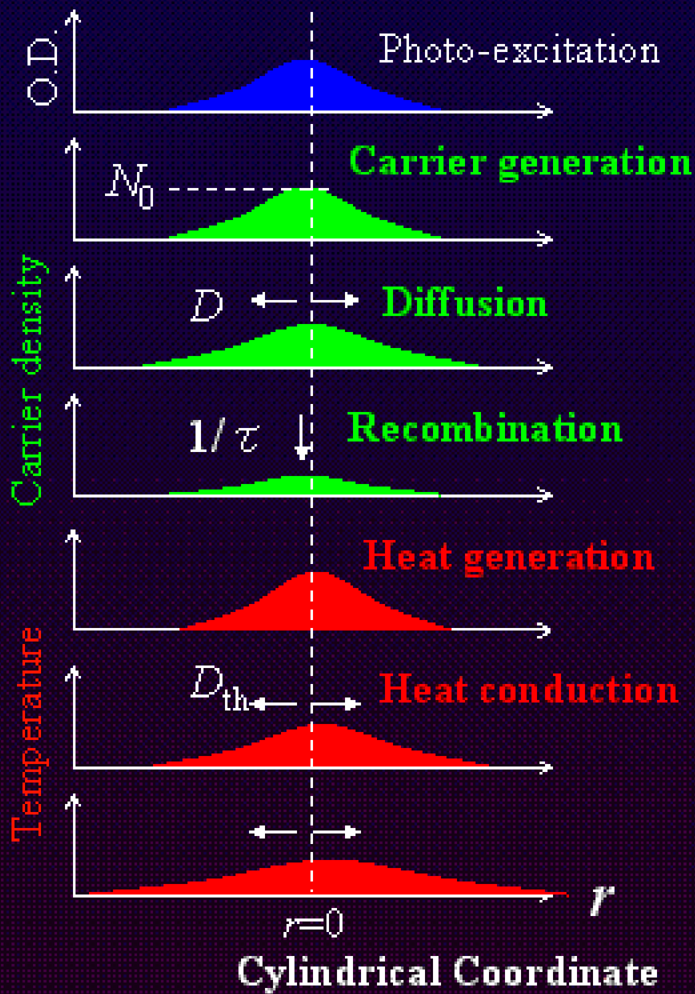
Very Easy and Simple

3rd order Nonlinear Spectroscopy + Spatial Resolution

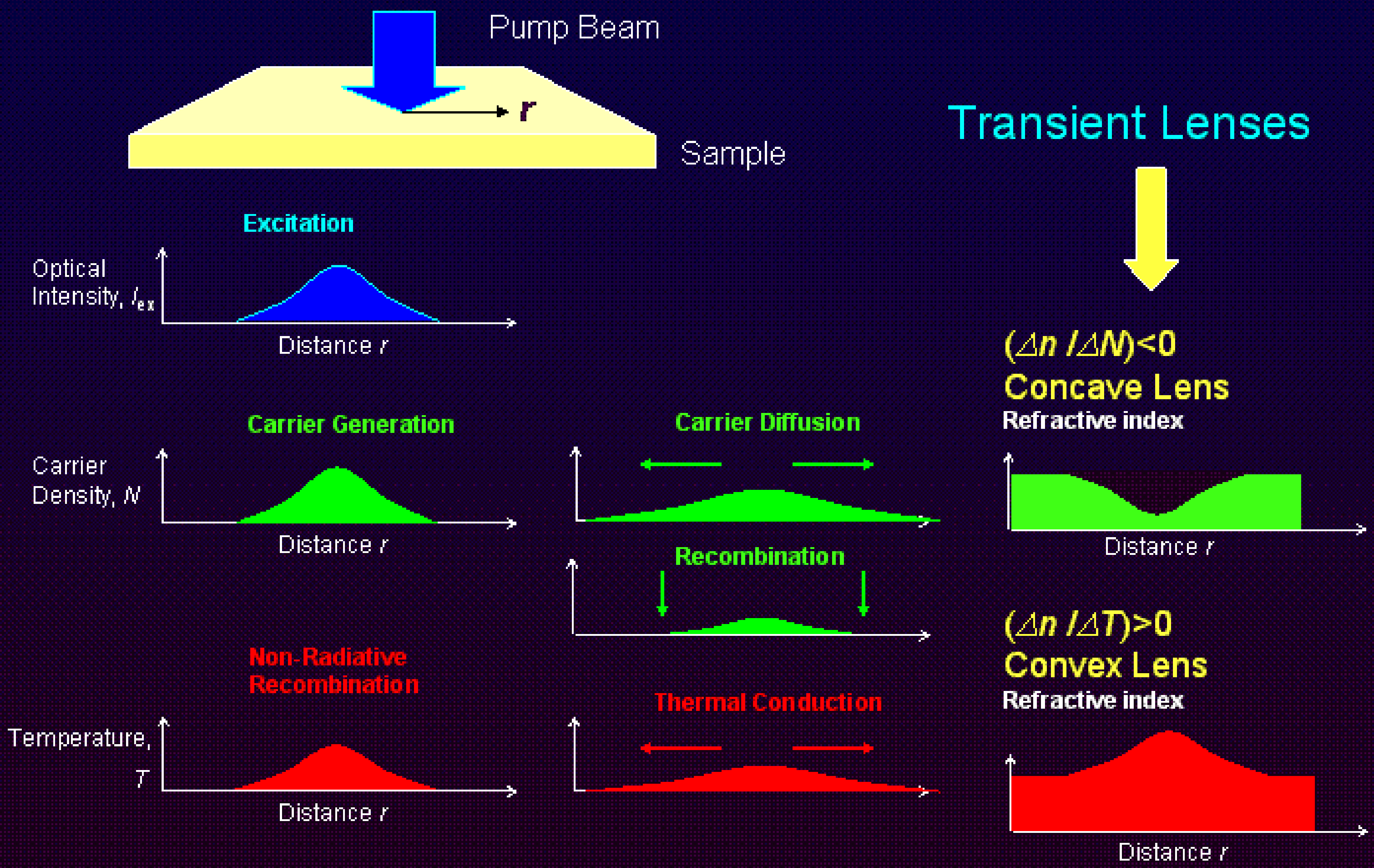
Transient Lens (TL) Spectroscopy



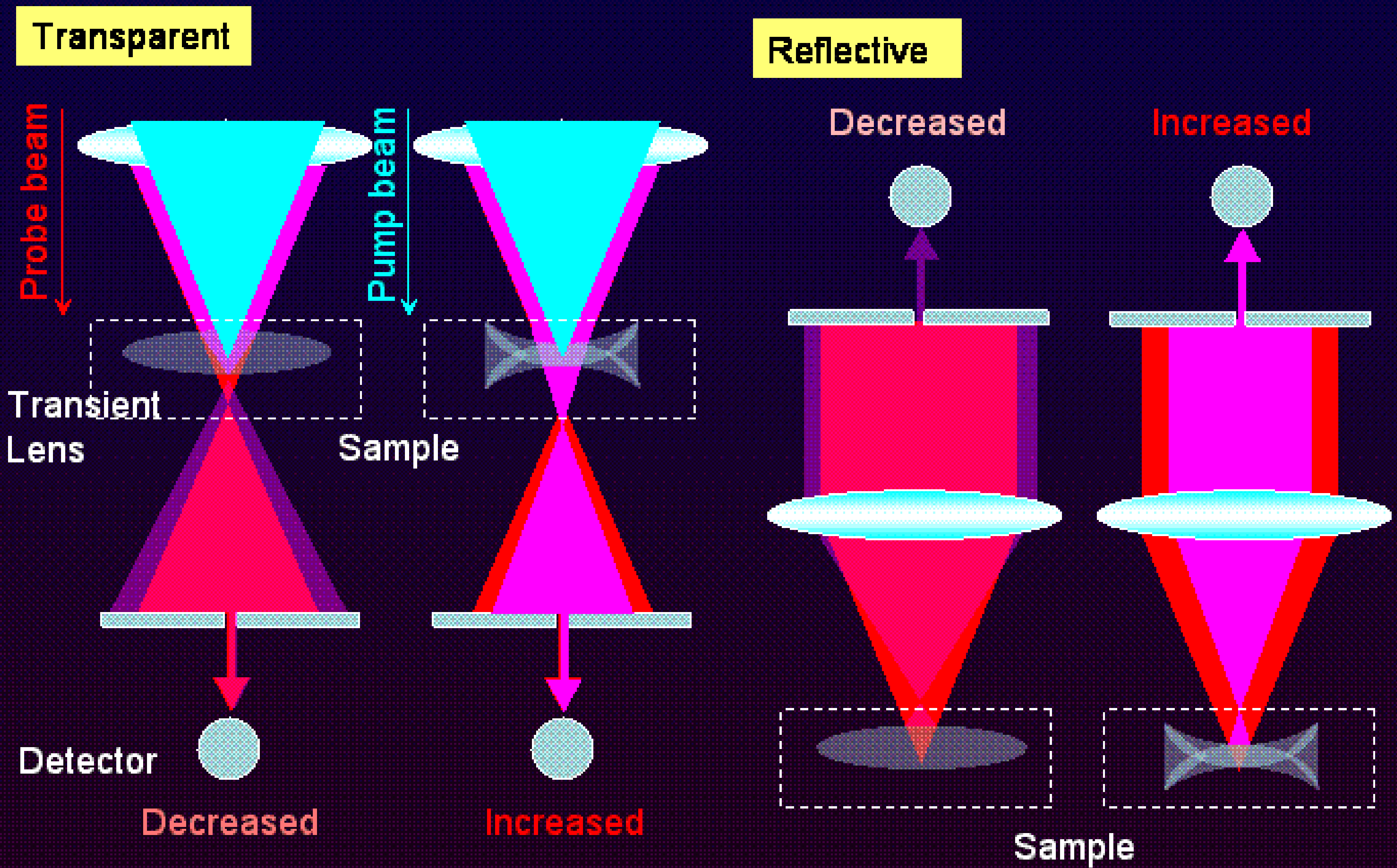




Transient Lens Effect



Detection of Transient Lens



Threading dislocation (TD)

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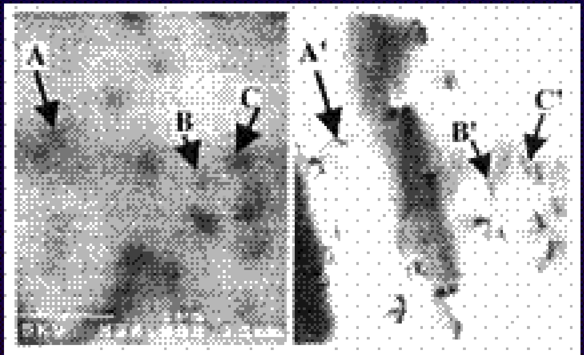
At the room temperature, a large amount of carriers lost the energies by the nonradiative recombination

What is the origin of the nonradiative recombination center (NRC)??



T. Sugahara et al., Jpn. J. Appl. Phys. 37, L398 (1998)

Comparison between transmission electron microscopy (TEM) and cathodoluminescence (CL) mapping

Threading dislocation (TD) should act as the NRC

low dislocated GaN have been achieved by using the ELOG technique

Eptitaxial Lateral Over Gowth

T.Mukai et al,:Jpn.J.Appl.Phys.37 L839(1998)

Emission efficiency of the LEDs grown on ELOG-GaN were not so enhanced

S.Chichibu et al,:Appl.Phys.Lett.74 1460(1999)

Optical properties of low dislocated region were not so difference with high dislocated region.

T. Izumi et al.; Journal of Luminescence 87-89 1196 (2000)

Difference of emission spectra and lifetimes was not observed at each region

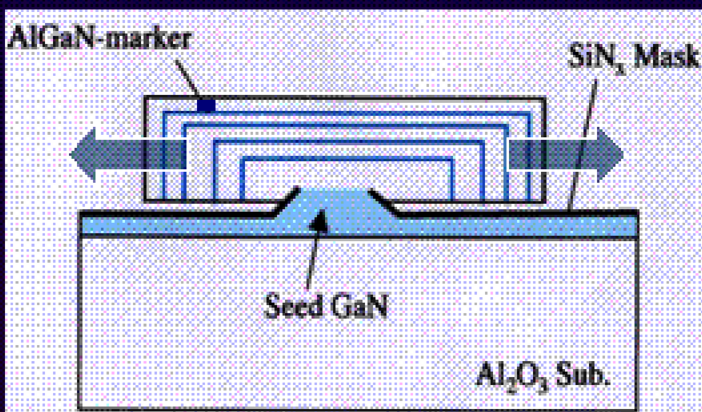
TD should not act as NRC ??? Point defect should be more effective??

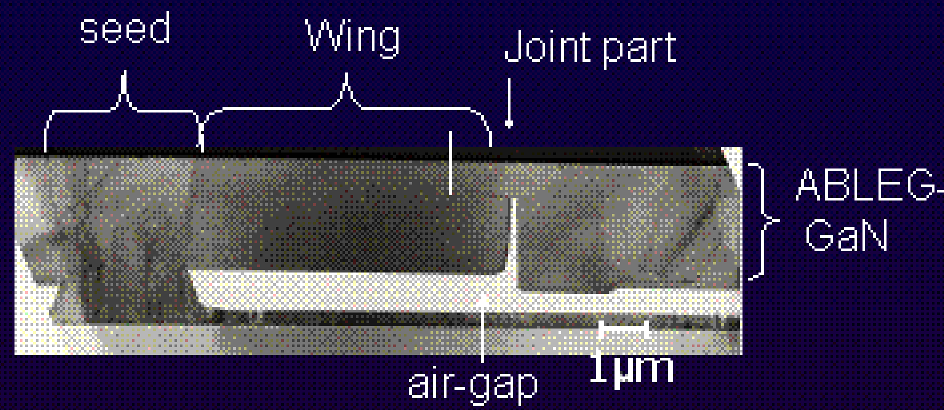
Air-Bridged Lateral Epitaxial Growth (ABLEG)

© Koichi Okamoto

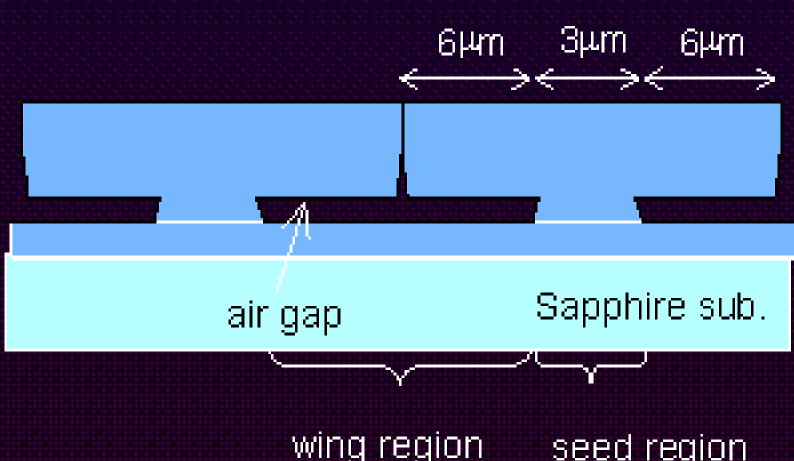
grown by A. Tsujimura, I. Kidoguchi,
Advanced Technology Research Labs., Matsushita Electric Industrial Co.

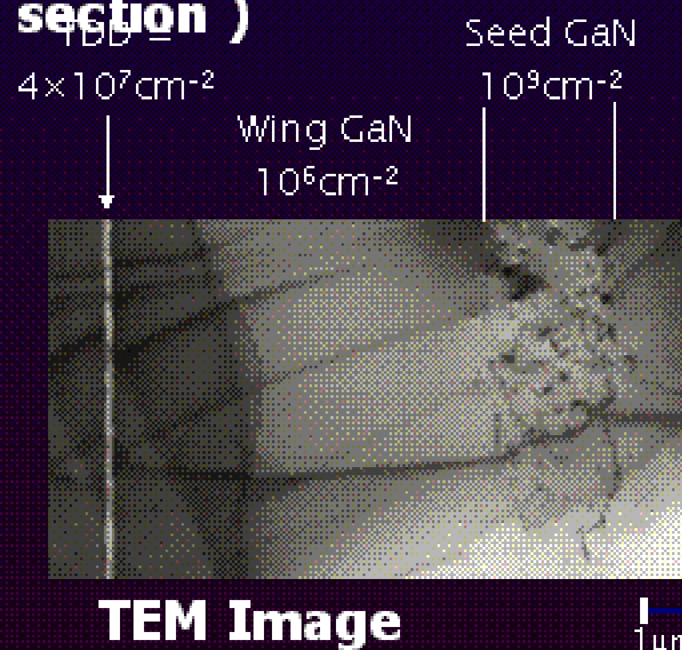
- ■Grew GaN (1 µm) on Sapphire(0001)
- ■Etched GaN for stripe structure
- ■Masked at bottom and side by SiNx
- ■Grew GaN on the non-Mask seed region





TEM Image (cross-section)





TEM Image

Optical Properties of ABLEG-GaN

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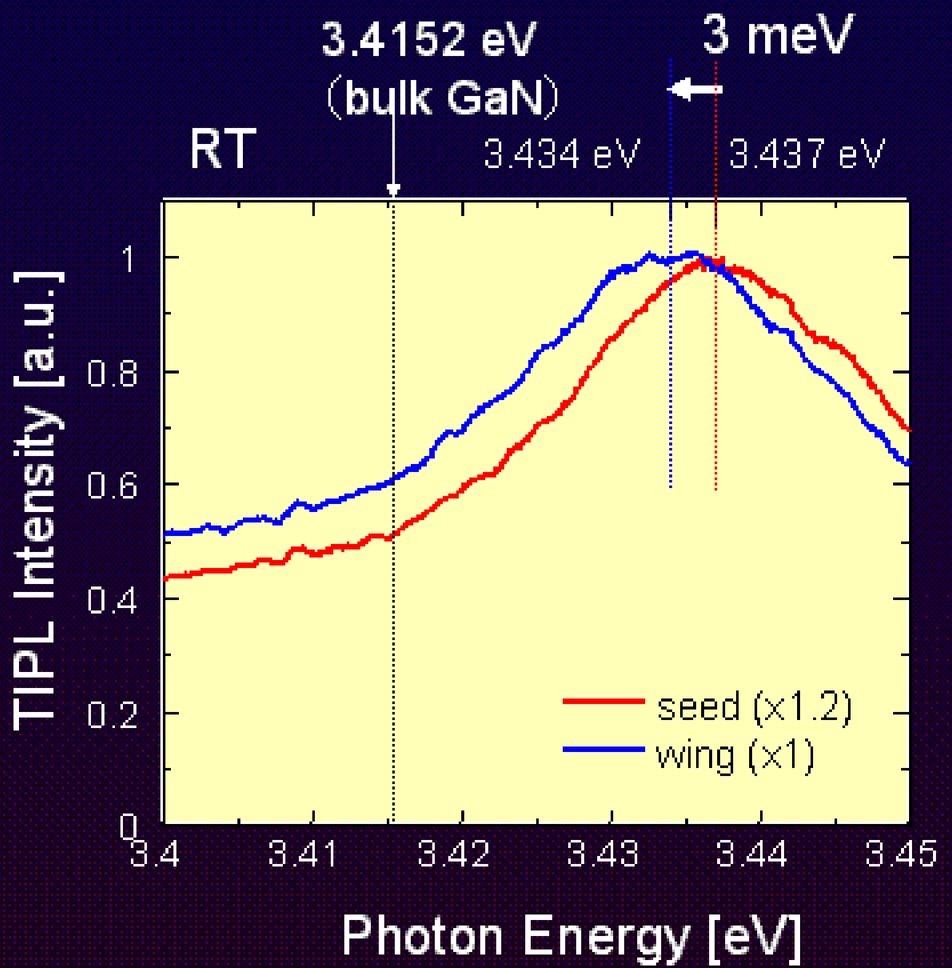
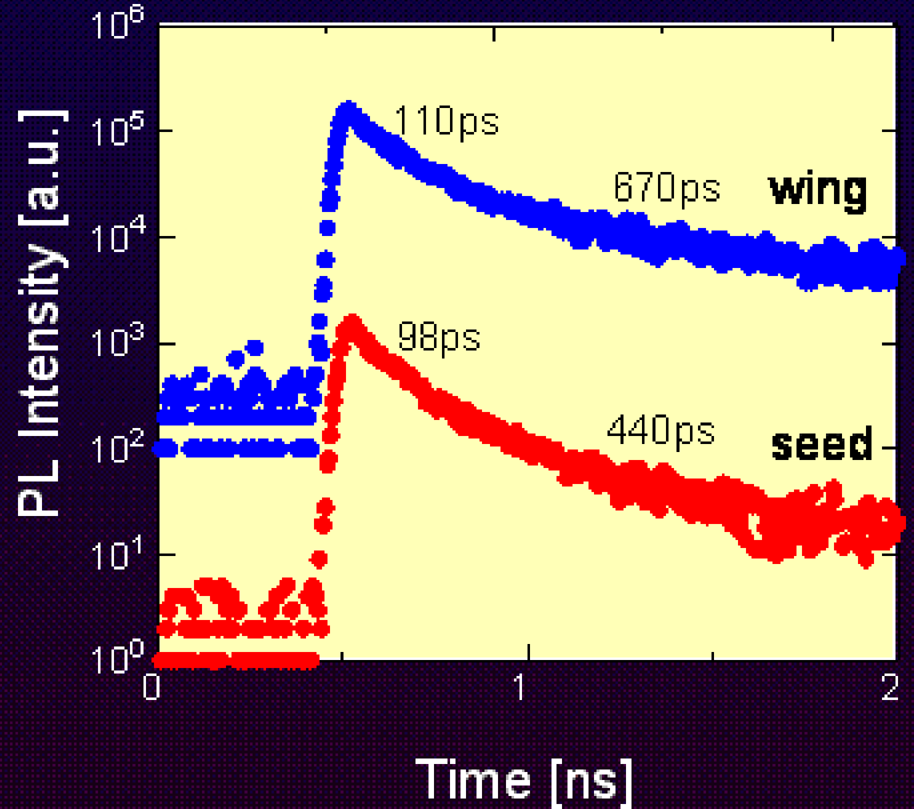
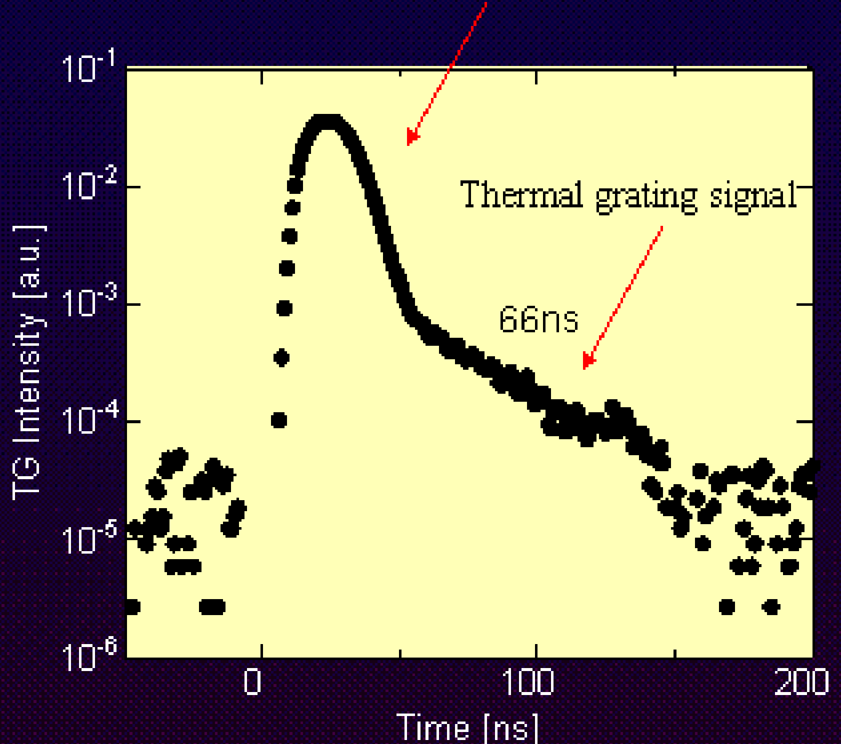


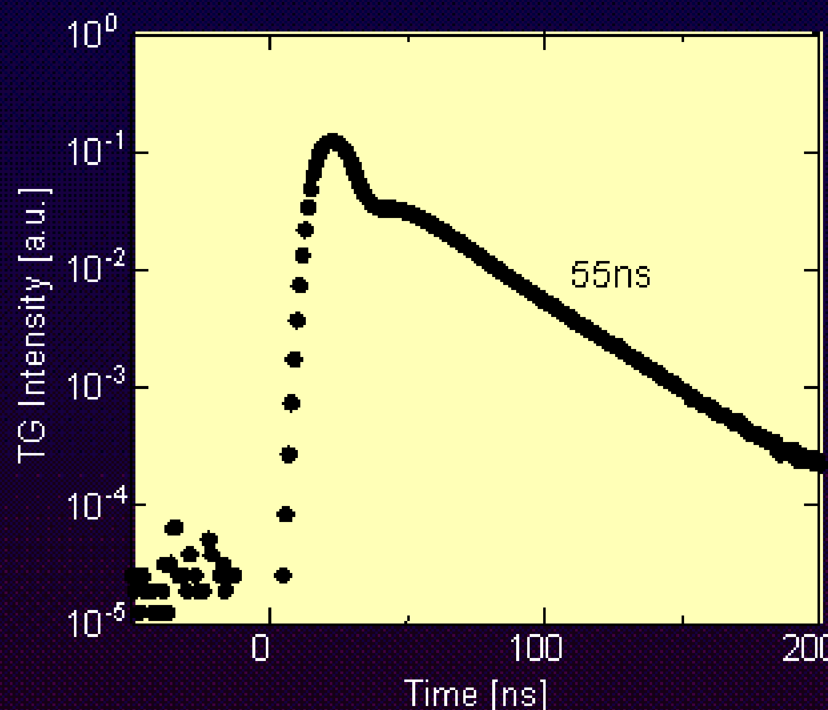


TG measurement of ABLEG-GaN

ABLEG-GaN



GaN



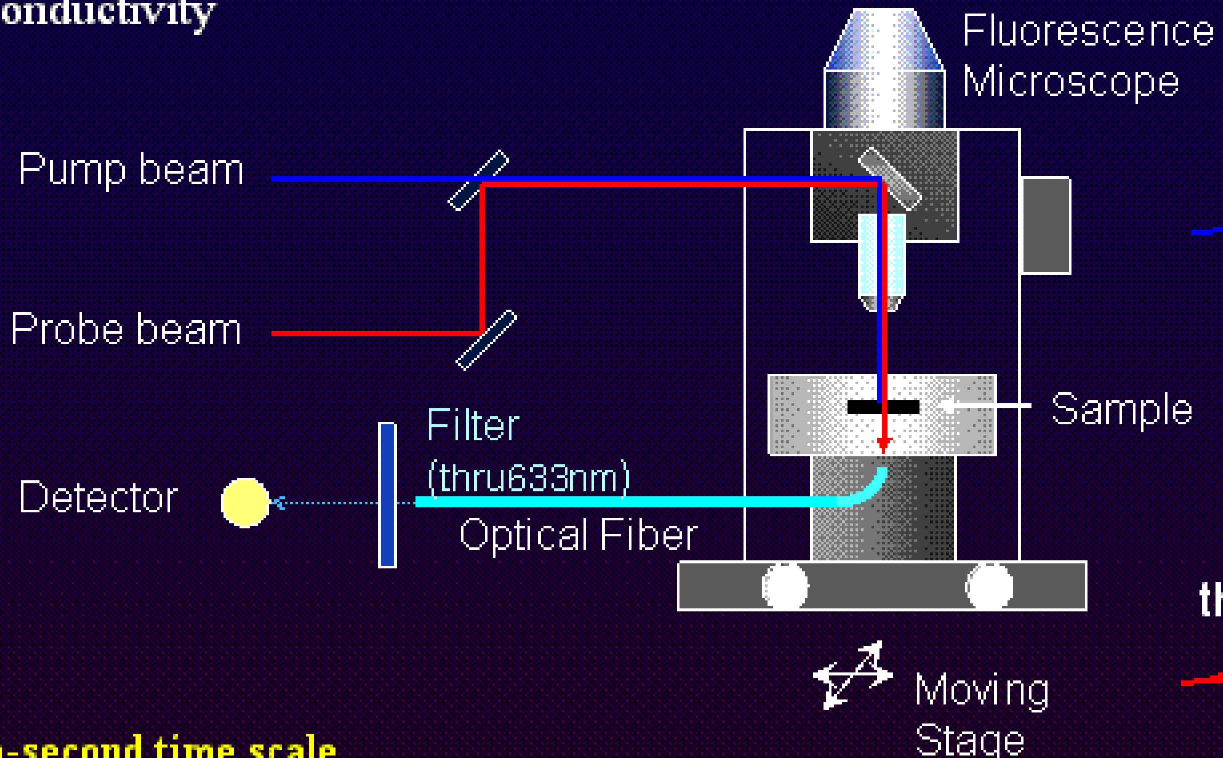
Thermal signal intensity; ABLEG-GaN < GaN

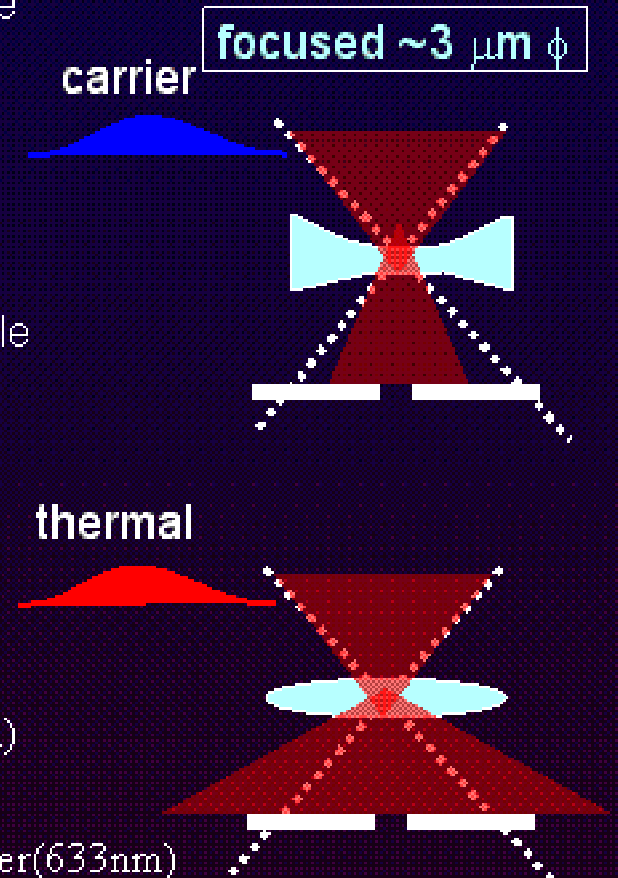
Heat generation of ABLEG-GaN should be reduced

→ Is this difference due to at the Seed region and the Wing region??

Experimental Setup of Micro-TL

Time and Spatially resolved observation of carrier diffusion, thermalization, thermal conductivity





Pico-second time scale

Pump:OPA of $Ti:Al_2O_3$ laser (355nm), Probe: $Ti:Al_2O_3$ laser (800nm)

Nano-second time scale

Pump:Frequency-tripled of Nd:YAG laser (355nm) Probe:He-Ne laser(633nm)

Continuum wave

Pump:He-Cd laser (325nm), Probe:He-Ne laser (633nm)

$$\left(\frac{\partial n}{\partial N}\right) < 0, \quad \left(\frac{\partial n}{\partial T}\right) > 0$$

Theory of Transient lens -1-

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Gaussian spatially distribution of the refractive index change δn can be written by cylindrical coordinate

$$\delta n(r) = \delta n_0 \exp(-r^2/w_0^2)$$

w_0 : pump beam width
n_0 : Refractive index change at the beam center

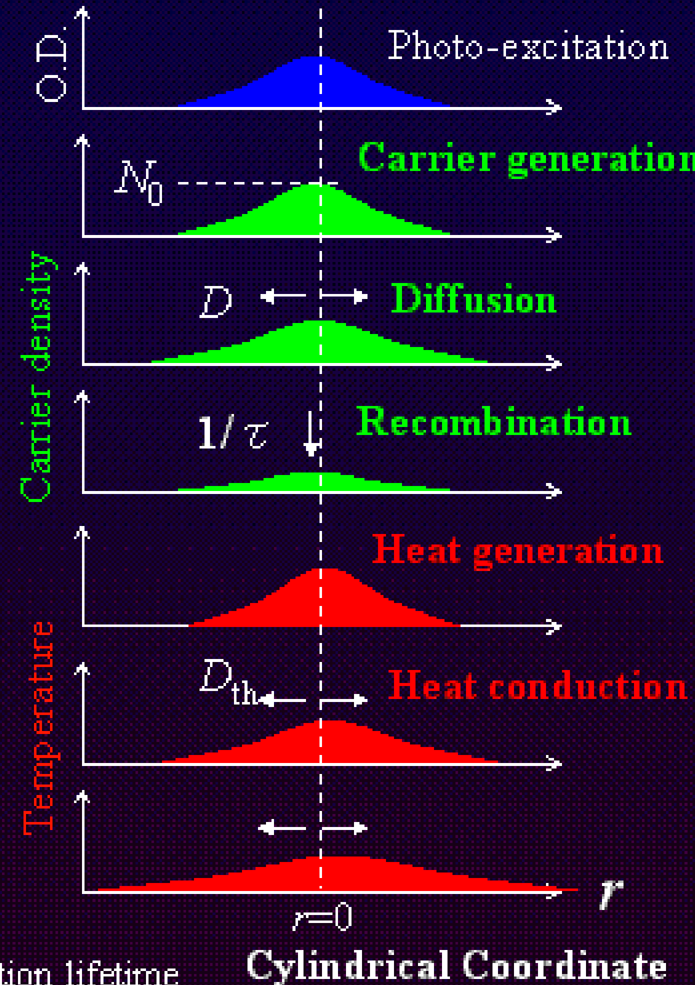
Modulation of the carrier density (δN) and the temperature (δT) by the nonradiatve recombination are given by

$$\delta n(r,t) = \left(\frac{\partial n}{\partial N}\right)\delta N(r,t) + \left(\frac{\partial n}{\partial T}\right)\delta T(r,t) \qquad \left(\frac{\partial n}{\partial N}\right) < 0, \quad \left(\frac{\partial n}{\partial T}\right) > 0$$

Time and Spatially dynamics of δn, δT are descried by following rate-equation.

$$\frac{\partial \delta N(r,t)}{\partial t} = D\frac{\partial^2 \delta N(r,t)}{\partial r^2} - \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right)\delta N(r,t) \qquad \text{Carrier density}$$

$$\frac{\partial \delta T(r,t)}{\partial t} = \frac{1}{\tau_{non-rad}}\frac{Q\delta N(r,t)}{\rho C_p} + D_{th}\frac{\partial^2 \delta T(r,t)}{\partial r^2} \qquad \text{Temperature}$$



D :Diffusion coefficient of carriers, D_{th} :Thermal diffusion coefficient
τ_{rad} :Radiative recombination lifetime, $\tau_{non-rad}$:Non-radiative recombination lifetime
Q :Heat amount released from unit density of carriers

Theory of Transient lens -2-

Solved the rate equation with the assumption of that the carrier recombination process is dominant because the pomp beam width (3µm) is much larger than the diffusion length of carriers (~50nm).

$$\delta N(r,t) = N_0 \exp\left[-\frac{r^2}{w^2} - \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} \right) t \right]$$

Carrier Dynamics

Thermal Dynamics

$$\delta T(r,t) = \frac{\tau_{rad}}{\tau_{rad} + \tau_{non-rad}} \cdot \frac{QN_0}{\rho C_p} \times \left\{ -\exp\left[-\frac{r^2}{w^2} - \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} \right) t \right] + \frac{w_0^2}{4D_{th} t + w_0^2} \exp\left(-\frac{r^2}{4D_{th} t + w_0^2} \right) \right\}$$

The optical pass of the probe beam at the transient lens given by the ABCD low of Gaussian beam

$$S(t) = \frac{I(t) - I(0)}{I(0)} \propto \delta n(r = 0, t)$$

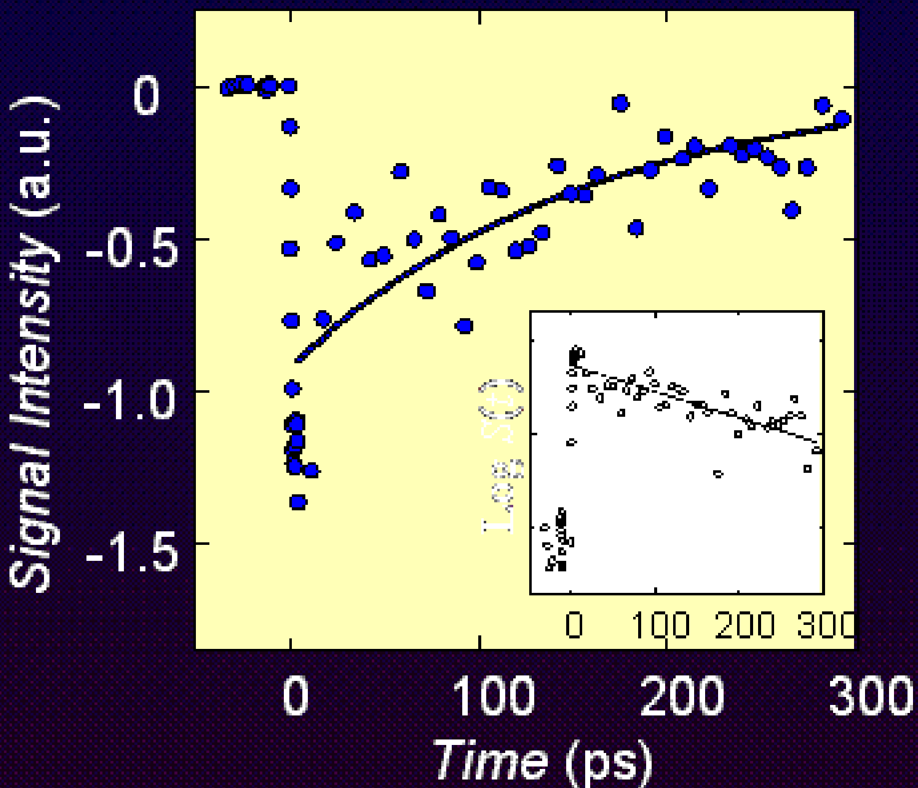
Therefore, the time profiles of the carrier lens and thermal lens signal can be written by

$$S(t) = S_0 \exp\left[\left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} \right) t \right] \qquad S(t) = S_0' \frac{w_0^2}{4D_{th} t + w_0^2}$$

The information about carrier recombination lifetime, amount of the heat generation, thermal conductivity can be obtained by the analysis of the time profile of $S(t)$

Time profiles of MTL signal (GaN)

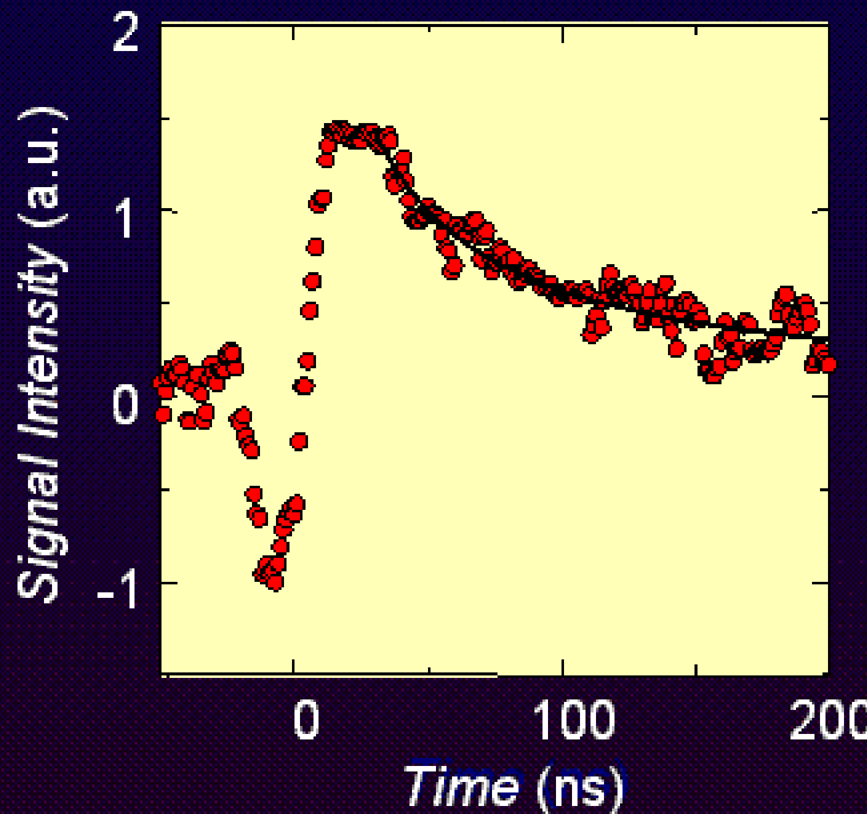
With Femto-second laser



$$S(t) = S_0 \exp\left[\left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right) t\right]$$

155ps

With Nano-second laser



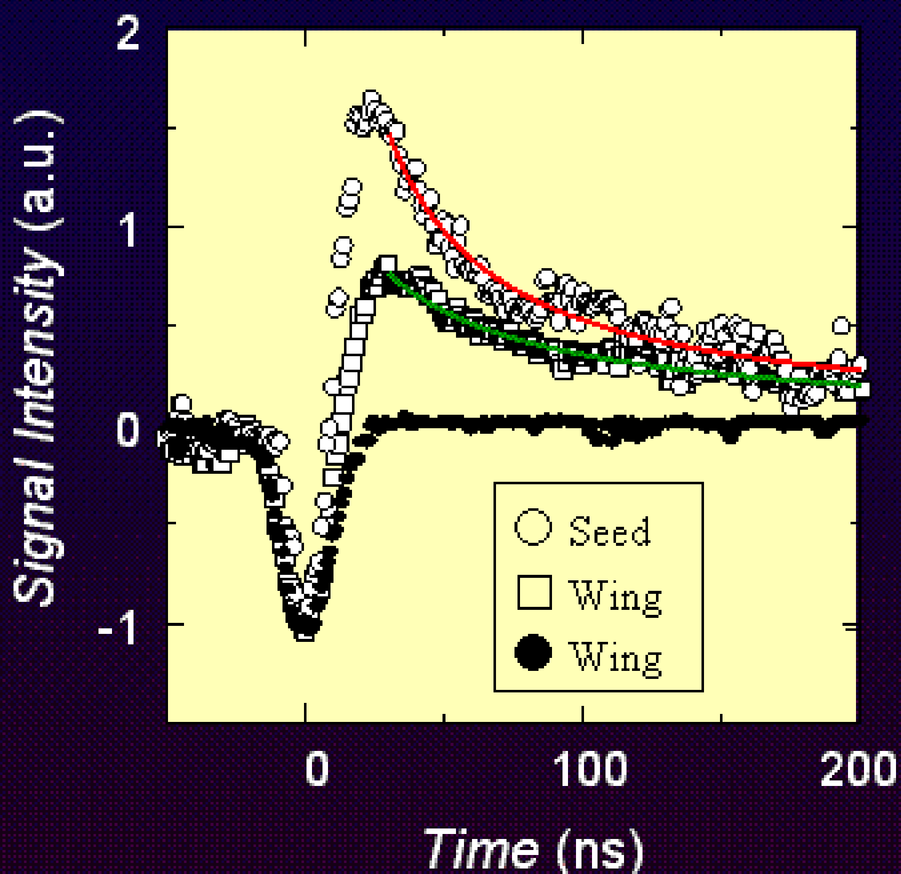
$$S(t) = S'_0 \frac{w_0^2}{4 D_{th} t + w_0^2}$$

$D_{th} = 0.77\,\mathrm{cm^2 s^{-1}}$, $w_0 = 2.6\,\mu\mathrm{m}$

TL measurement for ABLEG-GaN

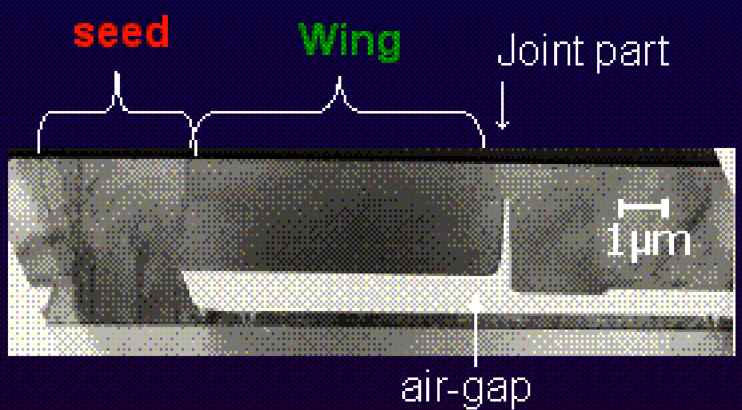
Spatial-resolved TL time-profiles

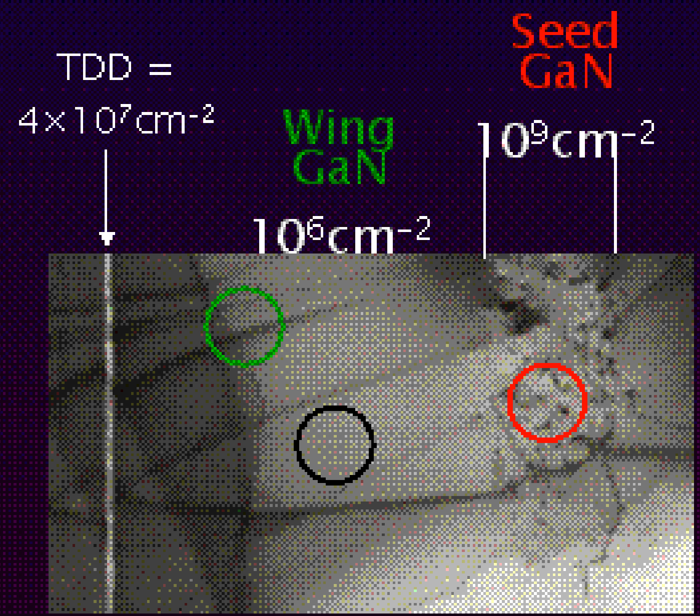
K. Okamoto, et al
Review of Scientific Instruments, 74, 575 (2003).



Thermal Signal Intensity

Seed region > Wing region





Spatial resolved measurement

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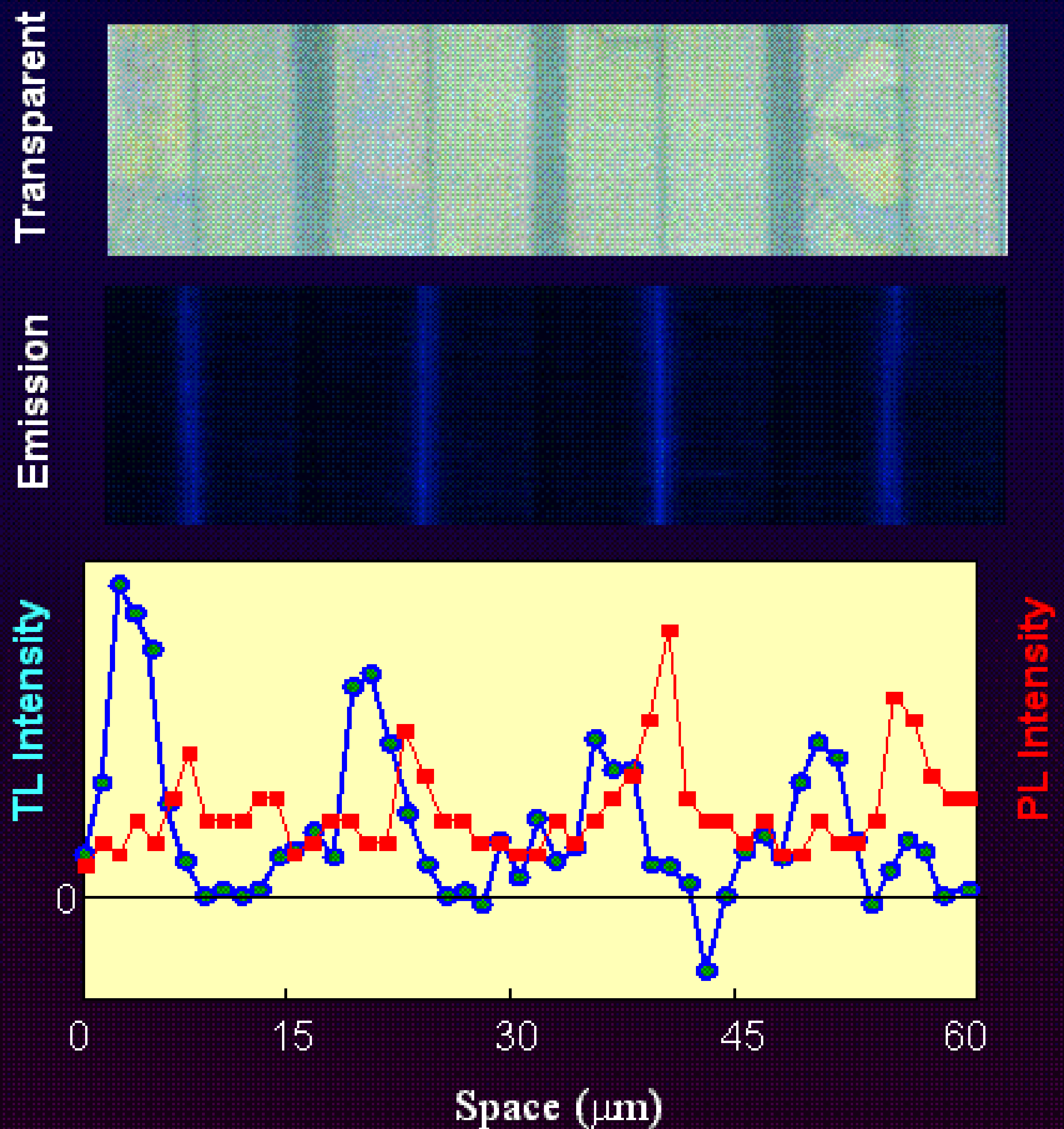
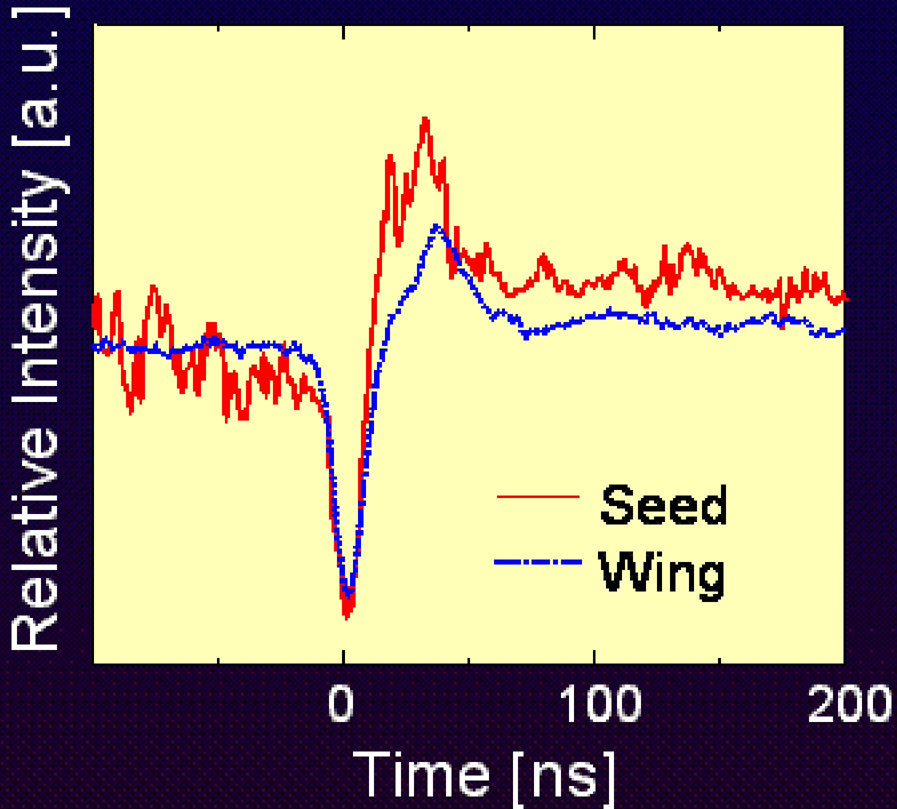
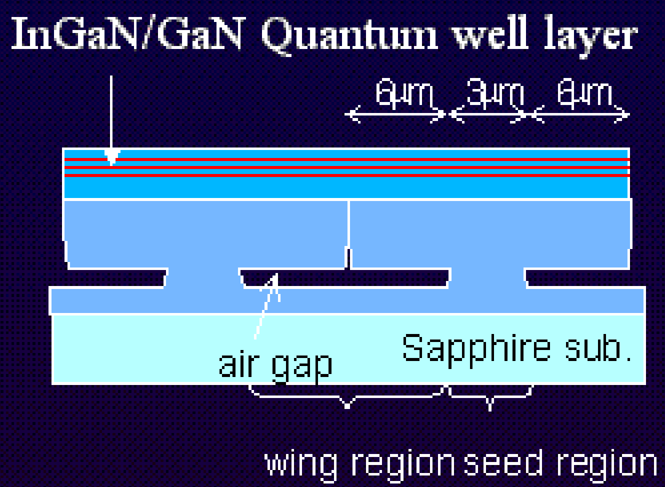
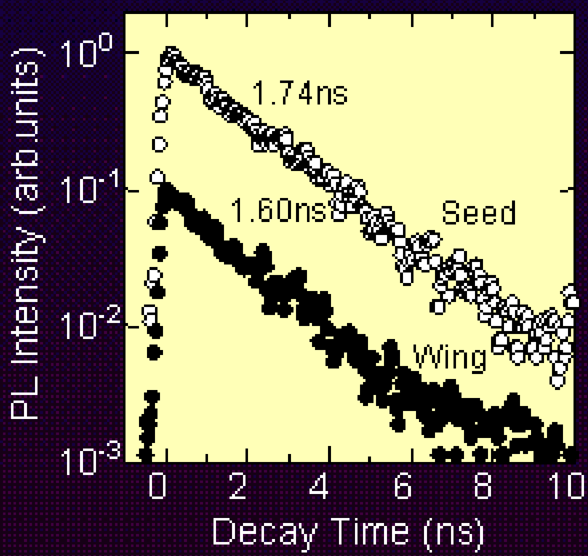


MTL signal (3QW on ABLEG-GaN)



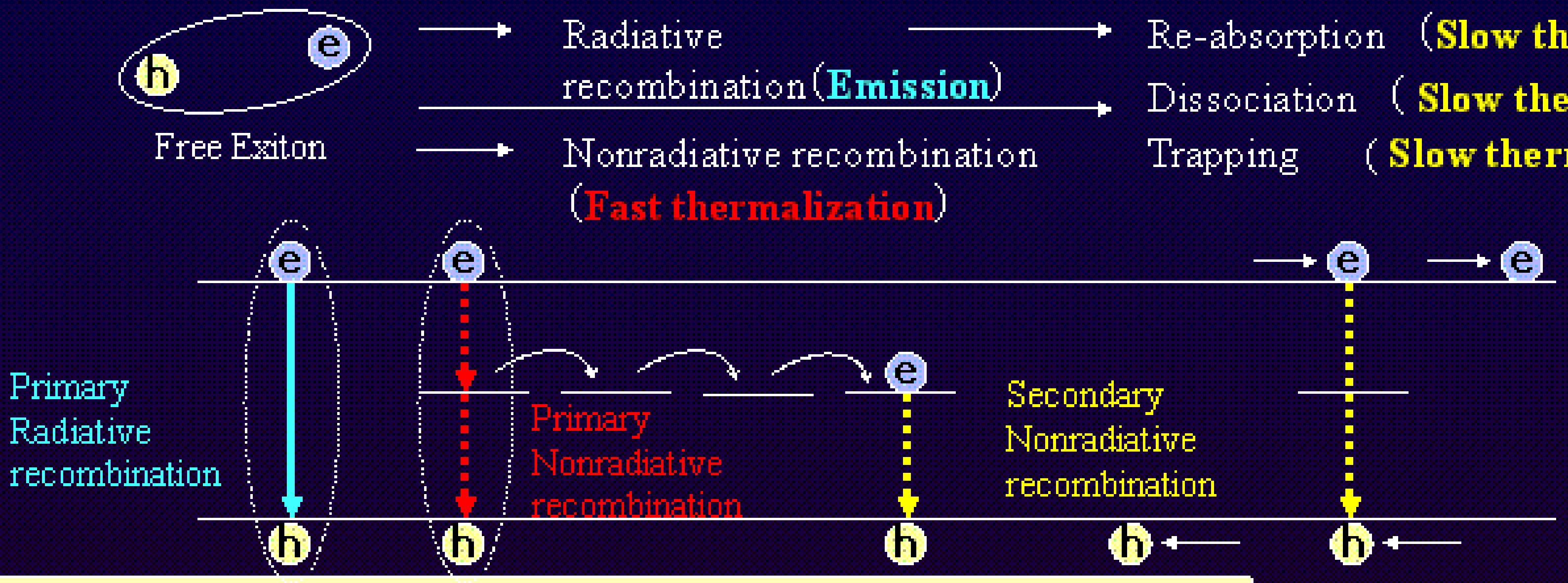




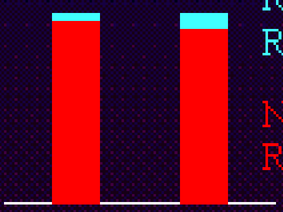
Thermal Signal Intensity

Seed region > Wing region

Thermalization Processes

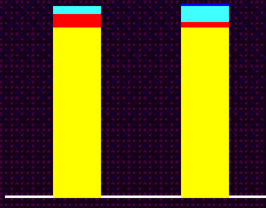


$$\frac{1}{\tau_{PL}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} \qquad \eta_{lum} = \frac{\frac{1}{\tau_{rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}} \qquad \eta_{th} = \frac{\frac{1}{\tau_{non-rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}}$$



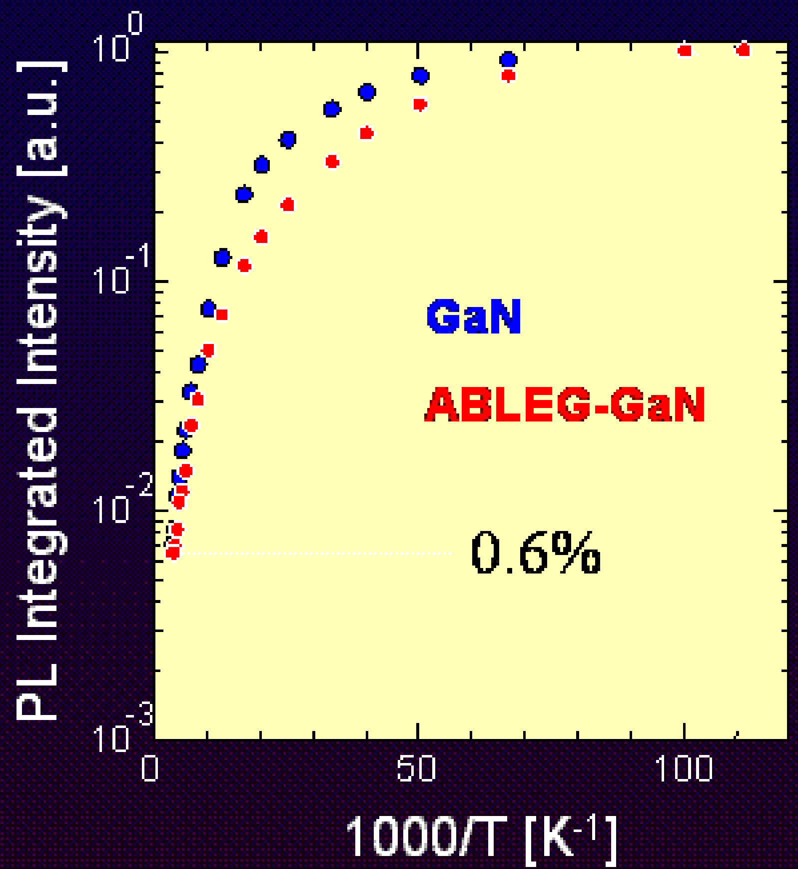
Take into consideration with re-absorption, thermal dissociation, or trapping in the deep level of exciton

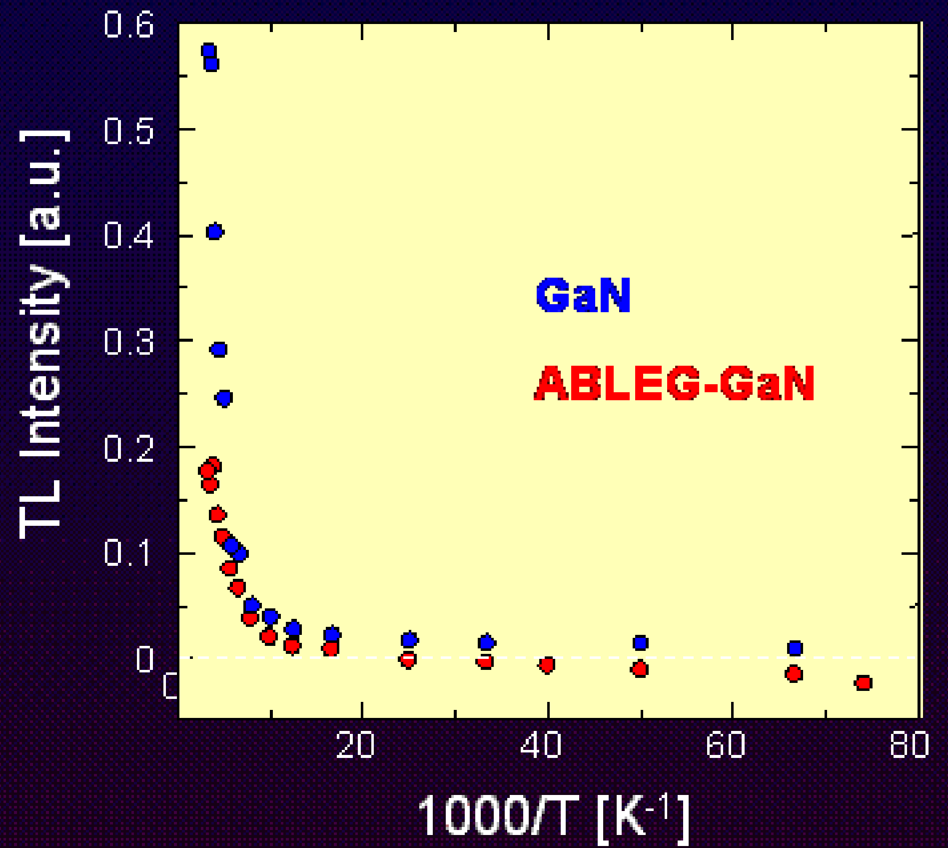
$$\frac{1}{\tau_{PL}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nonrad}} + \frac{1}{\tau_{diss}} + \frac{1}{\tau_{trap}} \qquad \eta_{lum} = \frac{\frac{1}{\tau_{rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} + \frac{1}{\tau_{diss}} + \frac{1}{\tau_{trap}}} \qquad \eta_{th} = \frac{\frac{1}{\tau_{non-rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}} + \frac{1}{\tau_{diss}} + \frac{1}{\tau_{trap}}}$$



TD act as NRC, but it is not effective to the emission efficiency

Temperature dependence of CW-MTL



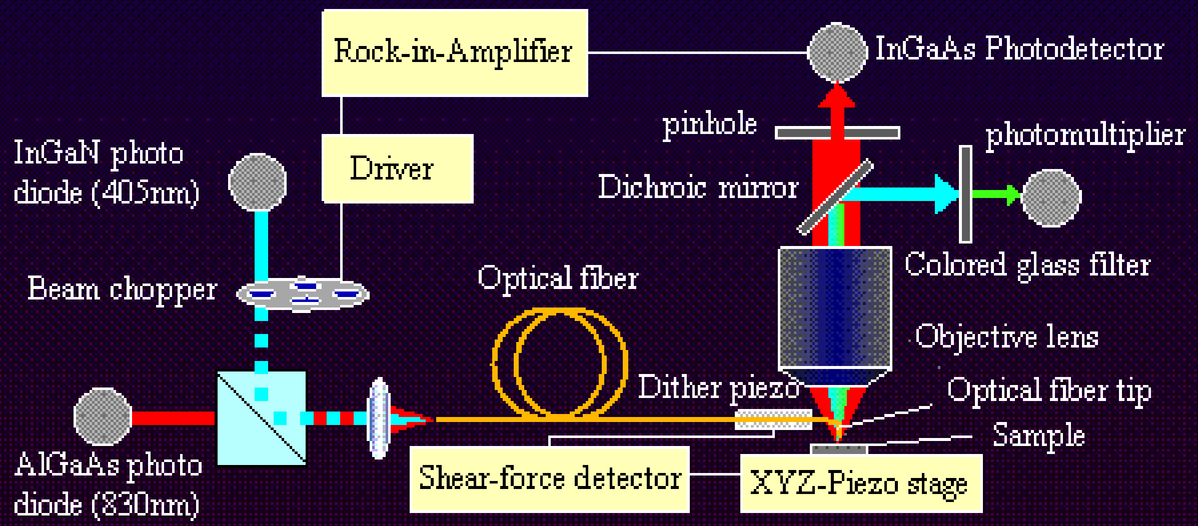


Near-field scanning optical microscope TL (NSOM-TL)

3rd order Nonlinear Spectroscopy

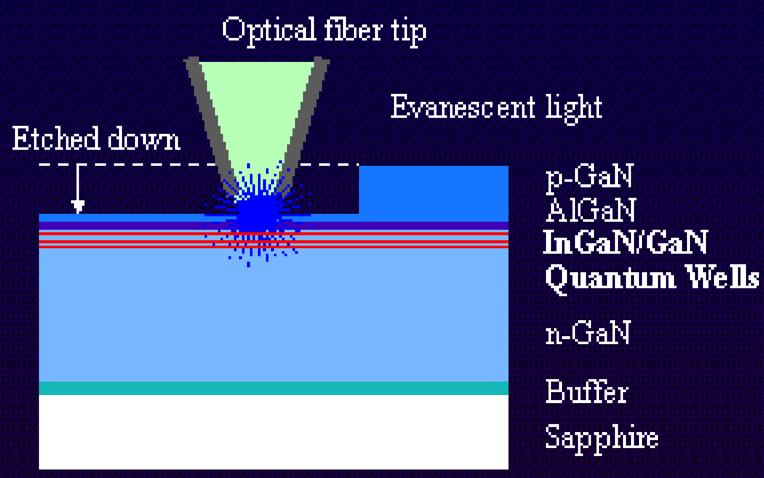
+ Near-field scanning optical microscopy

K. Okamoto, et al, Appl. Phys. Lett., 87, 161104 (2005).



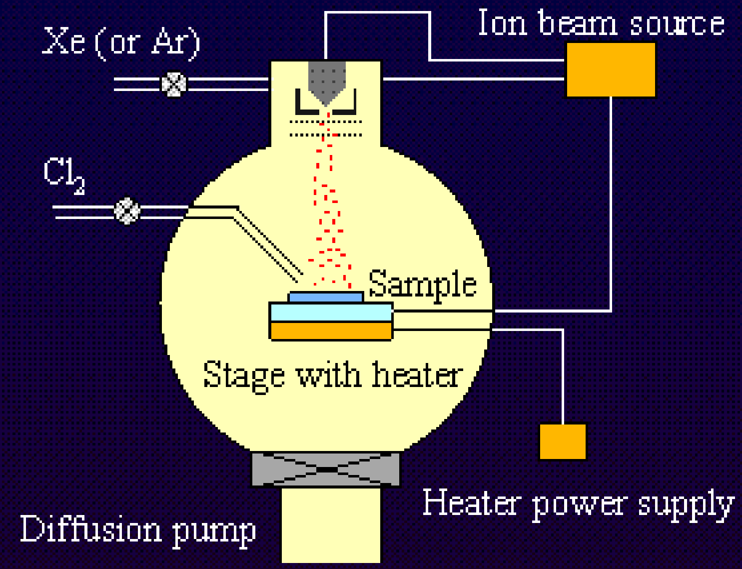
Experimental setup of Near-field scanning optical microscope TL (NSOM-TL)

Sample Structure and Properties

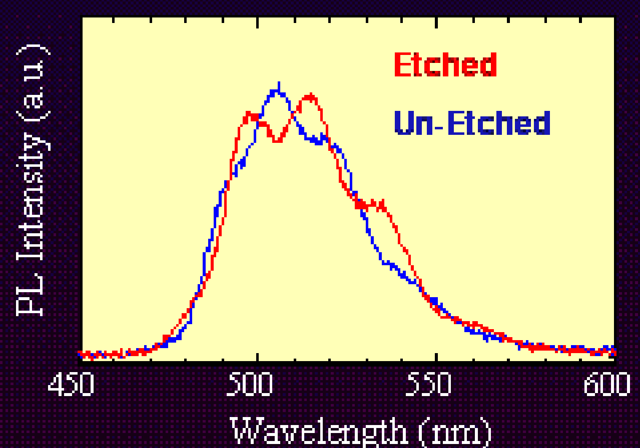


Purchased by AXT Inc.

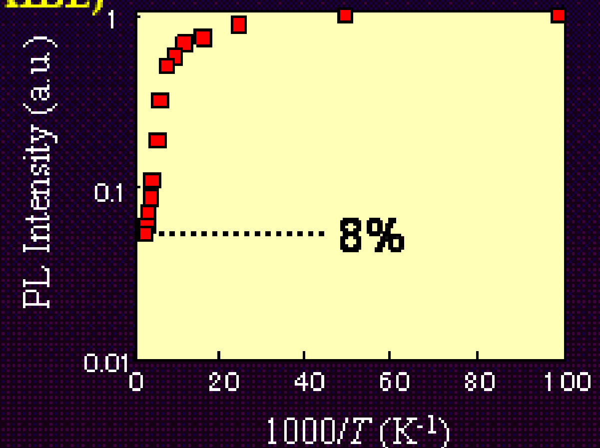
Sample structure of InGaN/GaN 3QWs



Chemically assisted ion beam etching (CAIBE)



Photoluminescence (PL) spectra



Temperature dependence of PL intensity

Numerical Calculation of TL time-profile

$$\delta n(r) = \delta n_0 \exp(-r^2/w_0^2)$$

w_0 : pump beam width

n_0 : Refractive index change at the beam center

$$\delta n(r,t) = \left(\frac{\partial n}{\partial N}\right)\delta N(r,t) + \left(\frac{\partial n}{\partial T}\right)\delta T(r,t) \qquad \left(\frac{\partial n}{\partial N}\right) < 0, \quad \left(\frac{\partial n}{\partial T}\right) > 0$$

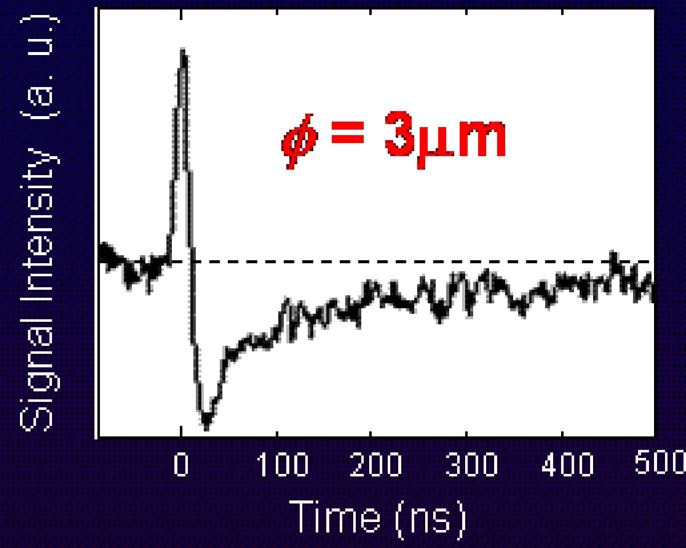
The carrier dynamics can be written by

$$\frac{\partial \delta N(r,t)}{\partial t} = D\frac{\partial^2 \delta N(r,t)}{\partial r^2} - \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}\right)\delta N(r,t)$$

Carrier density

$$\frac{\partial \delta T(r,t)}{\partial t} = \frac{1}{\tau_{non-rad}}\frac{Q\delta N(r,t)}{\rho C_p} + D_{th}\frac{\partial^2 \delta T(r,t)}{\partial r^2}$$

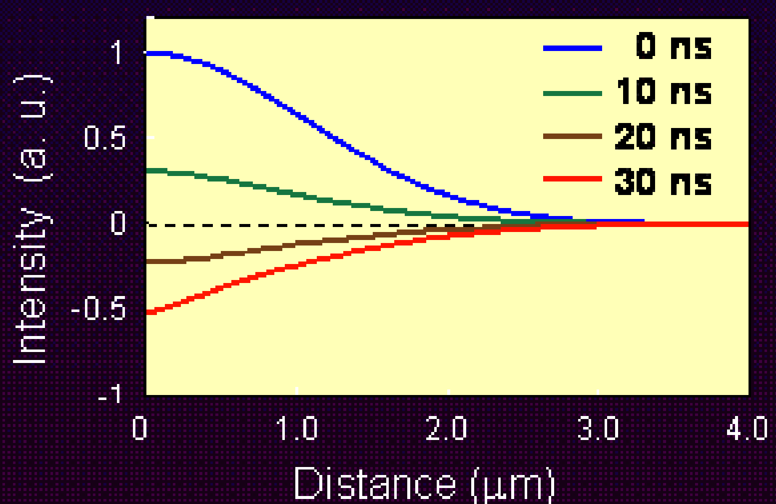
Temperature

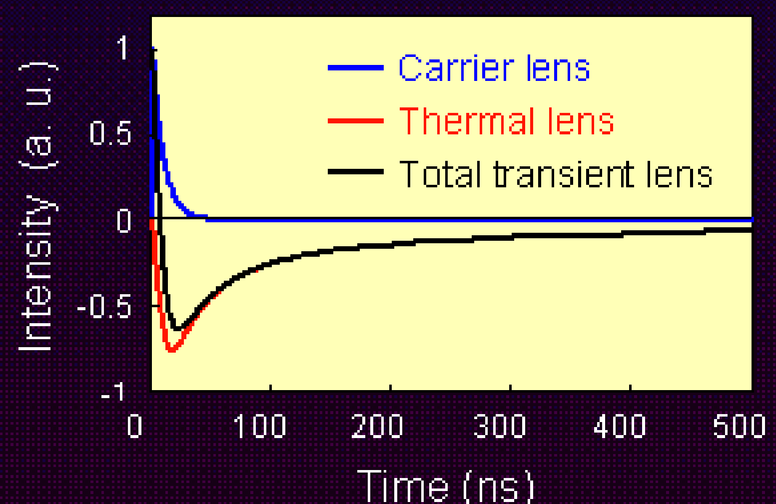


Numerical Calculation

r : 100 pixel, t : 500 pixel, D=0.5 cm^{2}s^{-1}, D_{th} =1.0 cm^{2}s^{-1}

τ_{PL} = 20 ns $(1/\tau_{PL} = 1/\tau_{rad} + 1/\tau_{non\text{-}rad})$





Results and Analysis of NSOM-TL

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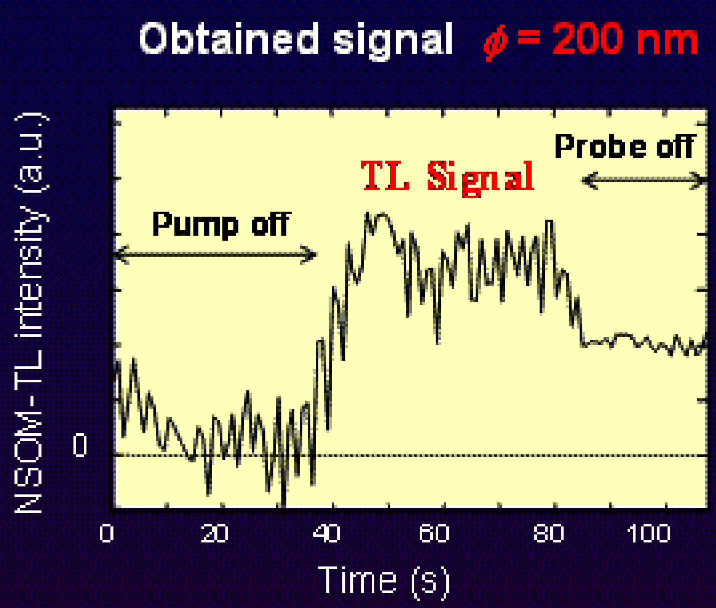
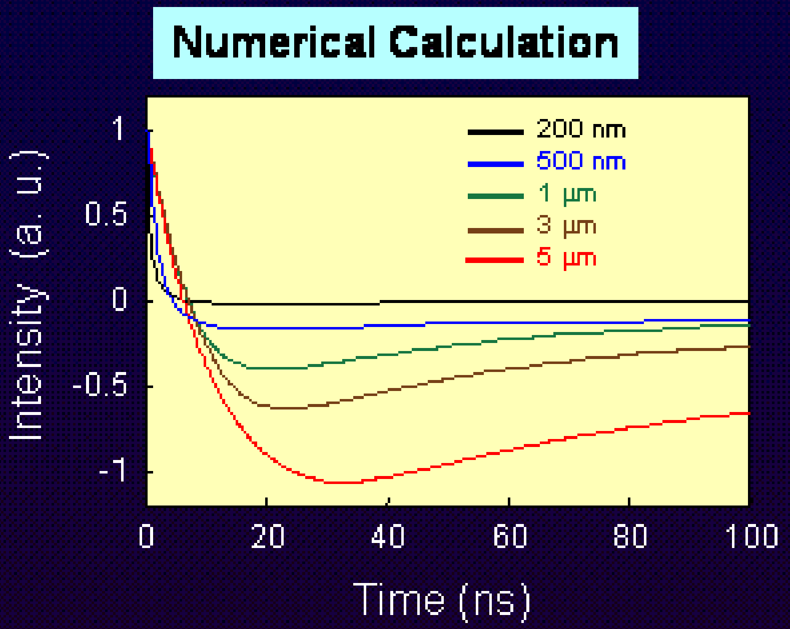
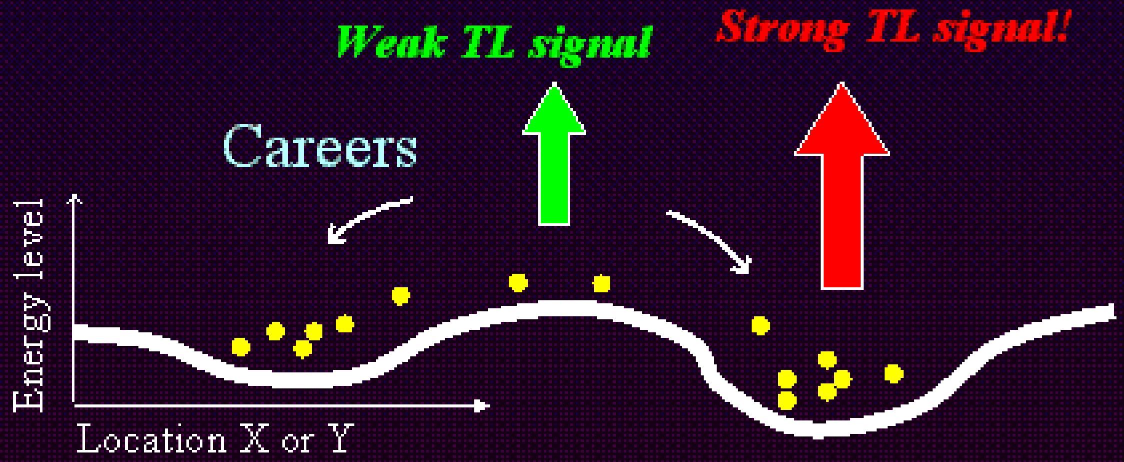
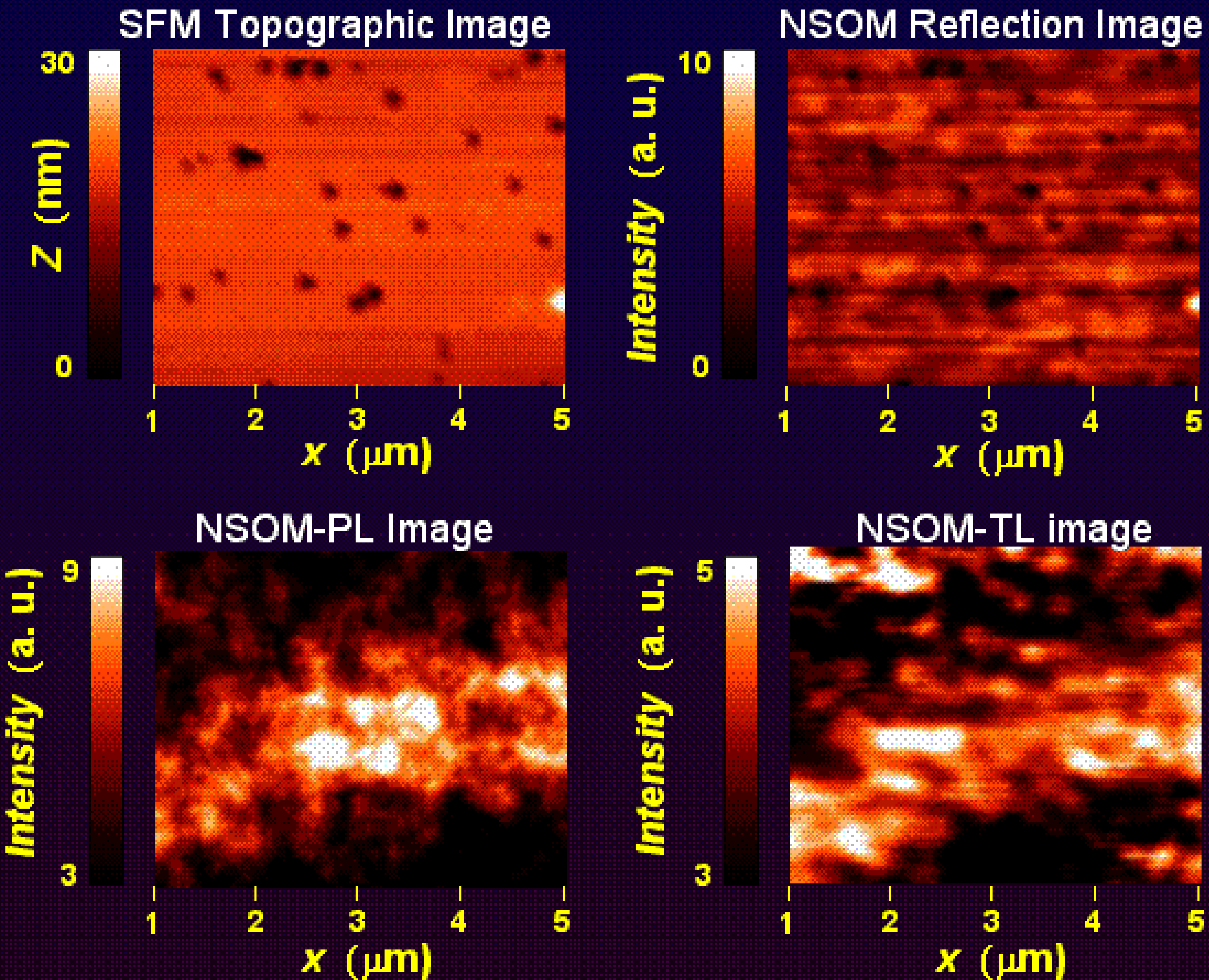




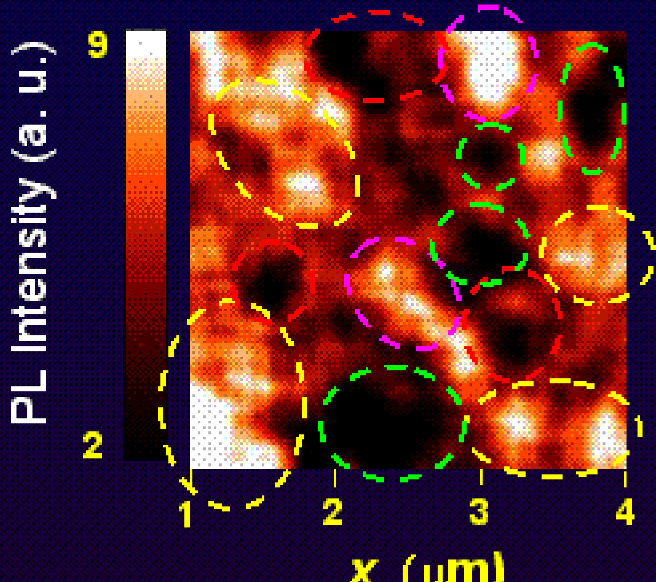
Spot size = 200nm; main component of the TL signal is Carrier density lens

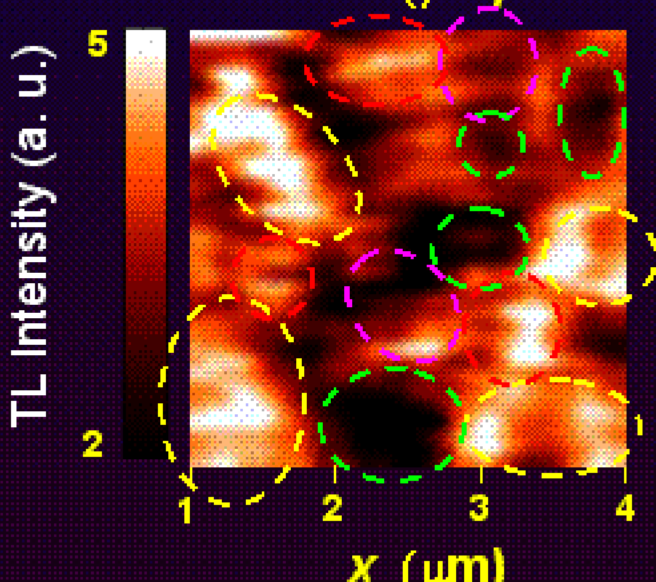


NSOM Images


SFM Topographic Image
30
Z (nm)
0
NSOM Reflection Image
10
Intensity (a. u.)
0
NSOM-PL Image
9
Intensity (a. u.)
3
NSOM-TL image
5
Intensity (a. u.)
3
1 2 3 4 5
x (μm)

NSOM-PL and -TL Images





Area A

PL signal → Strong

TL signal → Strong

Area B

PL signal → Weak

TL signal → Weak

Area C

PL signal → Weak

TL signal → Strong

Area D

PL signal → Strong

TL signal → Weak

Carrier Dynamics

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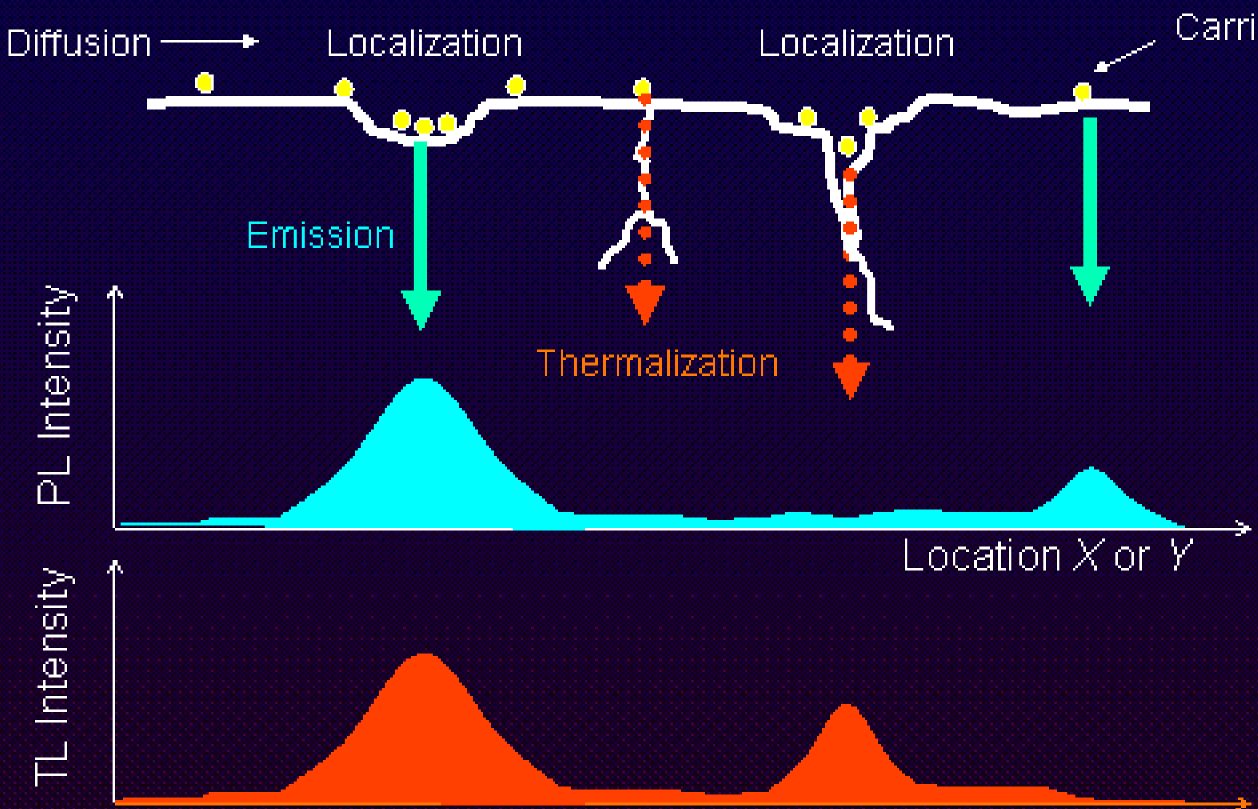


Area A　PL: Strong
　　　　TL: Strong

Area B　PL: Weak
　　　　TL: Weak

Area C　PL: Weak
　　　　TL: Strong

Area D　PL: Strong
　　　　TL: Weak

Area A　Area B　Area C　Area D

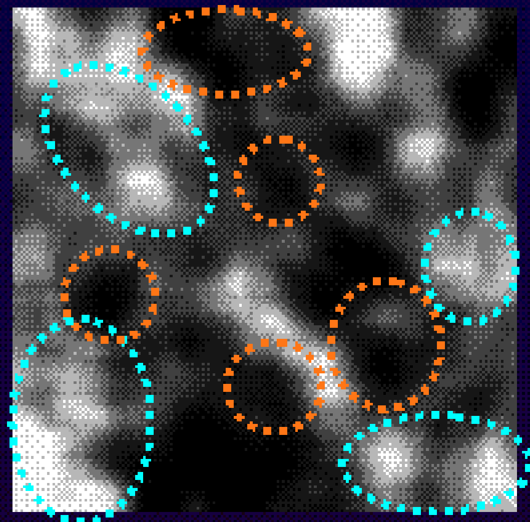
Radiative Reconbination Center

Non-Radiative Recombination Center

Diffusion and Recombination

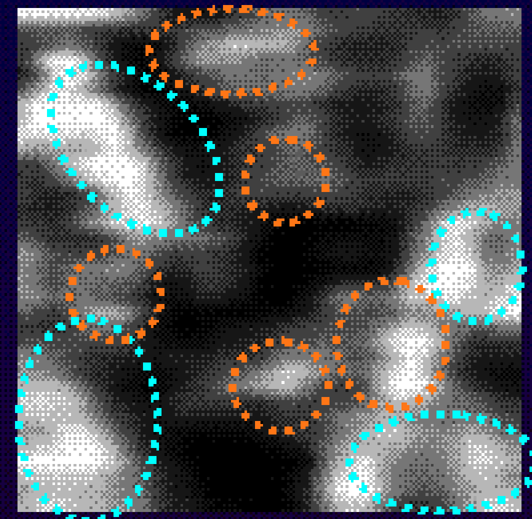
© Koichi Okamoto

500 nm



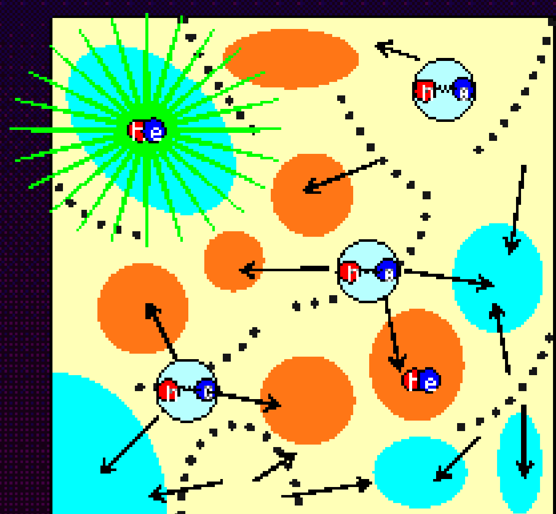
PL Intensity (arb. units)

500 nm



TL Intensity (arb. units)

500 nm



Radiative recombination centers

Non-radiative recombination centers

Carriers and/or excitons transfer

High potential energy region

Summary

Temporal and spatial-resolved nonlinear spectroscopies are very useful and powerful tools to characterize nonradiative processes (carrier diffusion, localization, recombination, and thermarization, etc) in GaN and InGaN/GaN.

Such information are very important to understand the emission mechanism and dynamics in order to develop the device performances and light emission efficiencies of optical materials.

⇩

For example, based on such measurements, we have invented the novel technique to enhance the emission efficiencies of InGaN/GaN