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Nano-optoelecrtronics based on III-V Semiconductor Quantum Dots

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KIST Korea Institute of Science and Technology

KIST

- Founded 1966, gouv. affilliated
- 4 Res. Div.s & 1 Res. HQ(future technol.)
  Materials, Systems, Environ., Bio-sci
- 654 (422(306 Ph.D.)researchers)
- 130MU$/yr, ‘04
- Future Technol. HQ
  Micro Systems Res. Ct.
  Nano Device Res. Ct.
  Simulation (supercom., cluster type)team

Nano Device Res. Ct.

- Mag. Mater. group + Semicon. Group (Spintronics)
- Semicon. group.

Joo Sang Lee, Young Ju Park (MIT lab)
Jin Dong Song (MBE)
Won Jun Choi (QD LD, QDIP)
Ilki Han (Hi pwr LD, SLD, QCL) (NRL)
Woon Jo Cho (nc Si)
Jung Il Lee (electrical charac.)
~ 20 studs & 1 PD

Collaborators- domestic

SRC:
- QSRC (TWKang, Dongguk U.), GaN
- QPSI (YPLee, Hanyang U.), polymer PC

NRL:
- VCSEL (YHLee, KAIST)
- QD Technol (SKNoh, KRISS)
- Ultrafast Phenom (DSKim, SNU)
- Compound Semi Epi (EJYoon, SNU)
- QD Opt Dev (DHLee, CNU)1.5QD, SOA
- QD PL (YHCho, Chungbuk NU)

Collaborators- international

Germany: Wuerzburg
UK: Sheffield
France: CNRS(IEF, LPN, LSP, LEOM, IMEP, LAAS)
China: CAS-SITP, -IoSemi
Japan: U.Tokyo, NICT
USA:

Programs

Dual: QCL –’07

Nano R&D (QM D/Wr Technol, 7U+KIST+3Co):

- QD(LD, SOA, Mod)
- PC(passive, active) -’11

ETRI: 1.55 um QD LD

ABITD: QSIP (KIST, KRISS, KAIST) -’04

Frontier(TND): Opt Interconnect (YTLee, GIST)

Growth Engin: GaN LED (KOPTI)

Contents

I. QD vs. QW

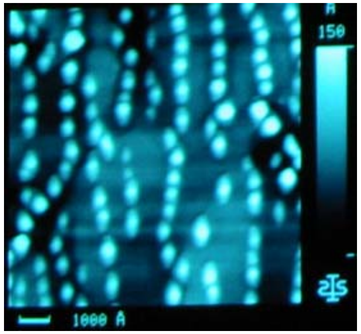
- Carrier localization & Discrete DOS:
  - Low leakage currents of LDs
  - Small active volume ; low transparent current density of LDs
  - Large activation (thermalization) energy ;
    High temperature operation of LDs and IR-PDs
    Stable operation of high power laser at high temp.
  - Low refractive index change by injection current ;
    Small α-parameter -> low chirping (high speed operation)
    small filamentation (high power LD)
- Inhomogeneous broadening due to size fluctuation:
  - Large gain bandwidth ; SOA, ECL, SLD

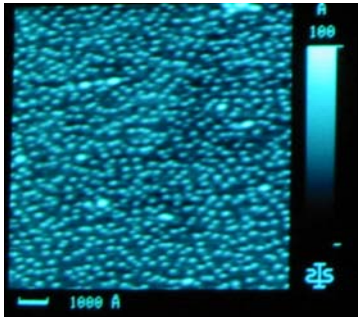
II. QD Growth (ALMBE)

ALMBE mode (ALE mode)

ALE:Atomic Layer epitaxy

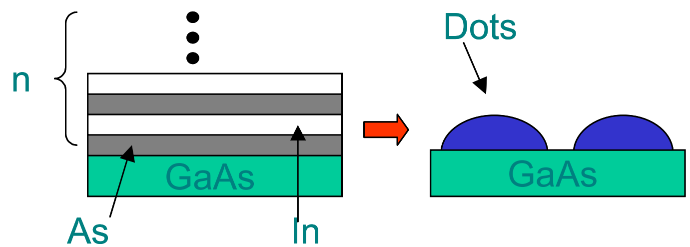
- Wetting layer is ignorable
- Relatively large dot size (> ~30 x ~10 nm)
- Wavelength (more than 1500 nm is possible)

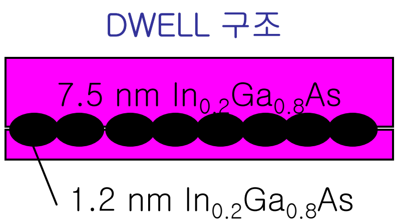


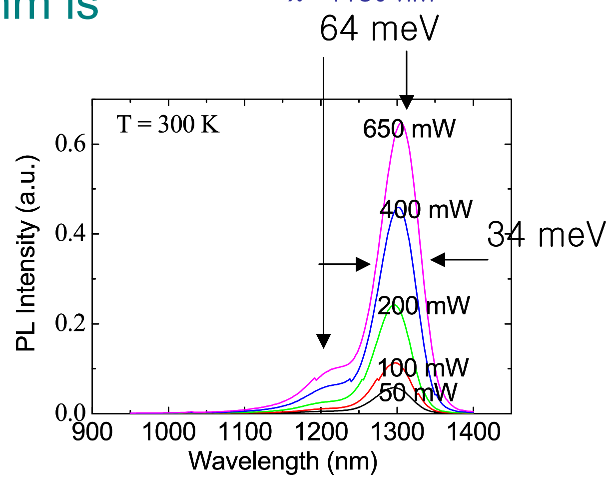


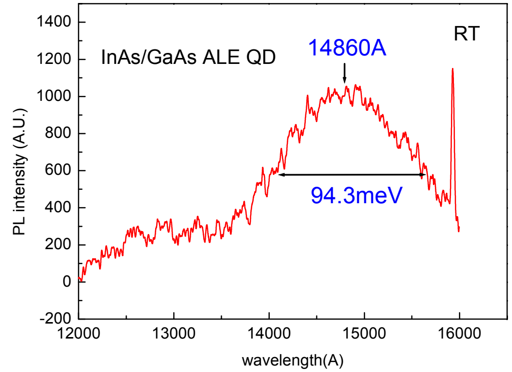
$In_{0.5}Ga_{0.5}As$ QD
λ= 1150 nm

InAs QD
λ= 1250 nm
D: 1.02 x 10^{11} /cm^2









Bandgap engineering of QD : 1150 ~ 1500 nm

Detection wavelength tuning possible

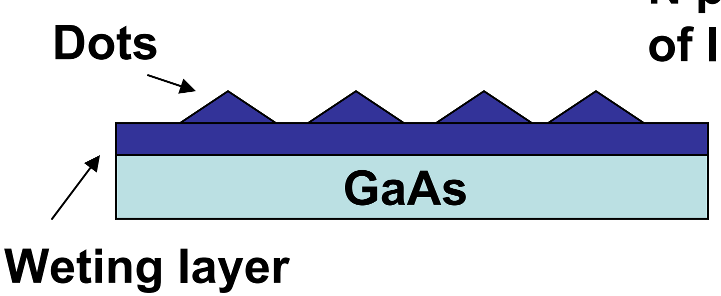
QD Growth

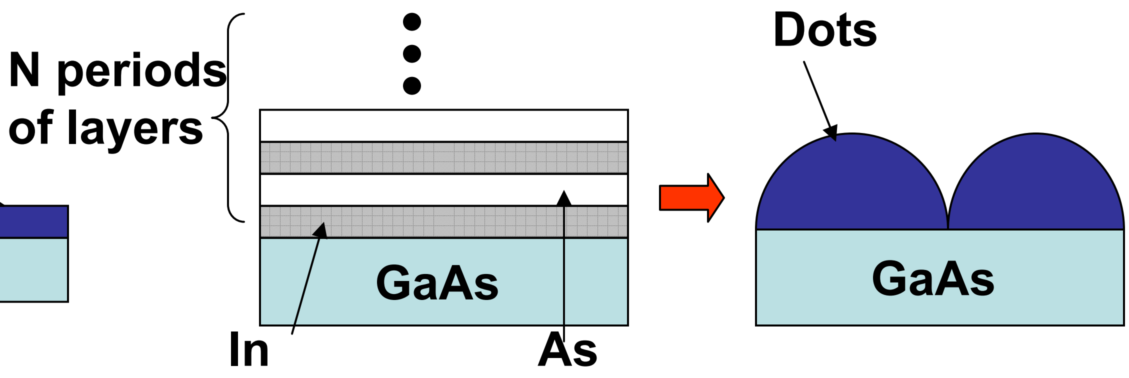
SK mode dot

- **Wetting layer is inevitable**
- **Relatively small dot size (≤ ~30 x ~10 nm)**
- **Wavelength (1000 ~ 1300 nm + α)**

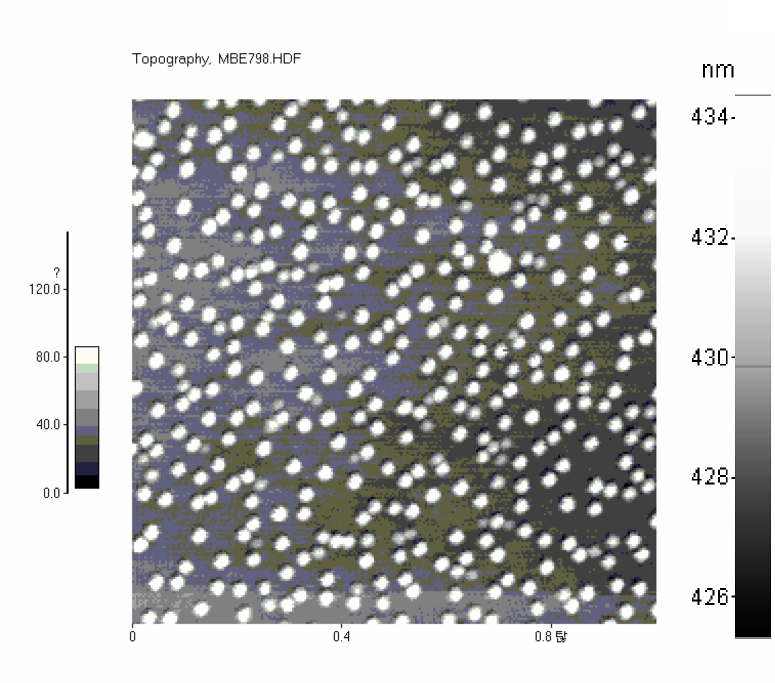
ALE mode dots

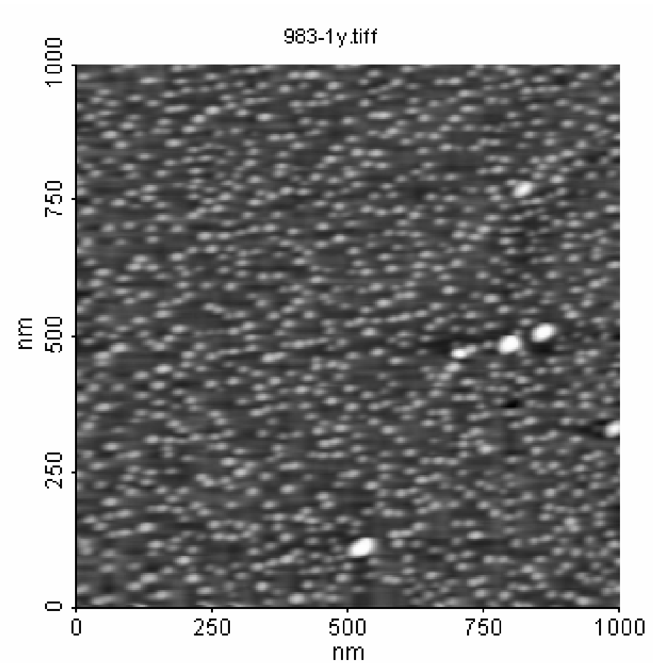
- **Wetting layer is not necessary**
- **Relatively large dot size (≤ ~60 x ~10 nm)**
- **Wavelength (more than 1500 nm is possible)**





AFM images



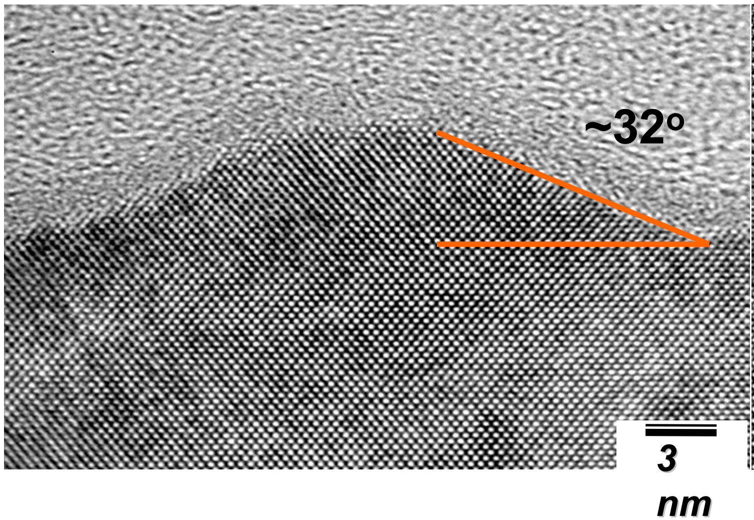


Sample #A(ALE)

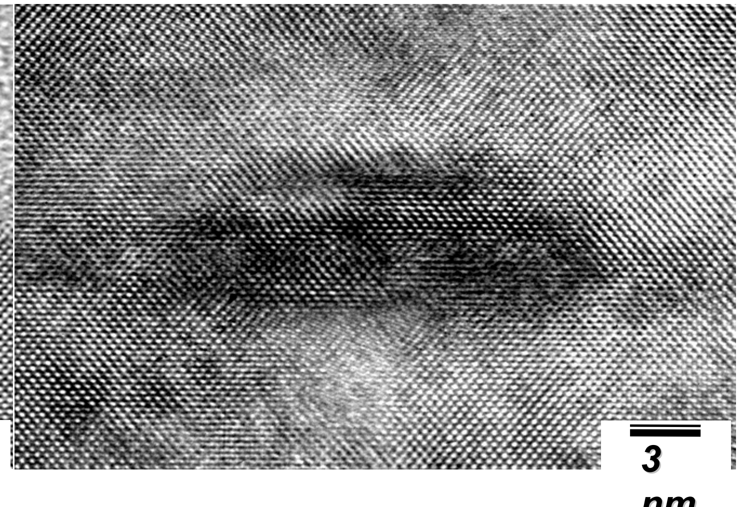
Sample #B(S-K)

Dot density, width and height of the sample #A are ~4.1x10^{10}/cm^2, ~40.8 nm, and ~7.2 nm, respectively,
In the case of the sample #B, 13.4x10^{10}/cm^2, ~31.0 nm, ~2.6 nm, respectively.

HR-TEM images (ALE dot)



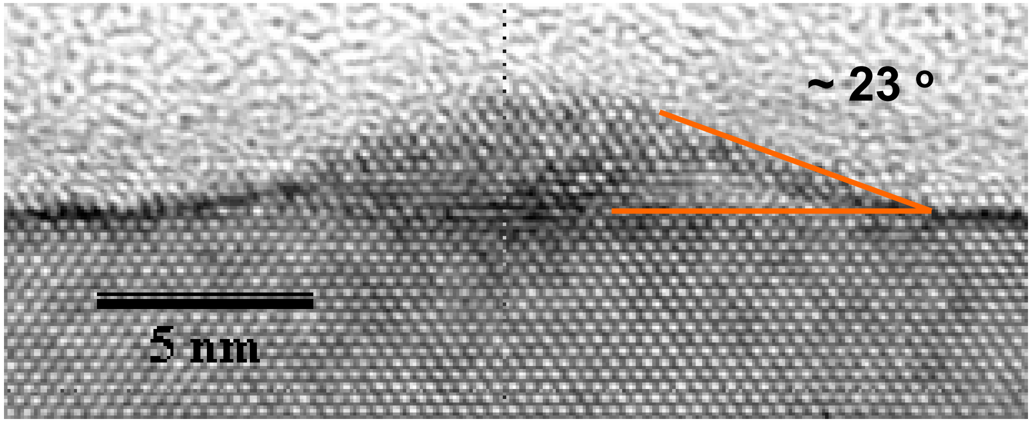
{136} facet formation

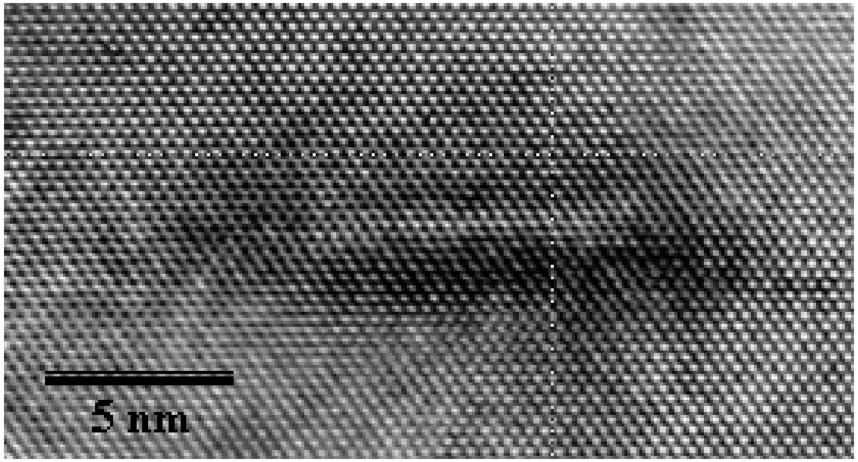


We can observe indium diffusion into GaAs below the QDs

Indium can diffuse into GaAs matrix below the QDs during growth interruptions, and this helps the QDs

HR-TEM images(SK dot)

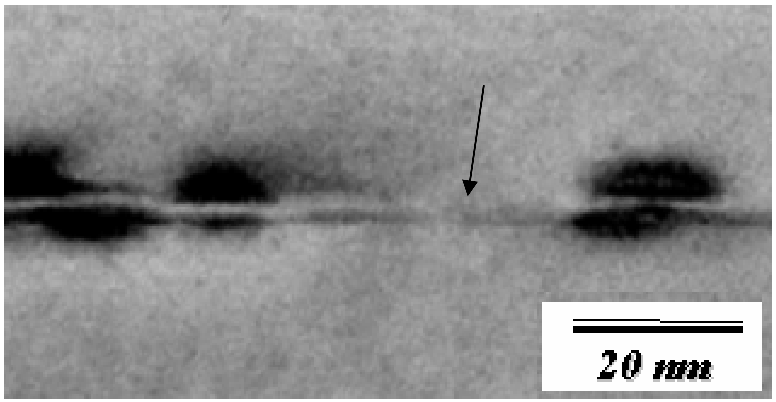




The QDs have flat bottom-shape

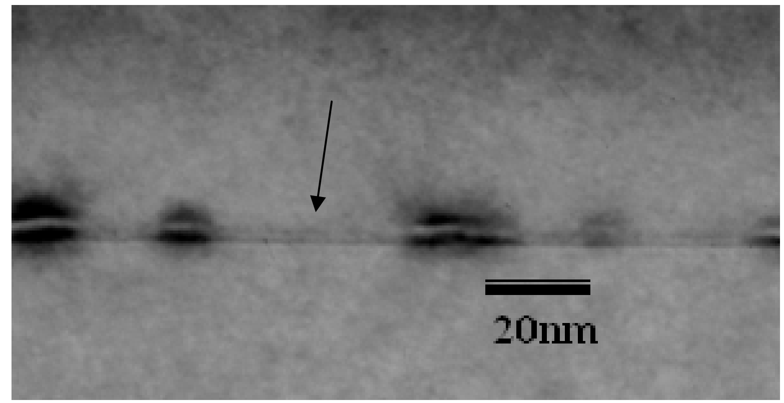
Wetting layer thickness

Sample #A(ALE)



Thickness of WL : ~ 2.1 nm

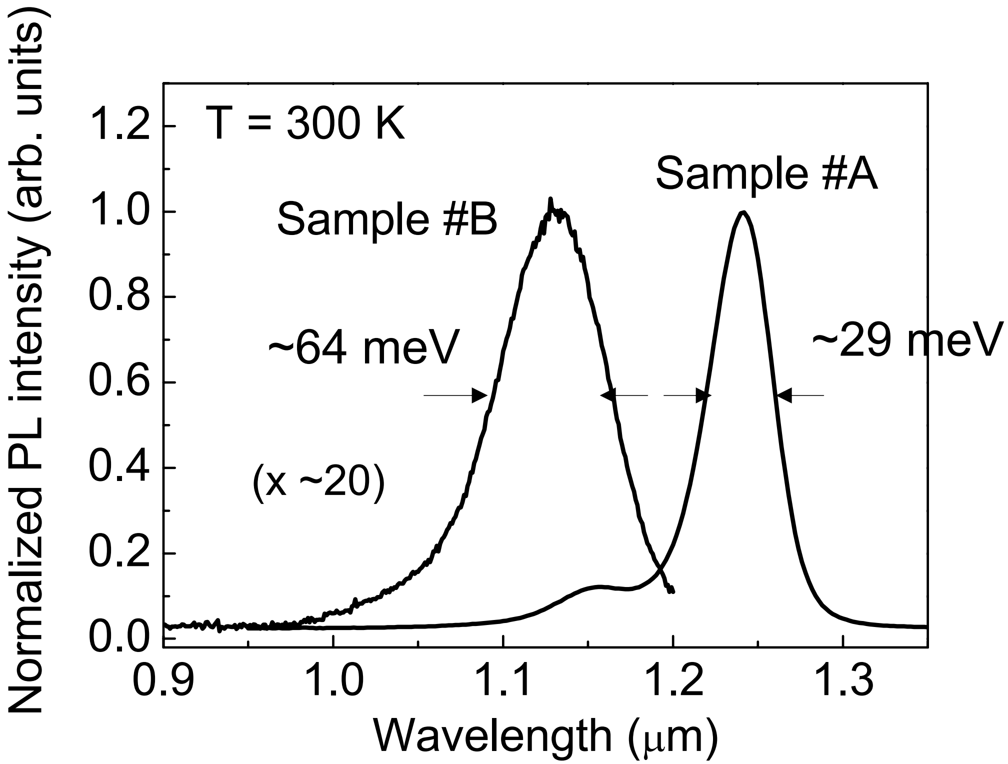
Sample #B(S-K)



Thickness of WL : ~ 4 nm

Reduced thickness of wetting layers in the QDs grown by ALMBE was predicted by Guryanov et al. Surf. Sci. 352-354, 651 (1996).

PL spectra



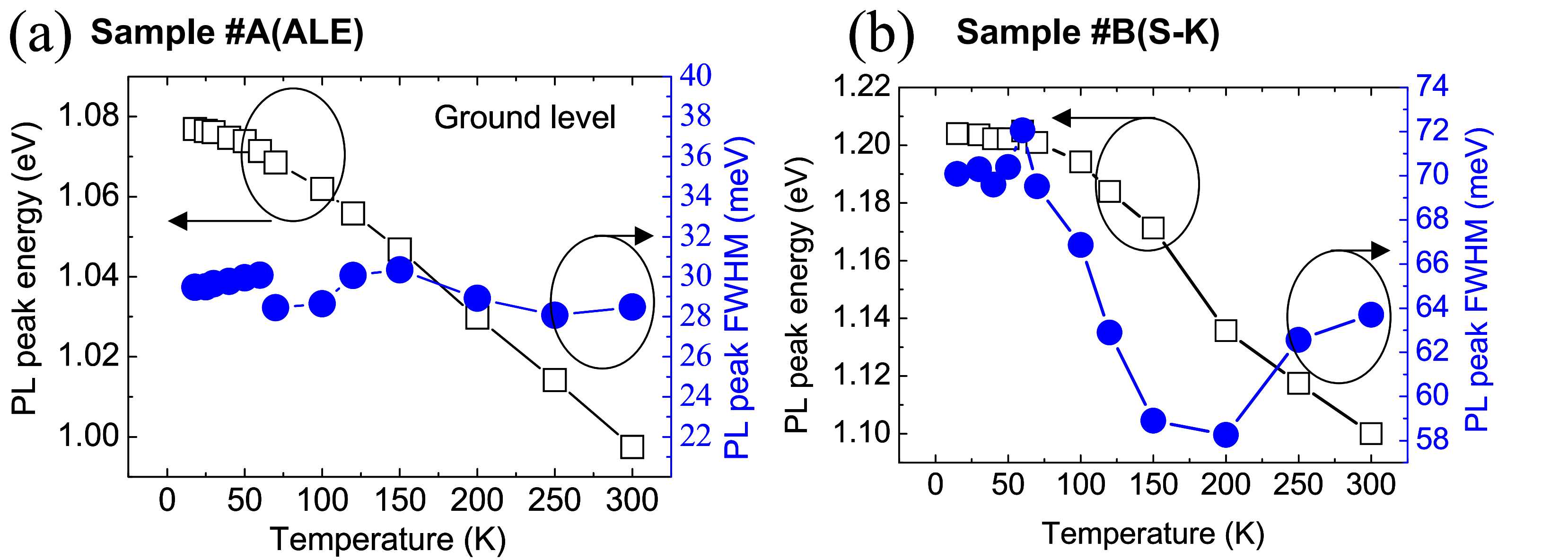
Sample #A has a 2 peaks.
(Ground and 1st excited level)

Sample #B has only 1 level.

FWHM of sample #A (~29 meV) is ~ half of that of sample #B (~64 meV).

This implies that size distribution of sample #A is more uniform Than sample #B.

Temp. depen't PL spectra

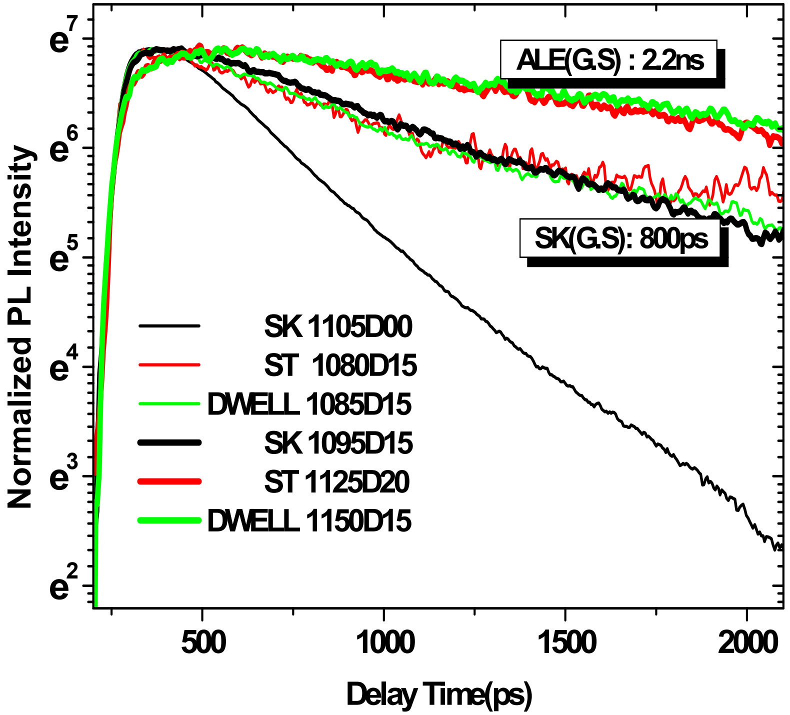


Temperature dependence of PL peak energy and PL peak linewidth of (a) the sample #A, and (b) the sample #B. In the case of the sample #A, only ground level is considered.

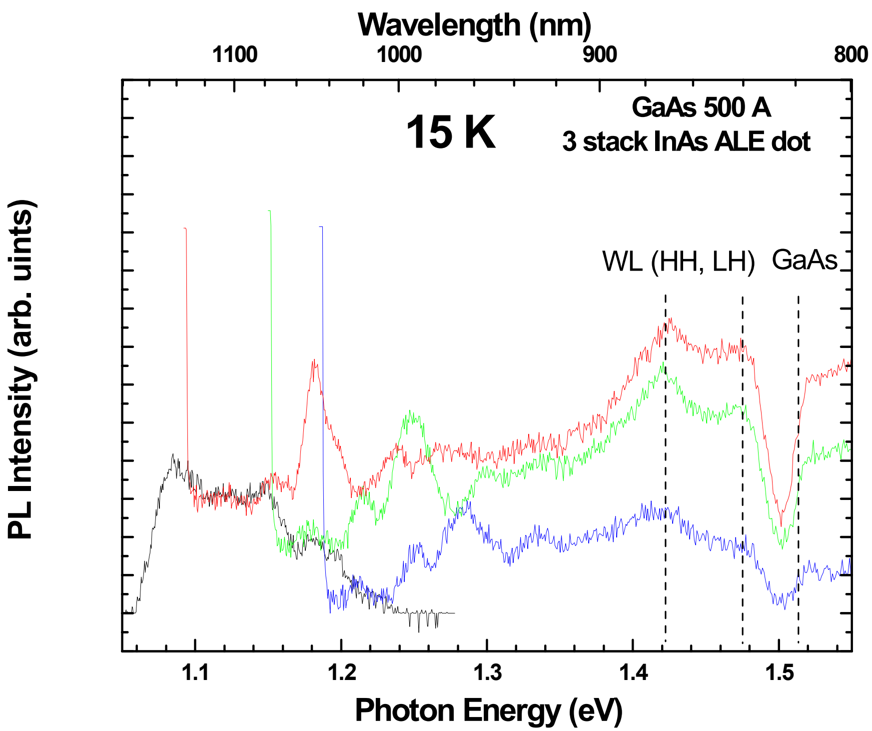
It is noteworthy that the PL linewidth of the sample #A is insensitive to cryostat temperature due to lack of wetting effect, that is, reduced thickness of wetting layers and/or uniform formation of QDs in ALMBE **APL 88, 133104(2006)**

Hi quality QD

S-K dot vs ALE dot



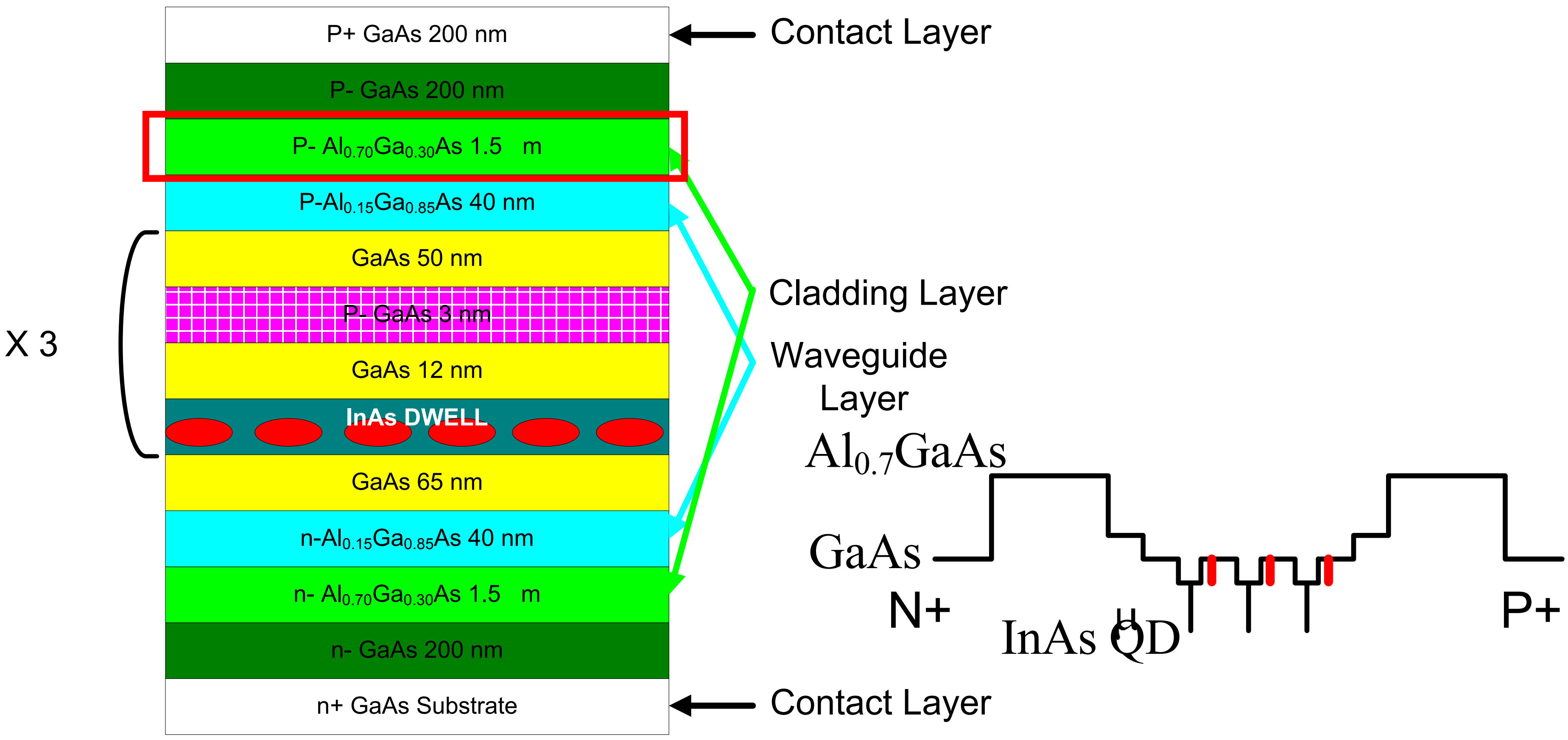
TR-PL



PLE

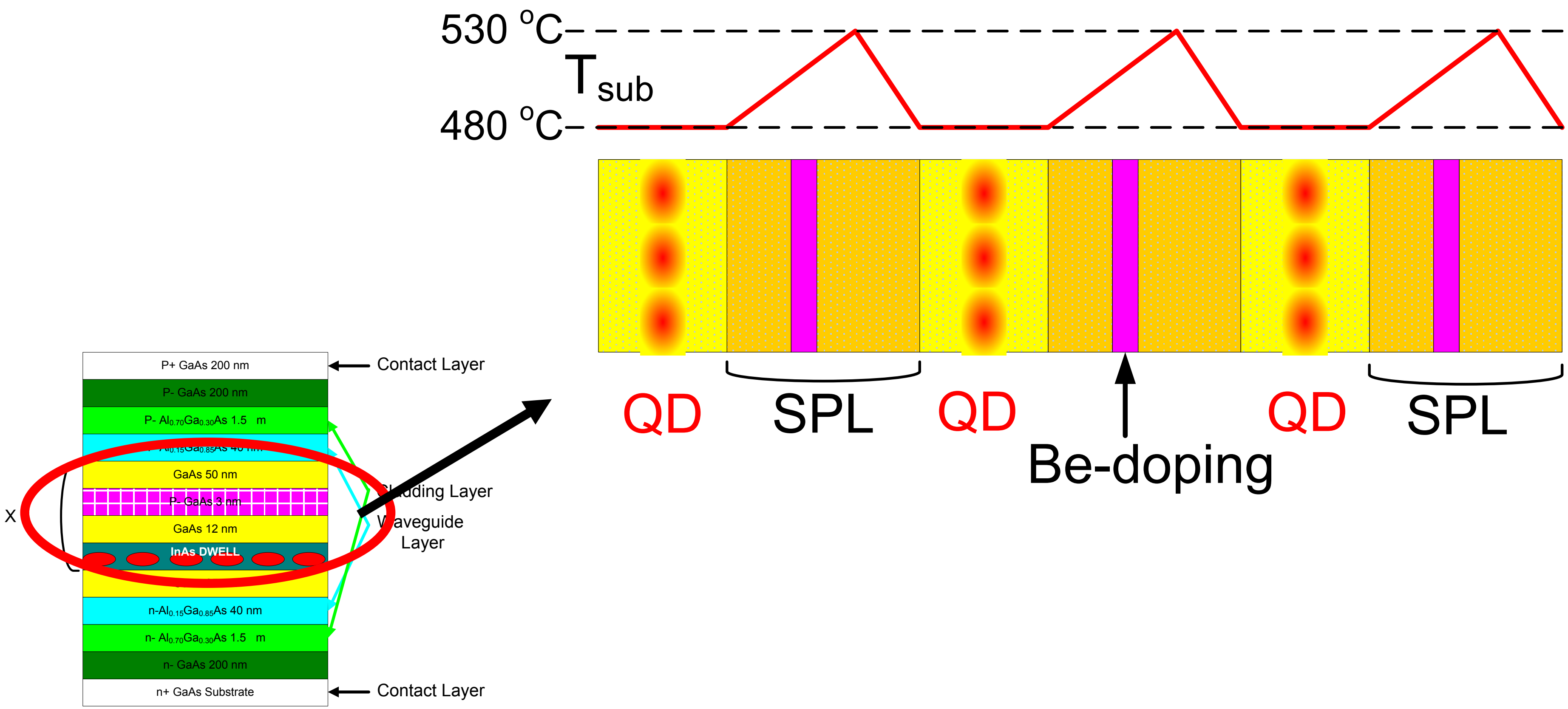
ALE dot: longer lifetime, thinner wetting layer

III. QD LD – Modulation doping



Hi T. grown spacer layer

HGTSL (High Growth Temperature Spacer Layer)[1]



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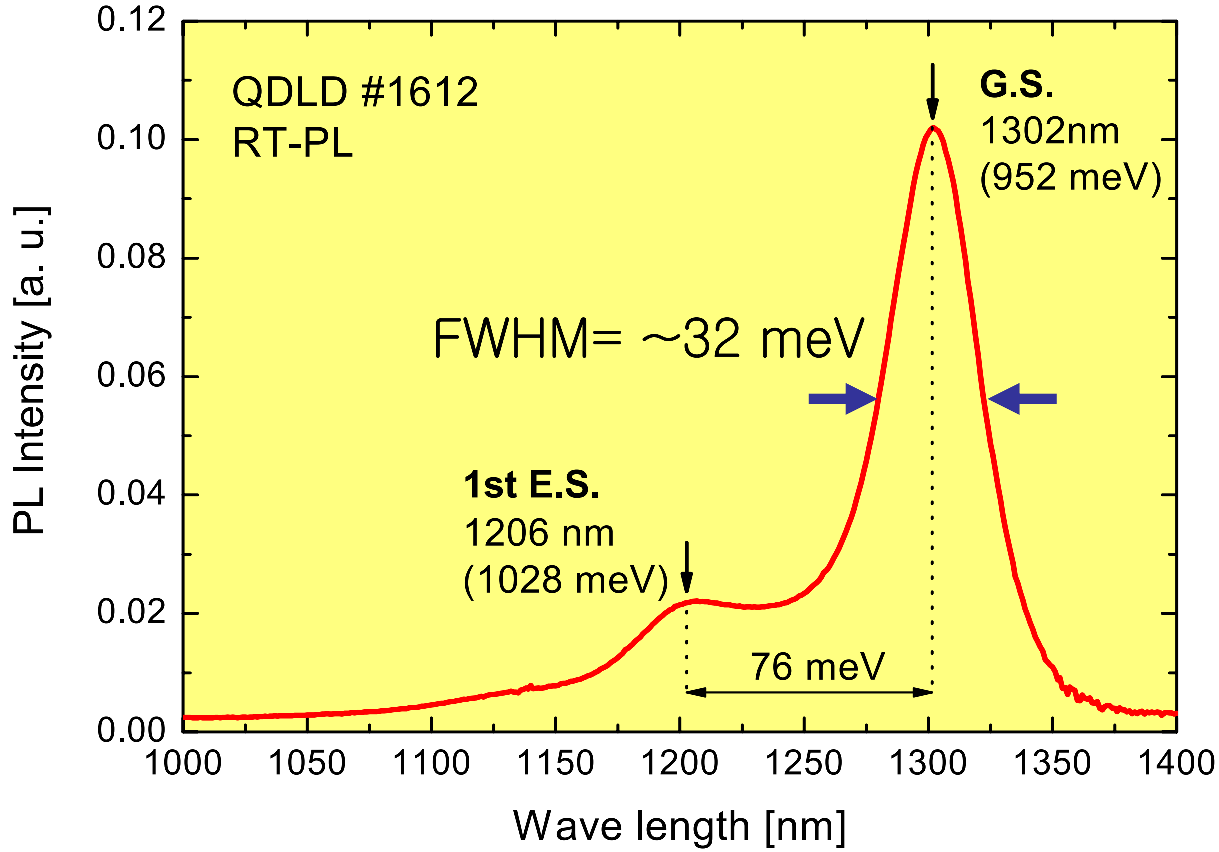
[1] H.Y. Liu et al., *JAP*, **96**, 1988, (2004) [*Sheffield*]

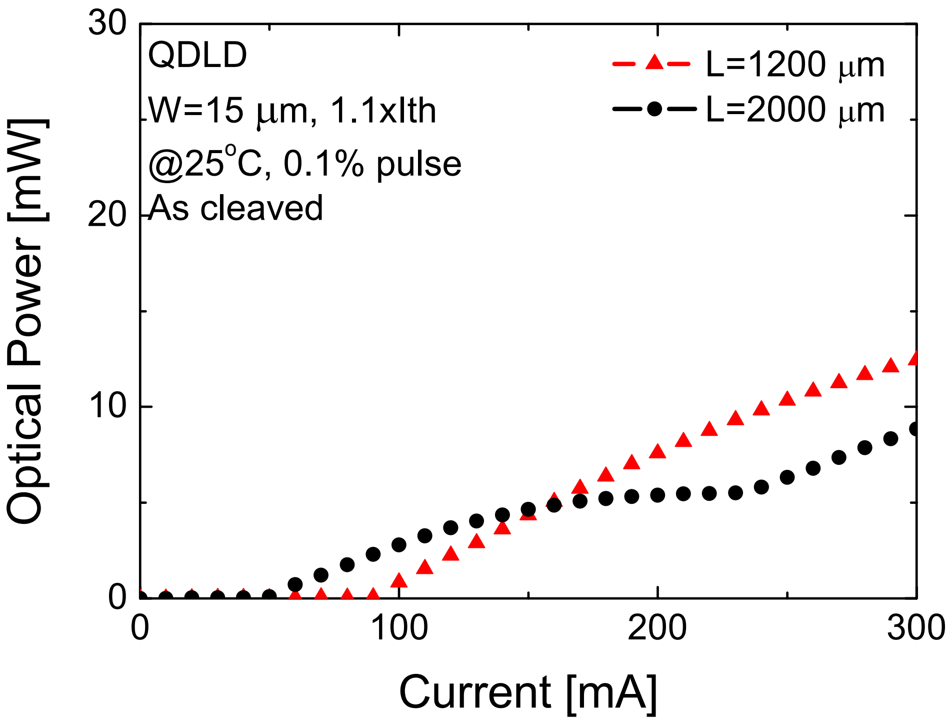
QDLD PL Spectrum

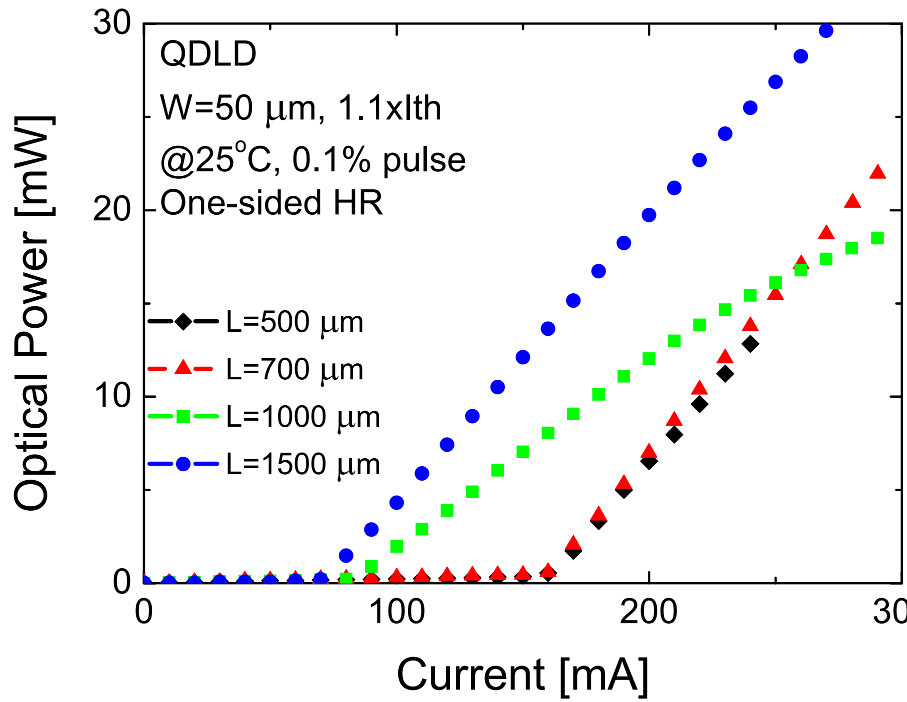


- Large Energy separation : 76 meV ⇨ improvement in the T sensitivity[1]
- Narrow FWHM : 32 meV ⇨ uniform size distribution of QDs

[1] O.B. Shchekin et al., *APL*, **77**, 466, (2000) [*Deppe*]

QDLD lasing cgaract. I



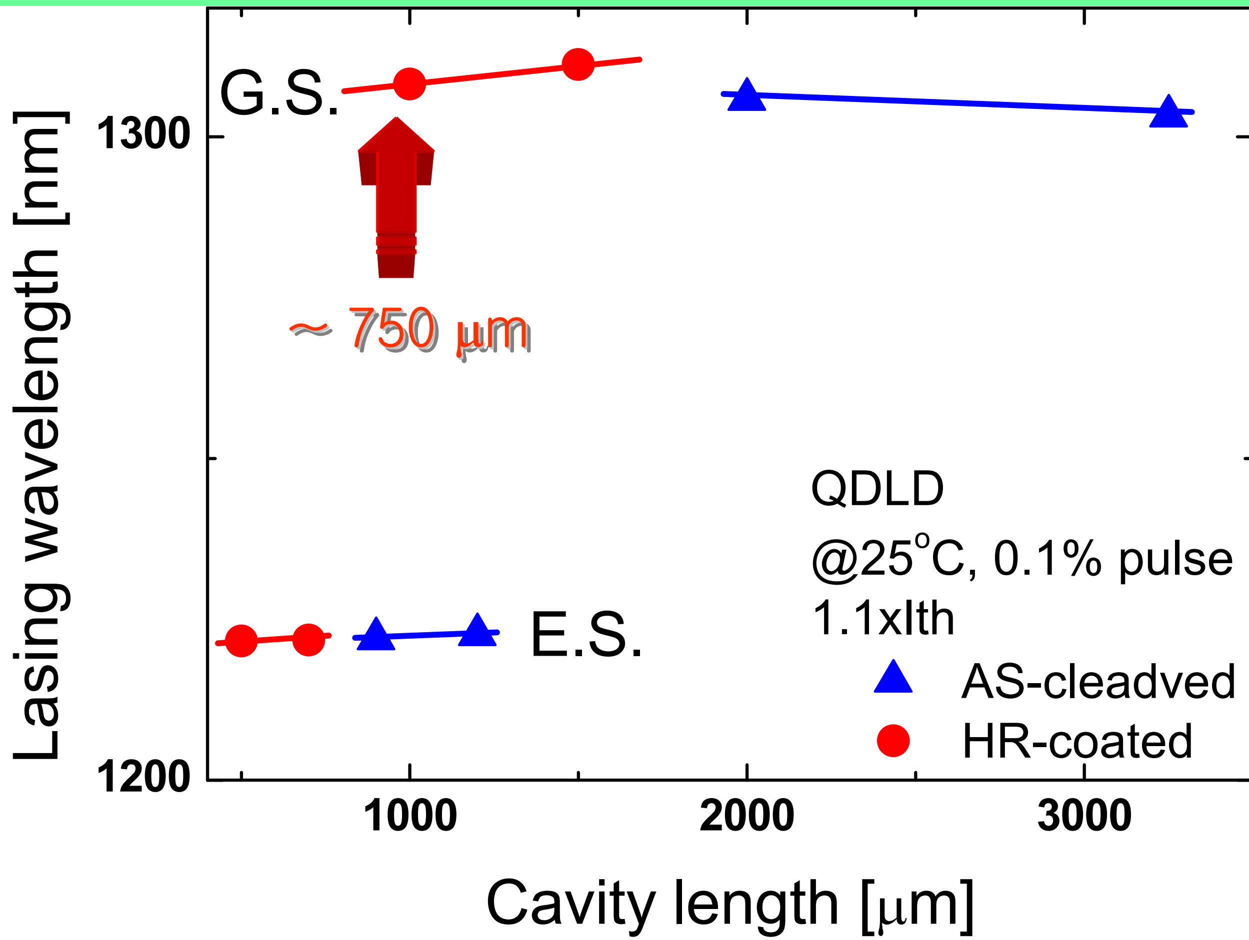


< L-I characteristics of L= 1200 μm & L= 2000 μm As-cleaved QDLD>

< L-I characteristics of L= 500 ~ 1500 μm HR-coated QDLD. >

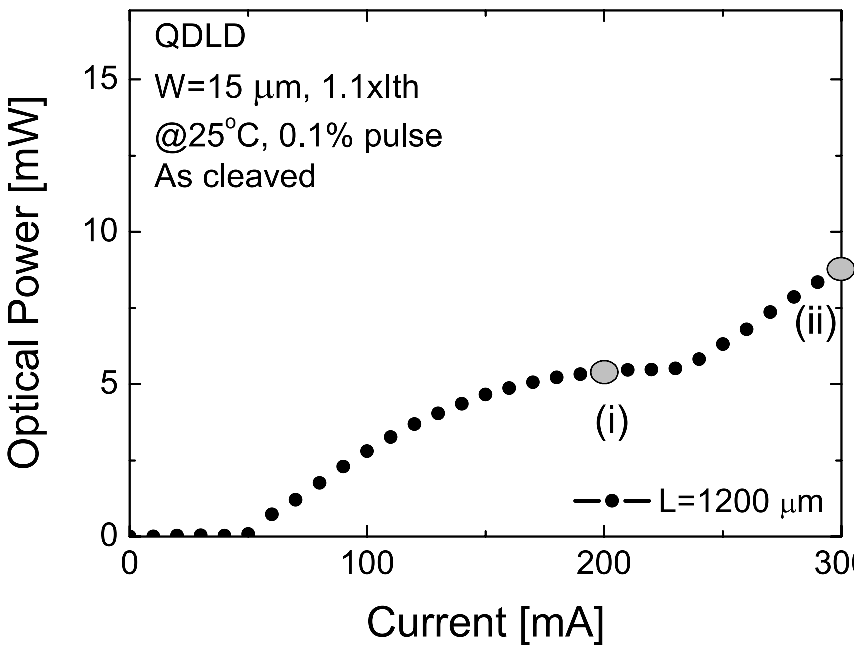
- AS-cleaved QDLD : J_{th}= 493, 155 [A/cm^2]
- HR-coated QDLD : J_{th}= 634, 452, 163, 95 [A/cm^2]

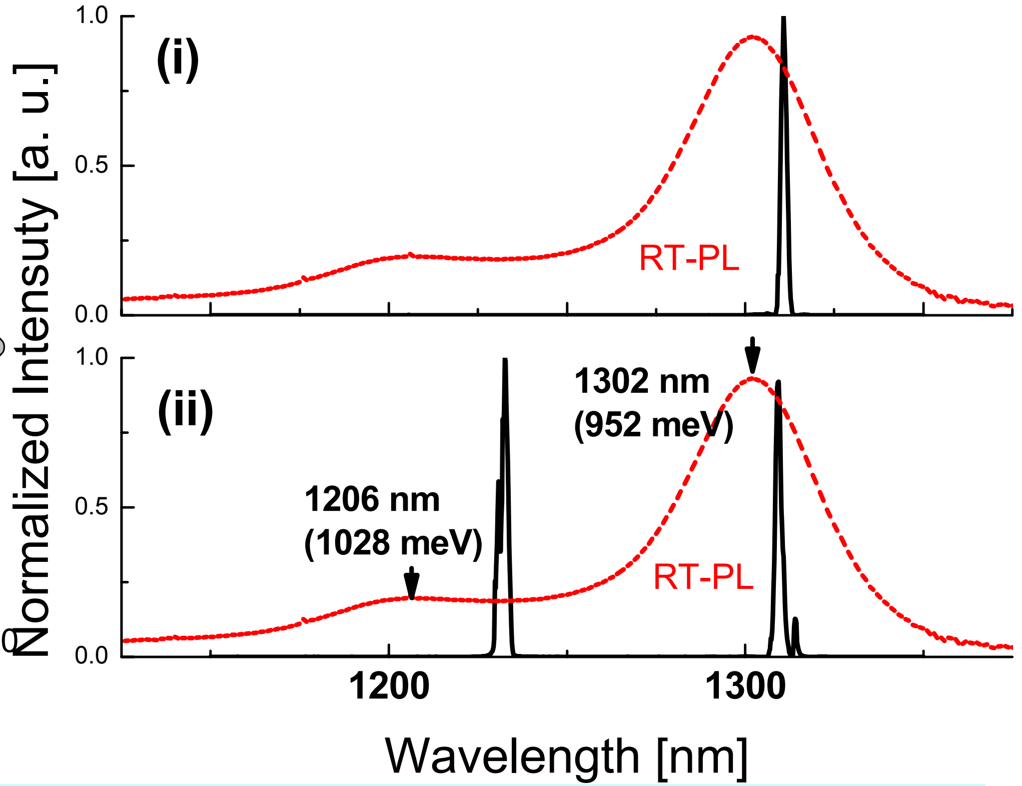
QDLD lasing charact. II



< Characteristics of lasing λ vs. cavity length L >

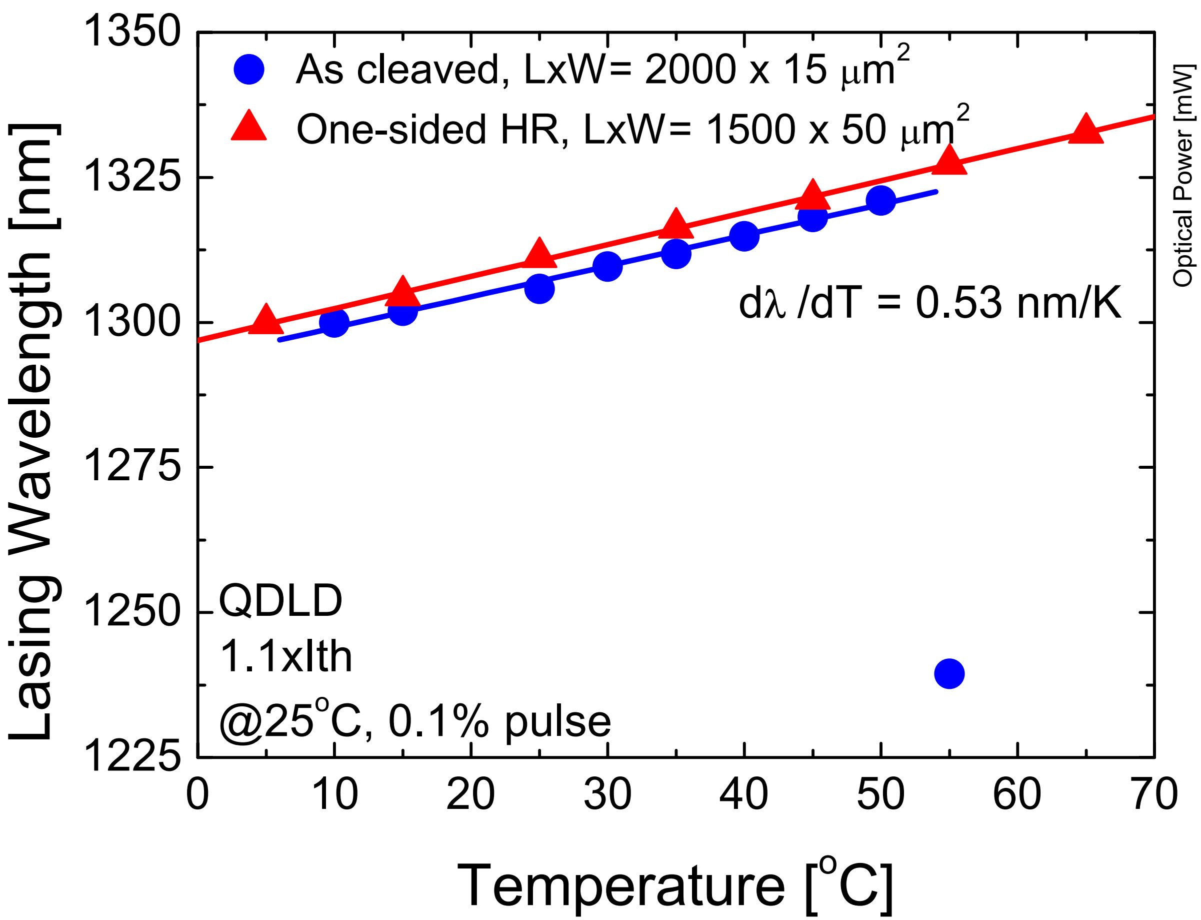
QDLD lasing charact. III

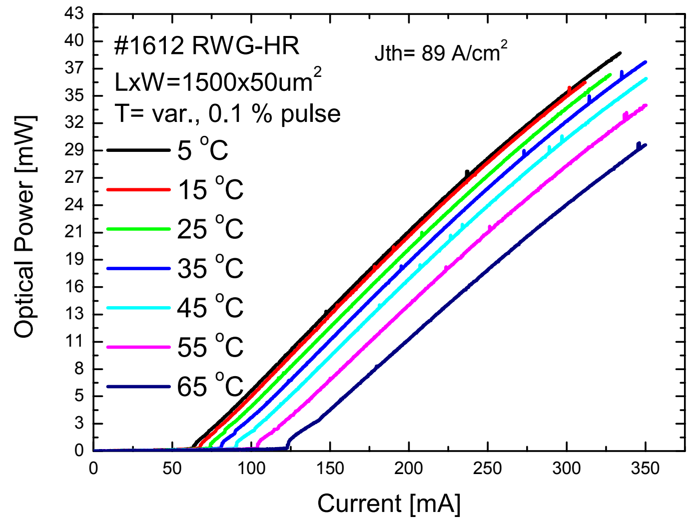




< L-I characteristics of L= 2000 μm. In point (i), only shows G.S. lasing but in point (ii), lasing spectrum shows both G.S. & E.S. lasing>

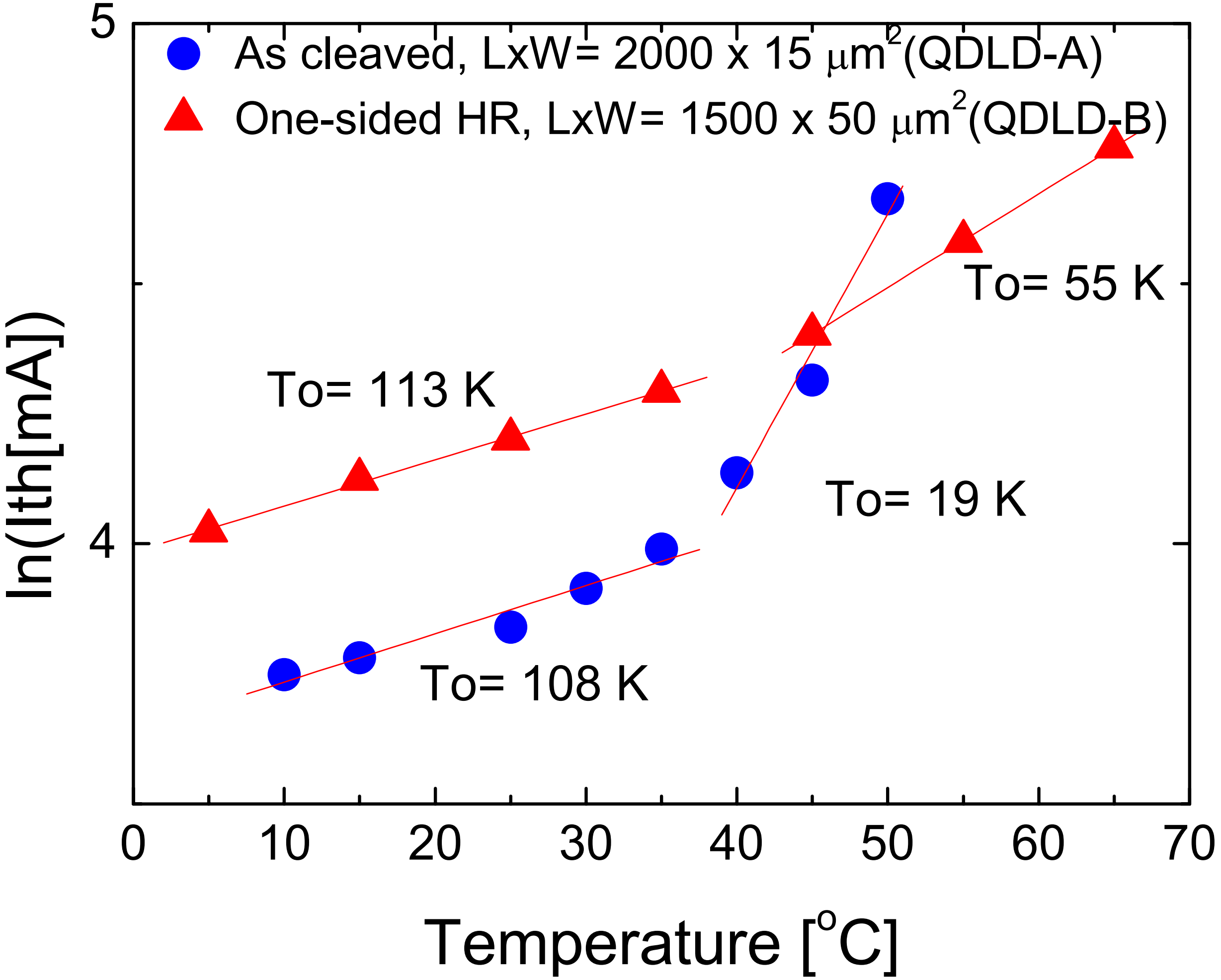
QDLD lasing charact. IV





- T < 50 °C, λ shifted to longer wavelength due to thermally induced band-gap narrowing
- T > 55 °C, λ switched to E.S. state
- HR-coated QDLD operated over 65 °C

QDLD lasing charart.V



- Temperature sensitivity
1. Lower growth T of $Al_{0.7}Ga_{0.3}As$ cladding layer
2. non-optimized p-modulation doping

참고 자료

HGTSL

Sheffield G. λ= 1307 nm @RT
Jth = 32.5 A/cm², To= 79 K
3-stack, WxL = 20x5000 μm²

P-doping

Deppe G. λ= 1290 nm @RT
Jth= 174 A/cm², **To= 200 K**
5-stack, WxL= 5x650 μm²

KIST

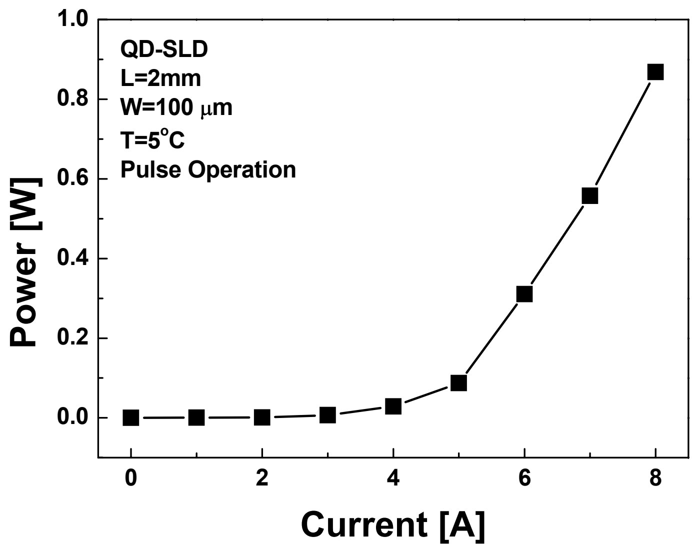
λ= 1310 nm @RT
Jth= 155 A/cm², **To= 113 K**
3-stack, WxL= 50x1500 μm²

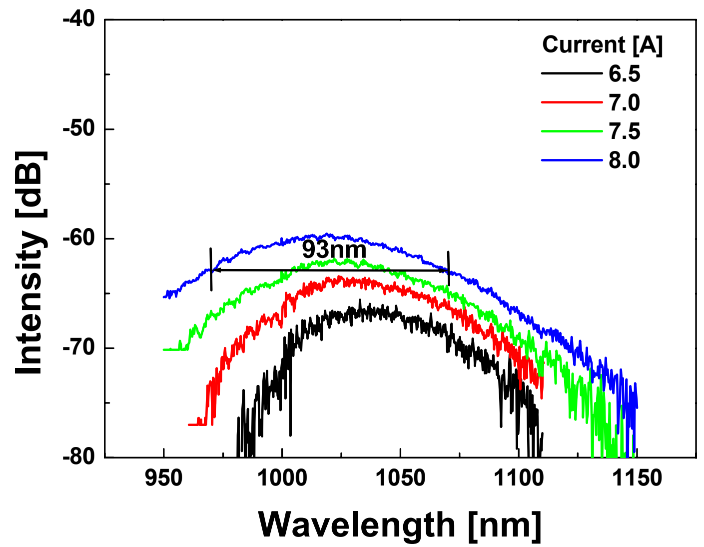
Bhattacharya G. λ= 1240 nm @RT
Jth = 180 A/cm², To= infinite
5-stack, WxL = 5x800 μm²

Bimberg G. λ= 1280 nm @RT
Jth = 147 A/cm², To= 150 K
10-stack, WxL = 100x1500 μm²

IV. SLD

Applications : Low coherent broadband light source for OCT
WDM-PON



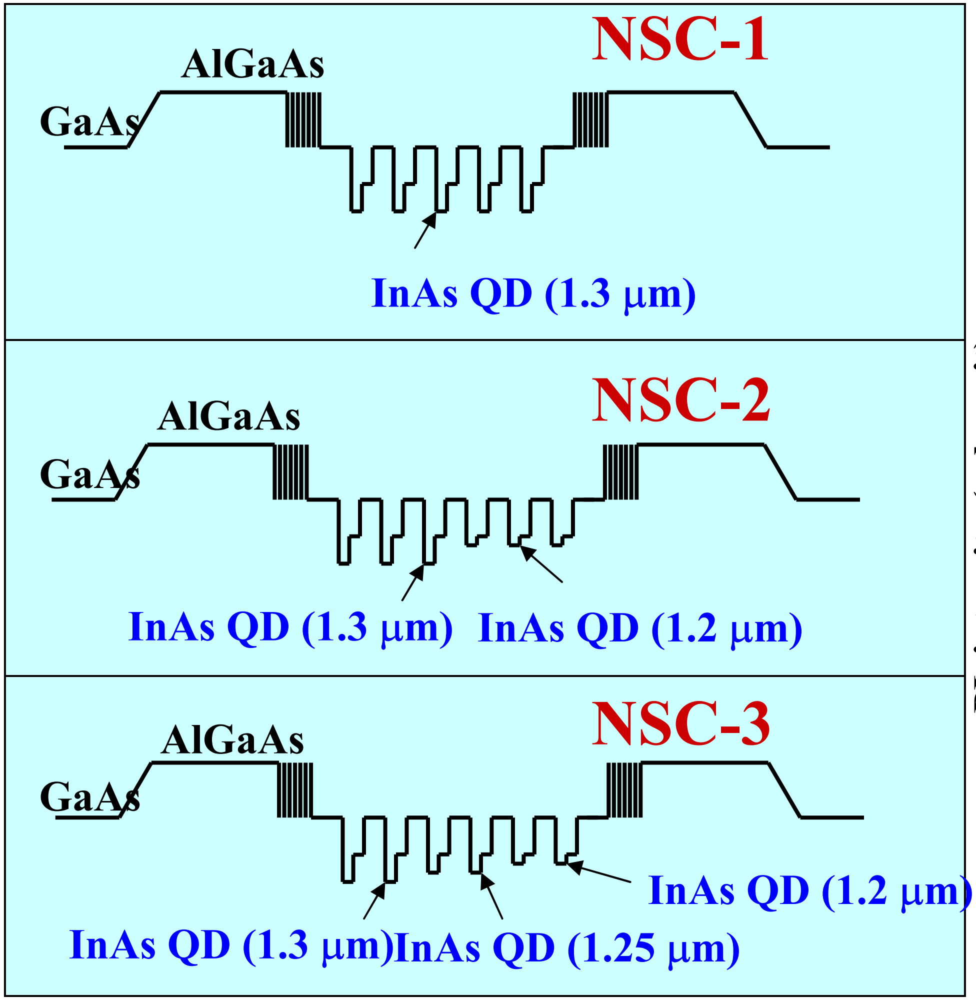


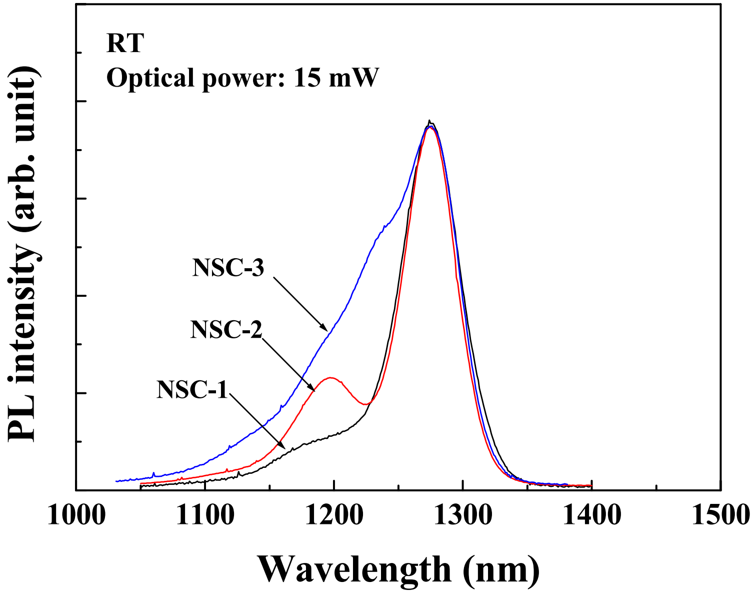
Max. Power ~ 0.9 W

Max. spectral bandwidth ~ 93 nm

SLD epi structure

❑ Chirped-QD (Quantum Dot) 구조

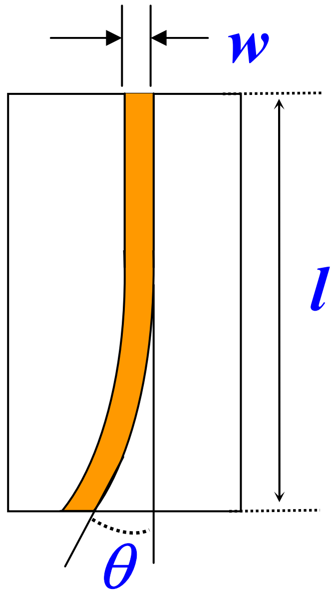


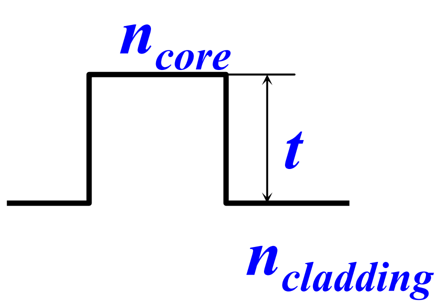


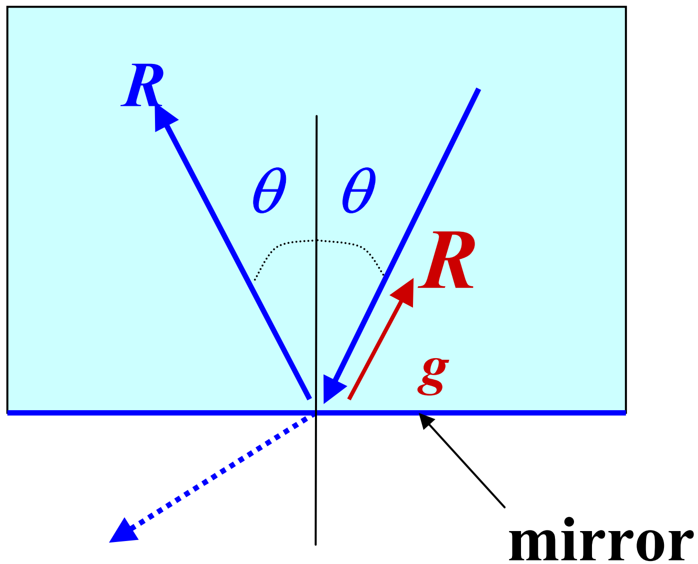
※NSC (NL Semiconductor)

SLD tapered structure

❑ Chirped-QD (Quantum Dot) SLD 제작





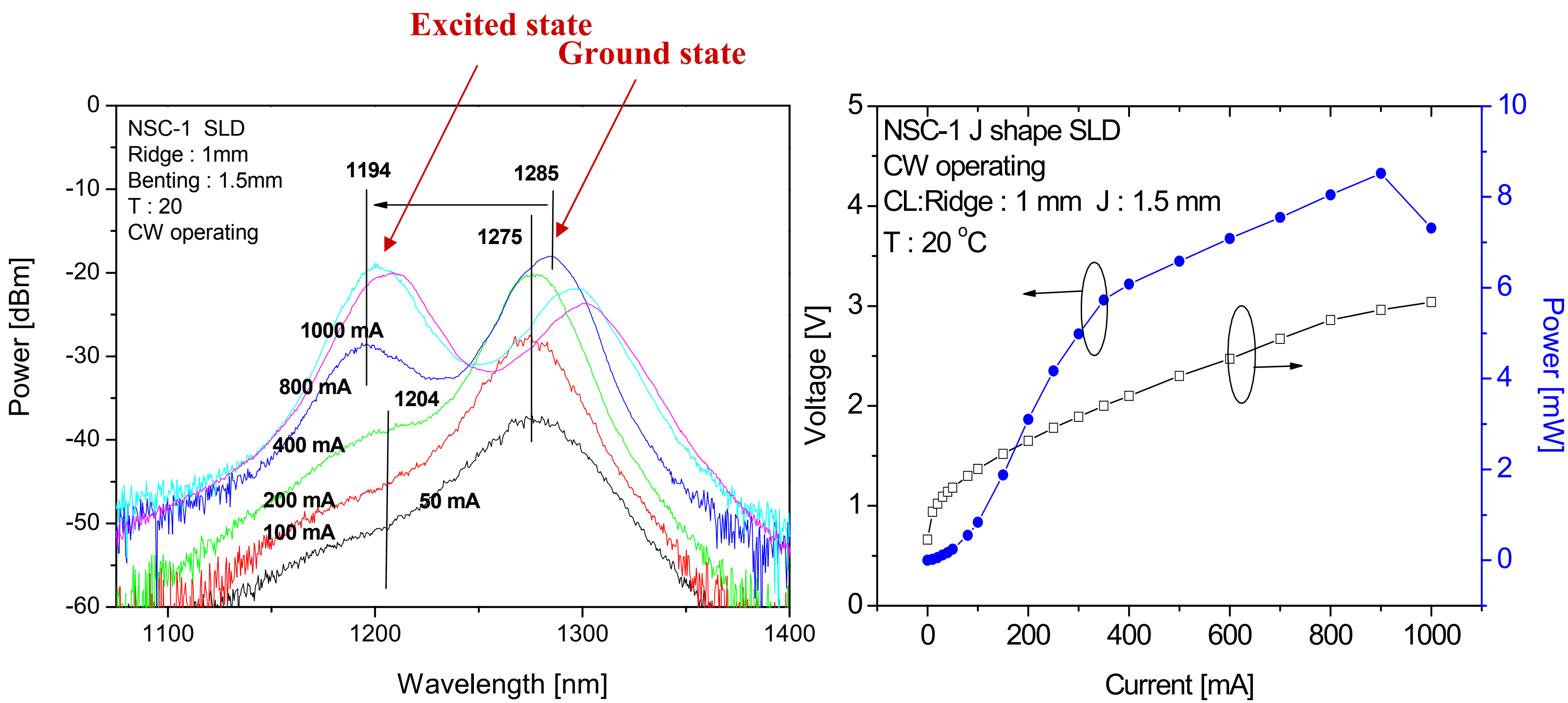


$$R_g = R_g\,(\lambda,\ \theta,\ \Delta n)$$

$$\Delta n = n_{core} - n_{cladding}$$

SLD 1

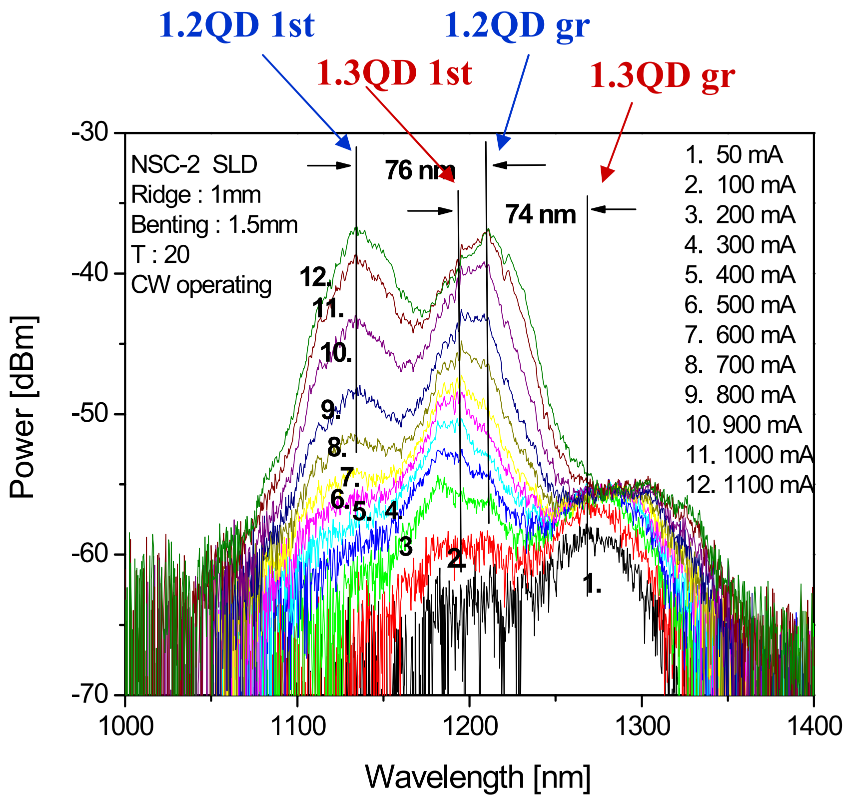
❑ QD (NSC-1) SLD

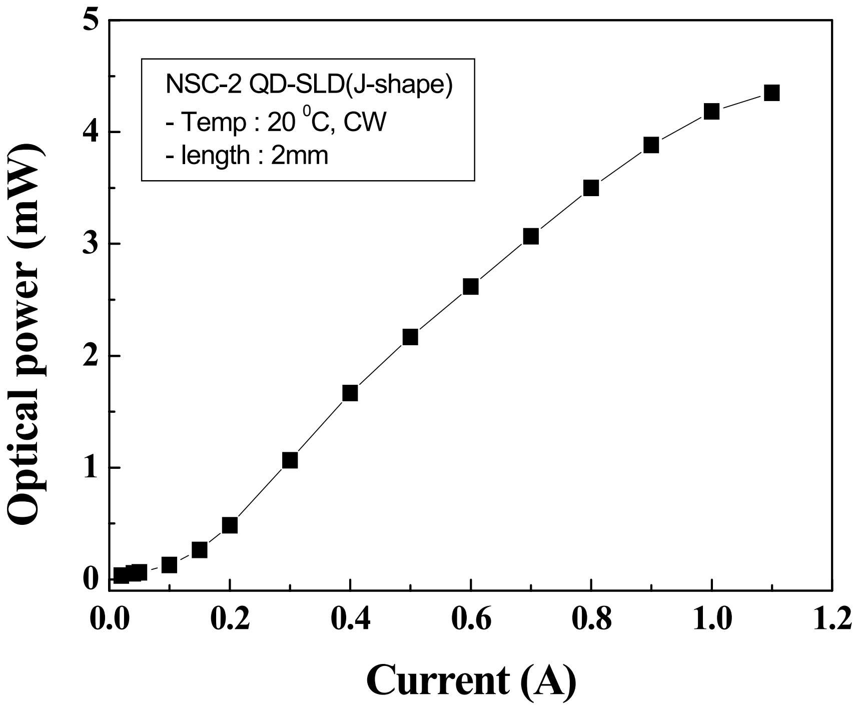


SLD 2

❑ QD (NSC-2) SLD

Jpn. J. Appl. Phys. 2005. 8

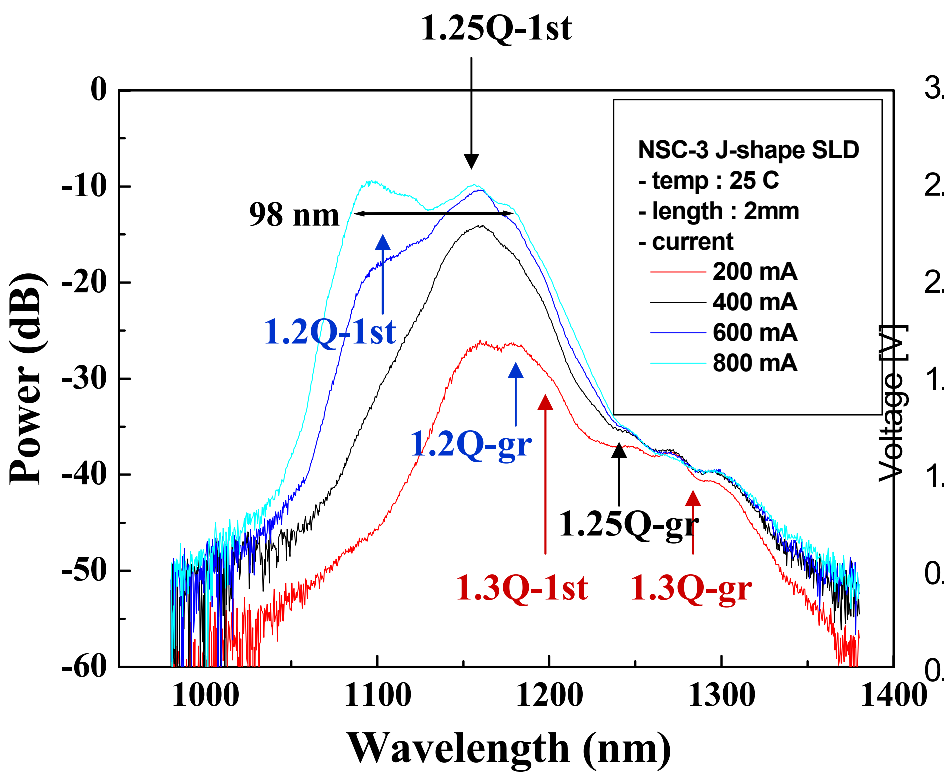


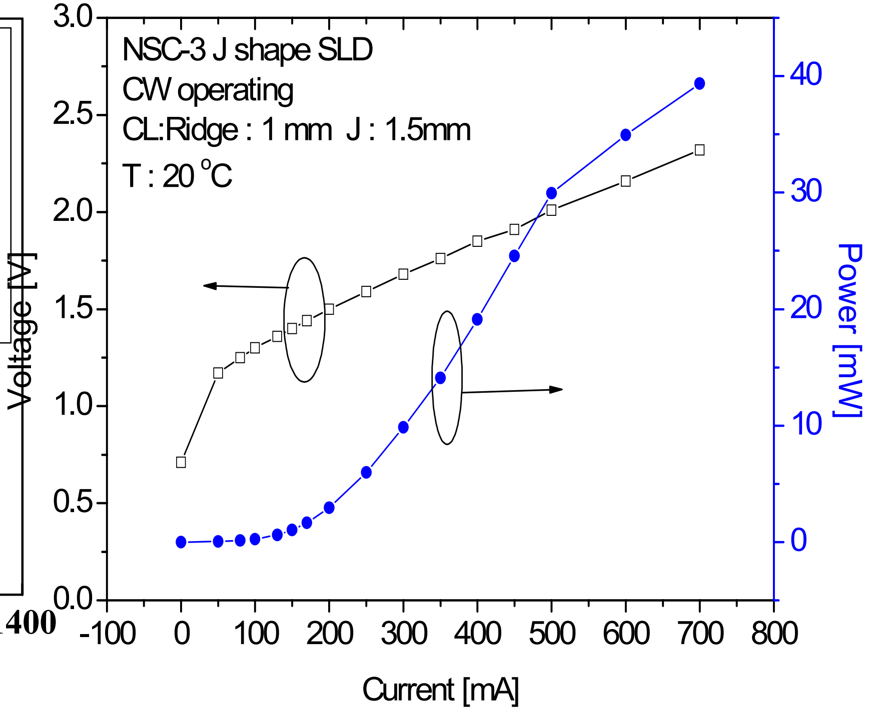


SLD 3

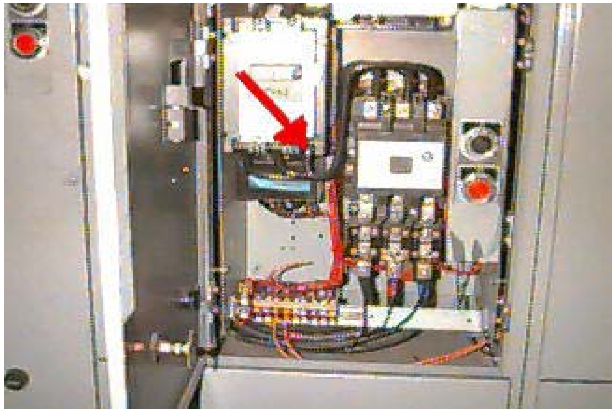
❑ QD (NSC-3) SLD

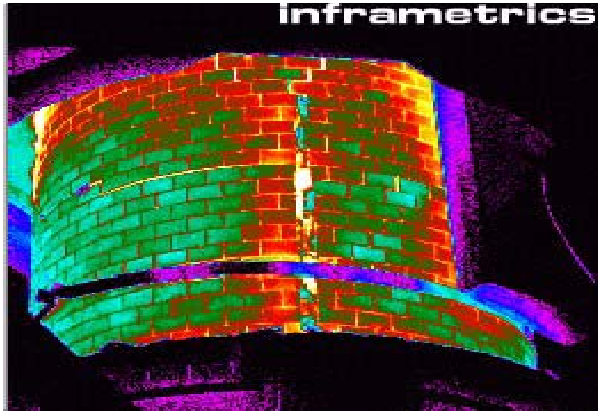
Appl. Phys Lett : submitted

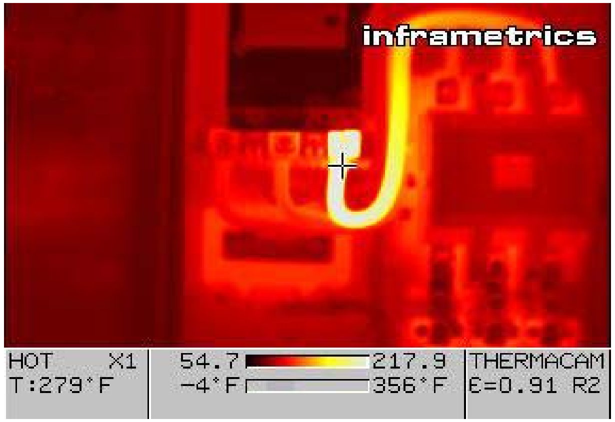


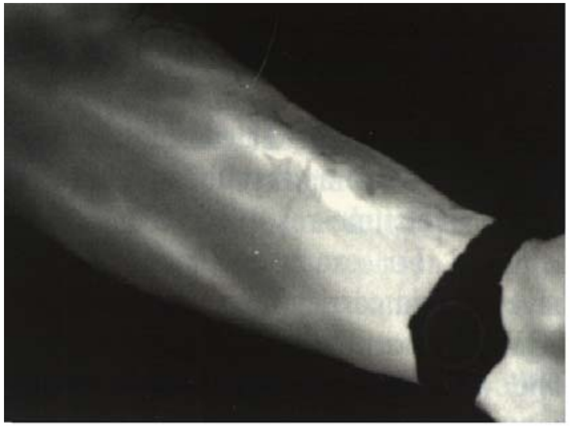


V. QDIP – IR PD Applications





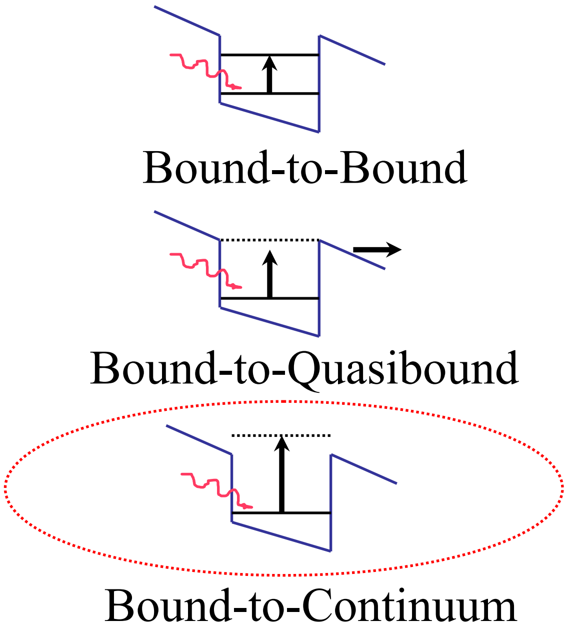


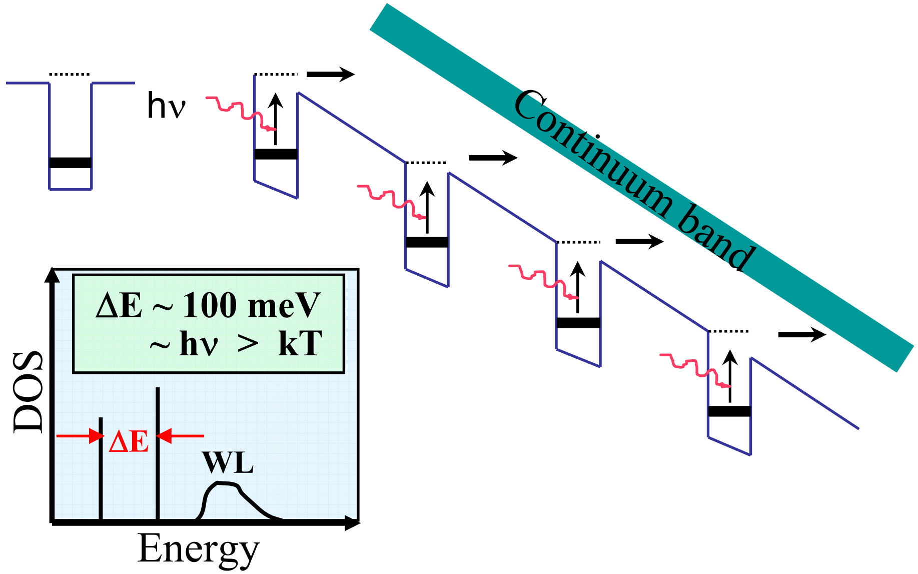


Introduction (Types of IR detector)

	Thermal detector	**Photon detector**	
Type	**- Bolometer type** **-Ferroelectric type** **- PN junction**	**Interband** - MCT(HgCdTe) - InSb	**Intersubband** - Si Schottky - Si QWIP / QDIP - GaAs QWIP / QDIP
Dis-adv	- low D* - very slow	- low T opeation (<77K)	- H**igh T. opeation(>77K)**
		- non uniform process	- low D*
Adv	- R.T. operation	- high D* - fast response	- **uniform and reliable** - 2D FPA **(easy fab)** - fast response

Quantum Dot for IR detector





Bound-to-Continuum Intersubband Transition

Quantum Dot **instead of Quantum Well**

- **Normal incidence operation - Pyramidal shape of QD**
- **Room-temp. operation - Strong confinement by 3-D QDs**
- **Small thermionic dark current - Atomic discrete energy level**
- **Large photoconductive gain - Lack of optical phonon scattering**

Issues in QDIPs

1. Operation Wavelength (3-5um, 8-12 um, > 12um)
   : Bandgap engineering by precise growth, post-growth technique
2. Device performance : Operation T, Responsitivity, Detectivity

$R = (e/hc)\eta\lambda G$; Responsitivity

$D* = A^{1/2} R/i_n$; Detectivity, i_n ; Noise current

For high D* and high temperature operation

Low noise(dark) current, high gain are required

QD : 3-dimensional confinement of electrons

-> promising for high temperature operation of IR detector

But grown at low temperature under strained material condition

-> defects and/or misfit dislocation is generated

-> control of defects is crucial for high quality QDIP

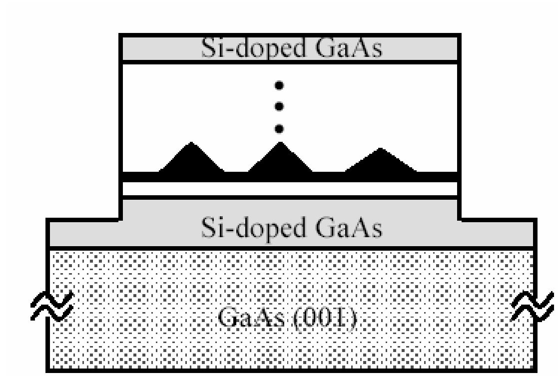
For low dark current;

High quality material (growth)

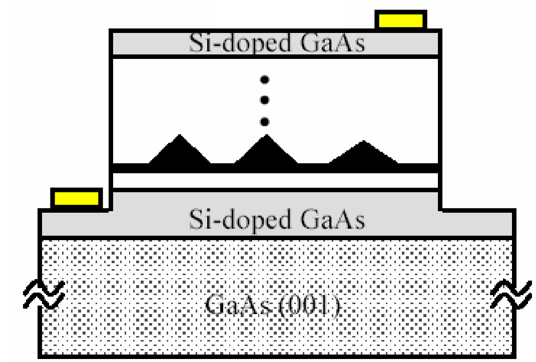
Post-growth treatment (Thermal treatment, H-passivation)

QDIP의 제작

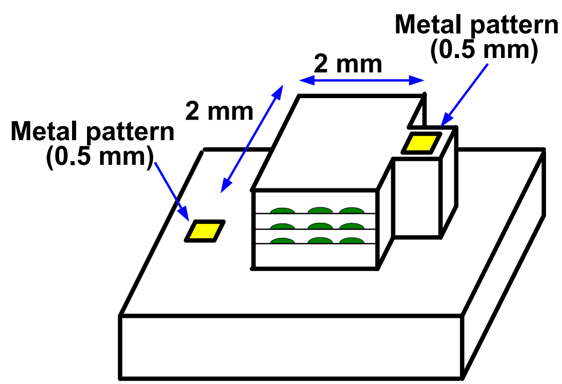
cleaning
↓
Mesa etching
↓
Metallization
↓
Packaging



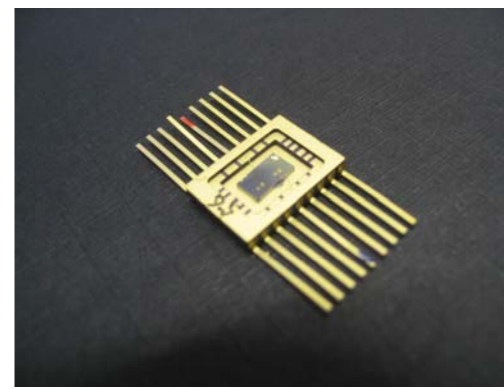
(1) Mesa etching



(2) Metallization and RTA



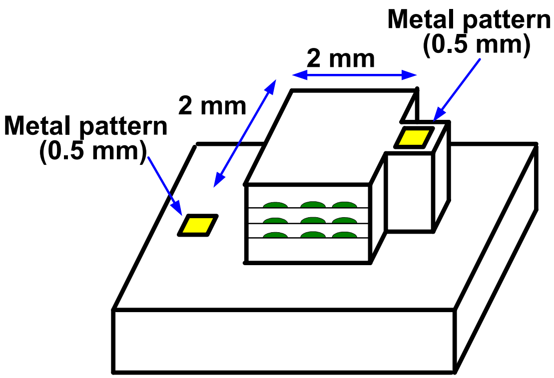
(3) Fabricated QDIP


(4) Packaging

QD IP

Quantum Dot **instead of Quantum Well**

- ❑ **Normal incidence operation - Pyramidal shape of QD**
- ❑ **Room-temp. operation - Strong confinement by 3-D QDs**



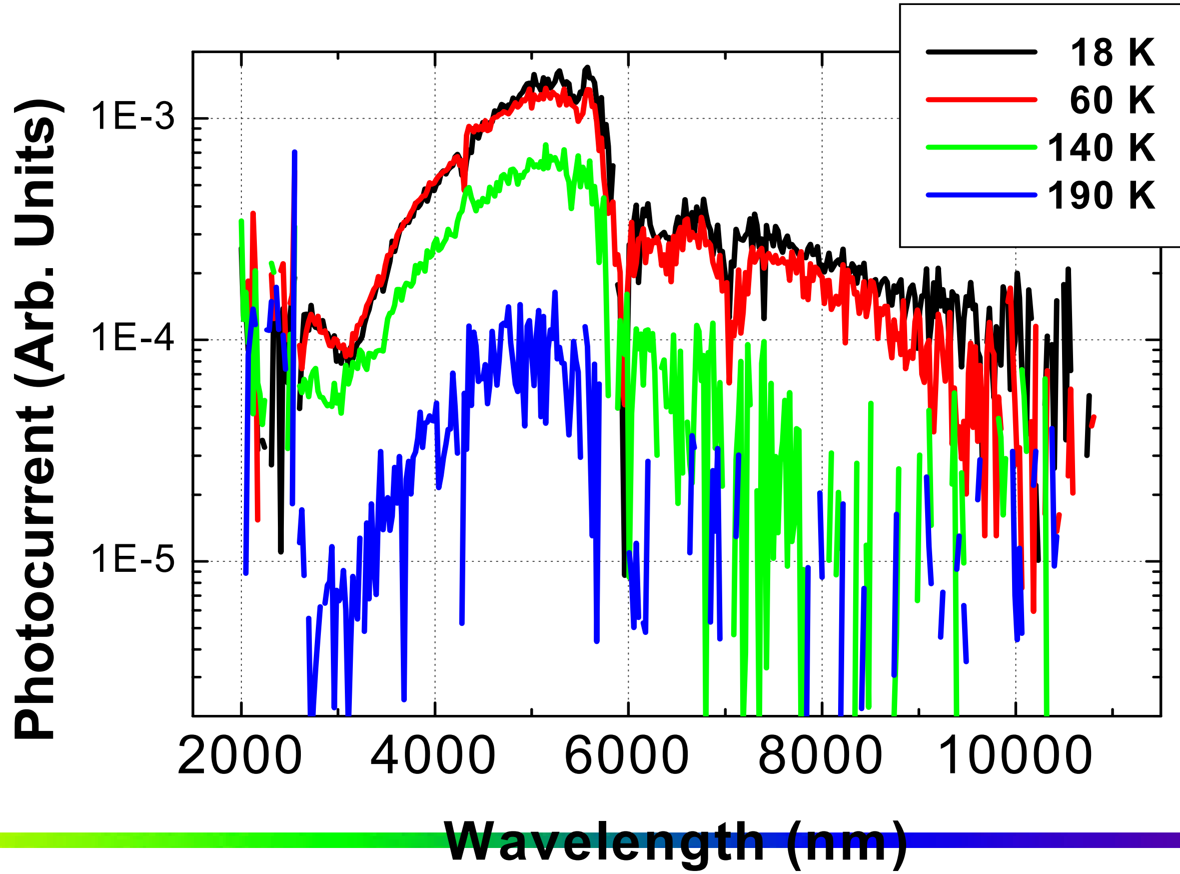
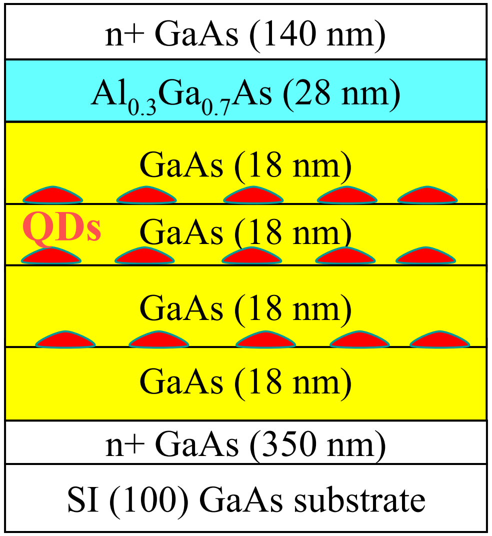
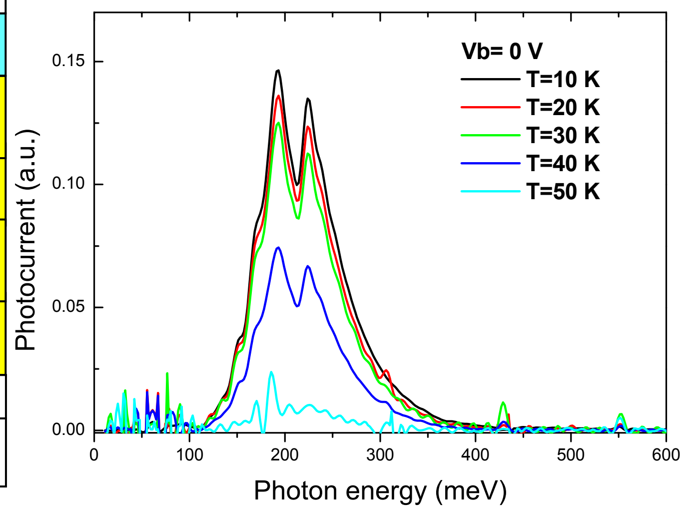
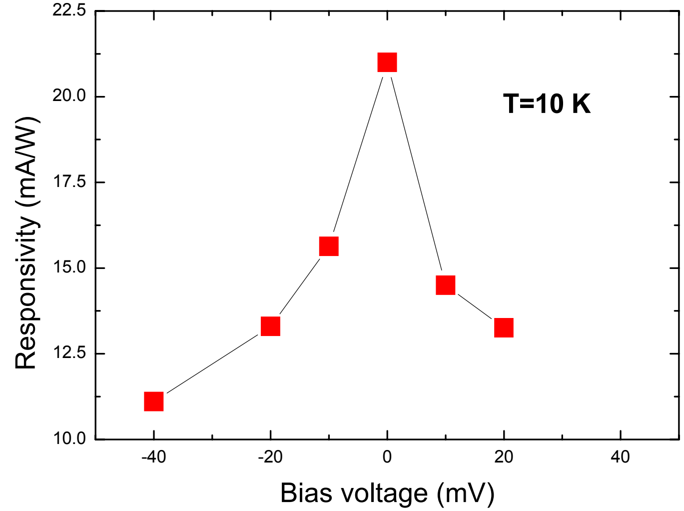


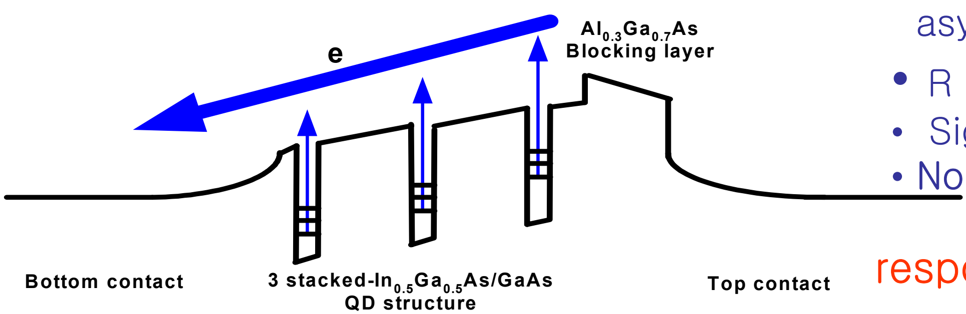
Photo-Voltaic QDIP







Direct Si doping ~ 2.0x10^{18} cm^{-3}



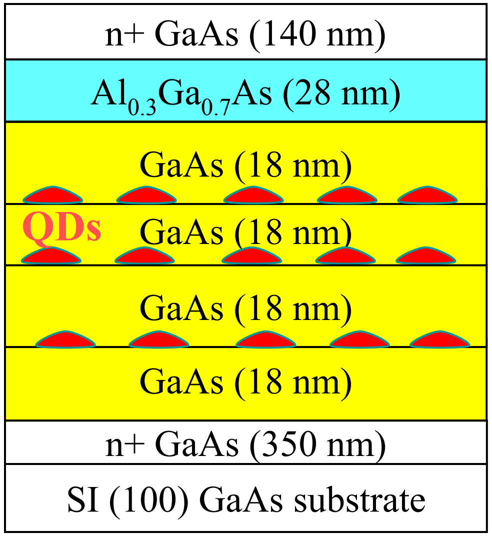
- Photo-voltaic effect due to asymmetric band structure induced by direct Si doping, AlGaAs barrier and asymmetric QD shape
- R = 21 mA/W at zero bias at λ~ 6.2 μm (200 meV)
- Signal detected up to 50 K
- No bias -> small dark current -> high detectivity

responsivity is 70 times larger than reported value

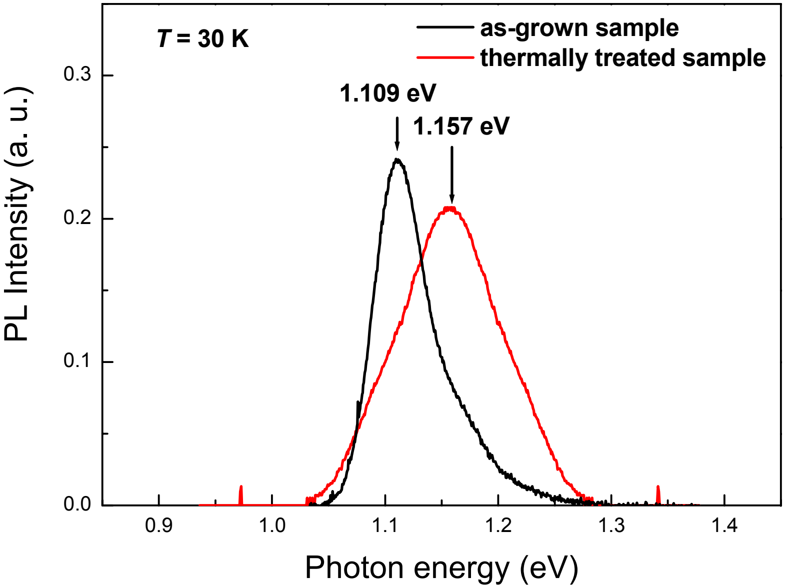
(MNE2004, Microelectron. Eng., accepted, 2005)

Post-growth treatment(Thermal annealing)

- Purpose
  - detection wavelength tuning with post-growth technique
- 300 nm SiO_2 capping and annealing (T=700 ^{0}C , 1 min)



Direct Si doping ~ 2.0x10^{18} cm^{-3}



- PL peak position : blue-shifted by 48 meV.
  (due to intermixing of In/Ga composition)
- PL FWHM : 60 → 110 meV
- PL intensity : decreased

Post-growth treatment(Thermal annealing)

Dark current

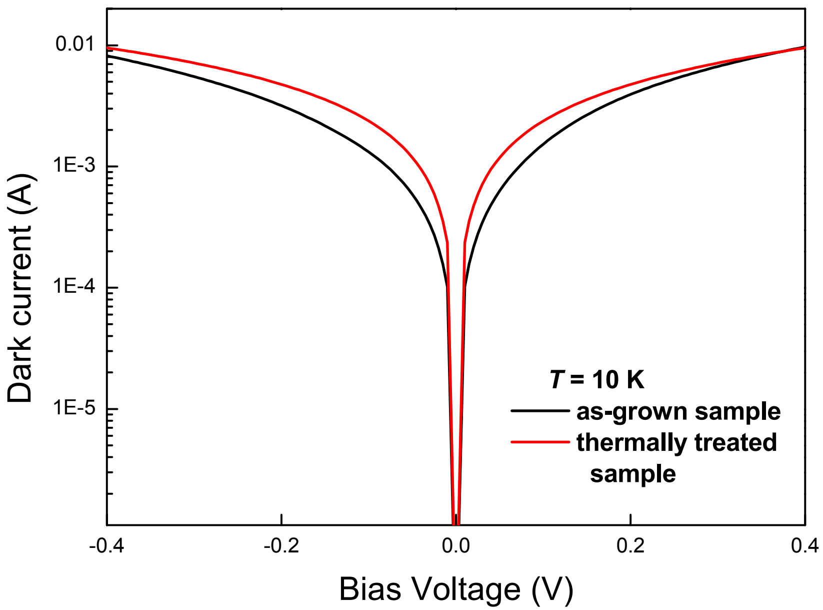
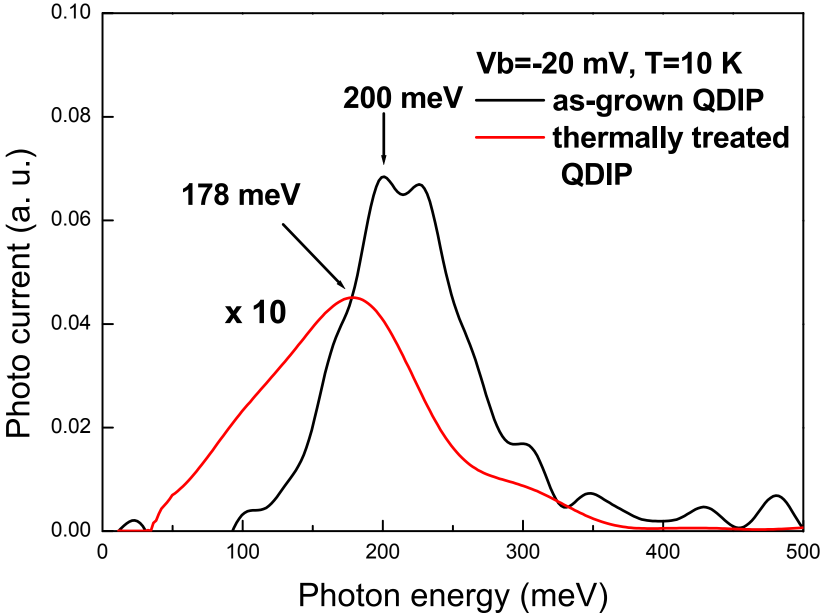


Photo-current



- Dark current level : 2 times larger.
  (due to defects generation)
- Relatively small increase than reported data*.
  (might be due to SiO_2 dielectric capping layer)

-Peak position(λ~ 6.9 μm) : red-shifted by 22 meV.

⇒ due to intermixing In/Ga composition.

-Responsivity : decreased (13.2 → 6.2 mA/W).

⇒ due to increase of defects.

1st demonstration of detection wavelength tuning !!

(JJAP, accepted, 2005)

*K. Stewart, *et al*, J. Appl. Phys. **94**, 5283 (2003).

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VI. Summary

- QD growth (ALE) more uniform and thinner wetting layer
- QD LD, I_{th}, T_0
- QD SLD, wide bandwidth w/ chirping structure
- QD IP, hi T operation, photovotaic structure, post growth treatment

VII. Prospects

Future Collaboration in:

- Optical Commun devices
- Intersubband devices, far-IR, THz
- Sensors
- LED
- Bio-photonics