Optics III
Intersubband transitions and unipolar optoelectronic devices

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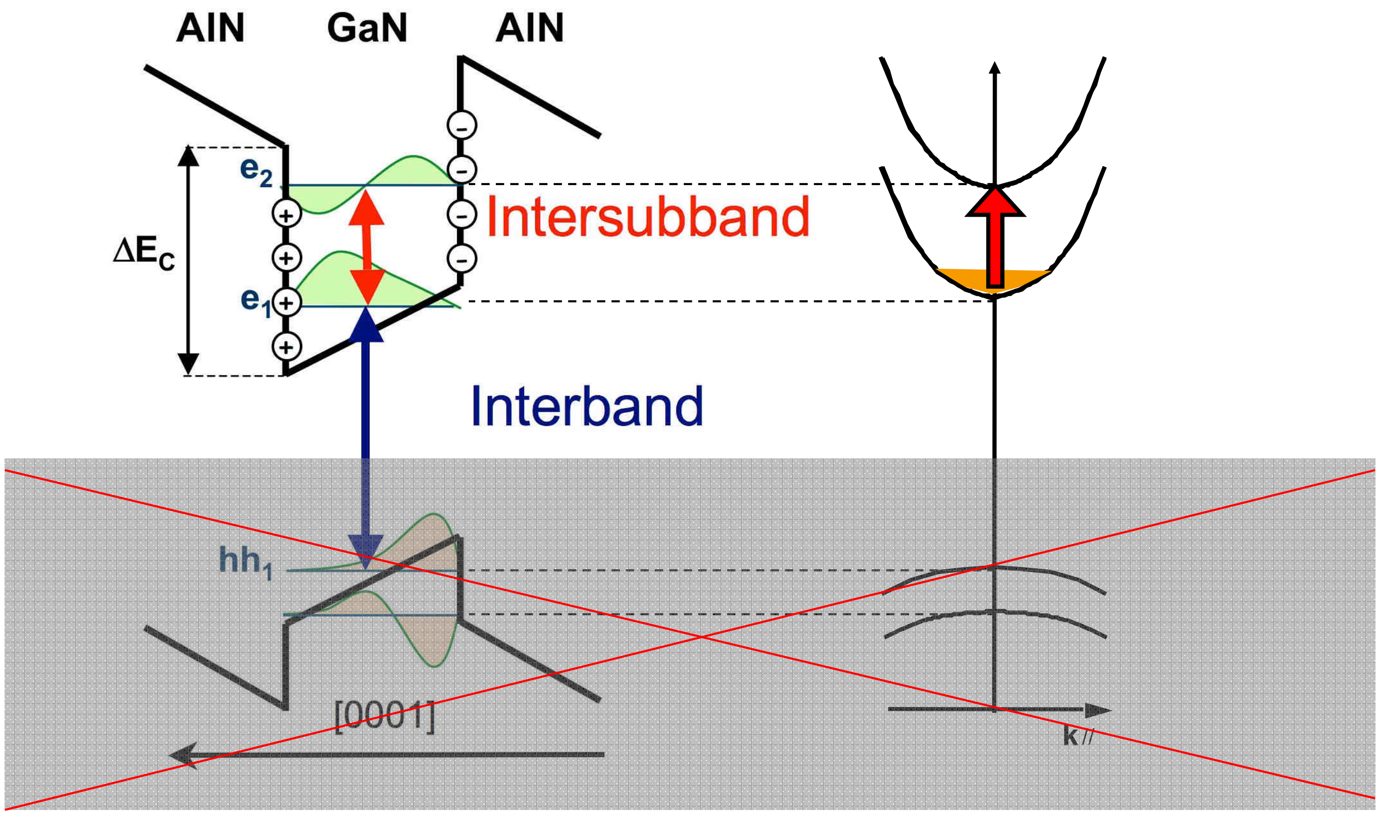
Outline

- Intersubband transitions in nitride heterostructures: theoretical aspects
  - General properties of ISB transitions
  - Modeling within the envelope function formalism
- Infrared spectroscopy of nitride quantum wells and quantum dots
- Nitride unipolar devices
  - Intersubband photodetectors
  - Intersubband light modulators
  - Intersubband light emitters
- Prospects for THz nitride lasers

What are intersubband transitions?

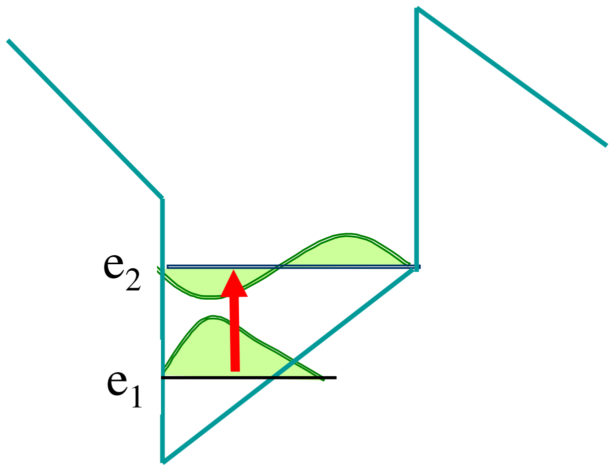
- Intersubband transitions are transitions between quantum confined states in the conduction (valence) band of quantum wells, wires or dots
- Only one type of carriers (usually electrons)
- ISB wavelength is almost temperature-insensitive

GaN/AlN quantum well

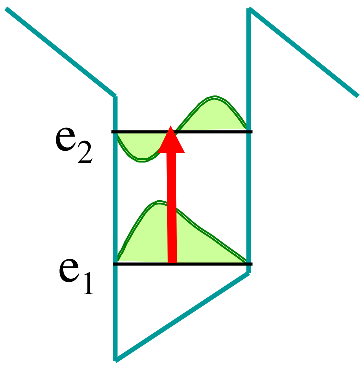


Wavelength tunability of ISB transitions

- Wavelength can be tuned by adjusting layer thickness – possibility to engineer the quantum confinement in order to make nitrides optically active at new wavelengths irrespective of their band gap
- ISB wavelength depends on the electric field (voltage tunable)
- Shortest wavelength is limited by the band discontinuity
- Large CB offset ~1.75 eV GaN/AlN ➔ ISB transition at 1.3 - 1.55 µm
- But large effective mass ($m^* = 0.22m_0$) ➔ Narrow QWs are required



Large quantum well



Narrow quantum well

Intersubband selection rules

Wavefunction $$F(r) = \sum_n \Psi_n(r)\, u_{n,k_0}(r)$$

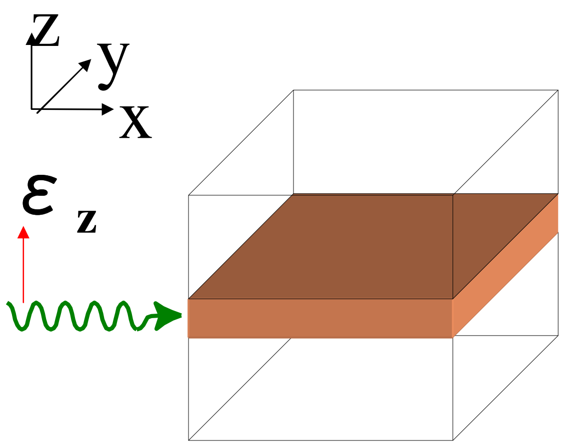
envelope function
slowly varying component

periodic part of the Bloch function
rapidly varying component

- Optical matrix element

light polarization vector

$$\underbrace{\langle u_f | \vec{\varepsilon}.\vec{p} | u_i \rangle \langle \Psi_f | \Psi_i \rangle}_{\text{Interband term}} + \underbrace{\langle \Psi_f | \vec{\varepsilon}.\vec{p} | \Psi_i \rangle \delta_{if}}_{\text{Intersubband term}}$$



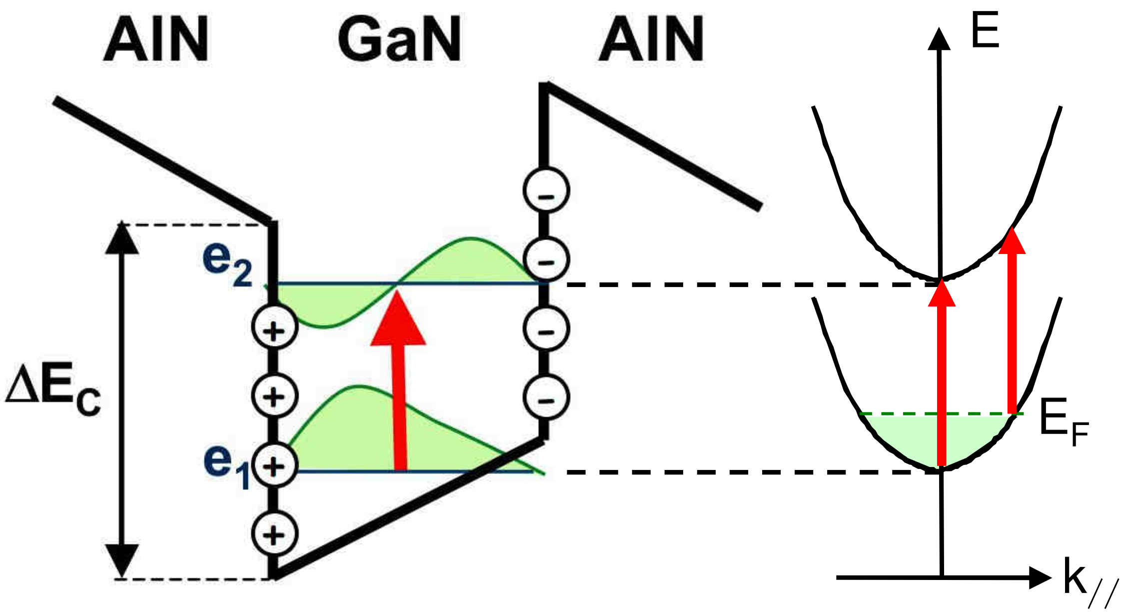
- ISB transition is allowed :
  - if incident light has a polarization component along the confinement direction (TM for QWs)
  - between states with opposite parity of envelope functions : $\Delta n = \pm 1, \pm 3$, etc.
  - internal field breaks the symmetry ➔ weak transitions for $\Delta n = \pm 2$

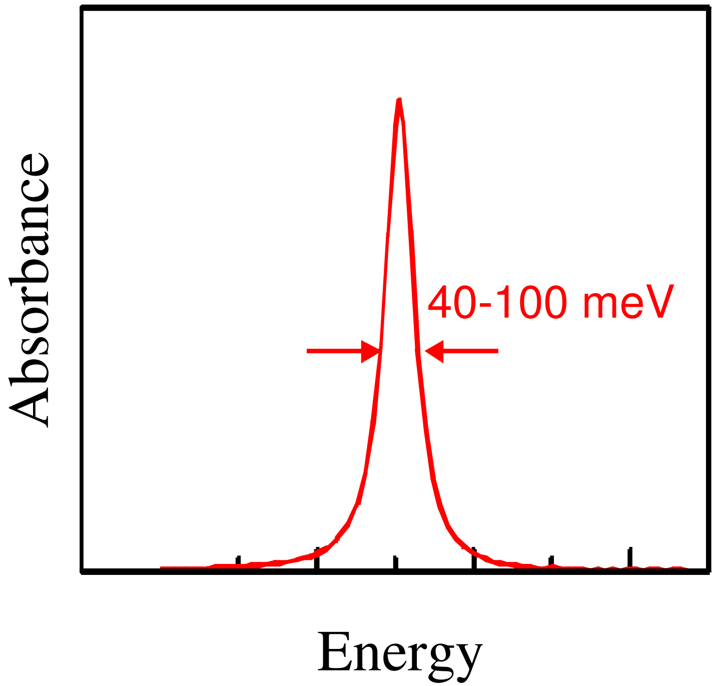
Properties of ISB transitions

- Resonant transitions (Lorenzian or Gaussian lineshape)

- Oscillator strength is large : optical dipole scales like enveloppe wavefunction extension $\vec{\mu}_{if} = e\left\langle \Psi_f \middle| \vec{\varepsilon}.\vec{r} \middle| \Psi_i \right\rangle$, for GaN/AlN QW $\mu_{12} \approx 0.25 eL$

- Absorption is controlled by doping, no absorption for undoped structure

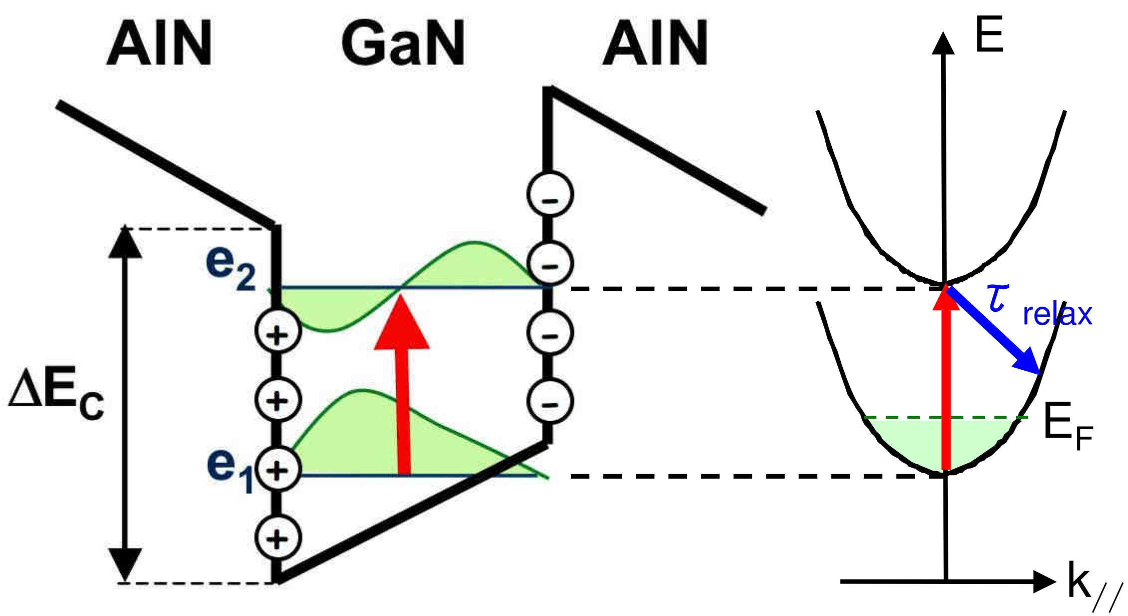




Specific properties of ISB transitions in nitrides

- Enhanced electron-LO phonon interaction in nitrides
- Very short absorption recovery time (0.15-0.4 ps)

➔ Prospects for ultra-fast ISB devices



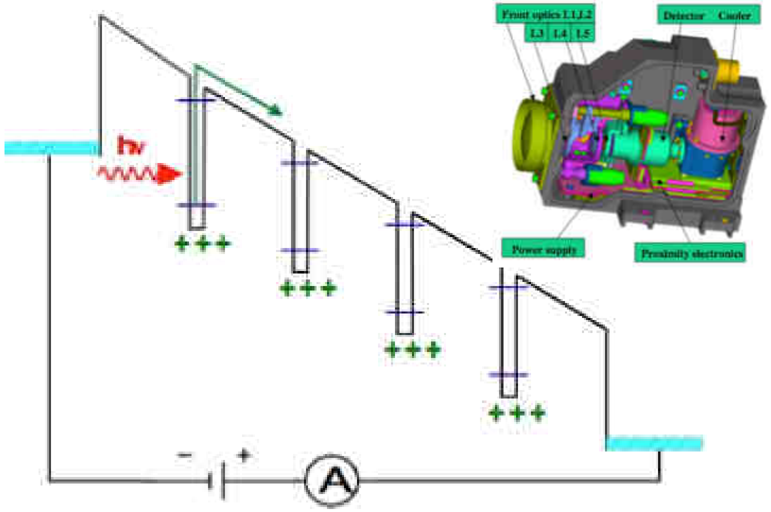
Other features

- Remote lateral valleys (>2eV)
- Large LO-phonon energy: 92 meV
- Low dielectric constant

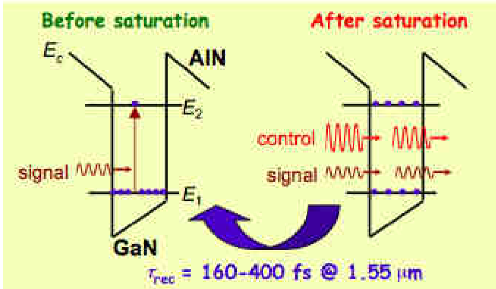
Comparison between intersubband and interband transitions in GaN/AlN QWs

	Intersubband	**Interband**
Spectral range	Near-to-far IR	VIS – to - UV
Carriers	unipolar (only electrons)	bipolar (electrons and holes)
Relaxation time	0.15-0.4 ps	0.2 ns up to µs
Temperature dependence	Almost none	Strong redshift : Eg(T) ≈ 70 meV (4K – 300K)
Selection rules Normal incidence	$\Delta n = \pm 1, \pm 3, \ldots$ ε_z (TM) No	$\Delta n = 0$ (neglecting field) $\varepsilon_{x,y}$ for X_A (TE) Yes
Optical dipole	0.25 e L_w	several Å
Lineshape	Resonant	Staircase-like+excitonic resonance
Absorption	Doping required	Doping is not necessary

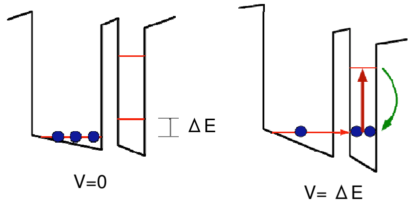
Why intersubband transitions ?
Intersubband control-by-design devices



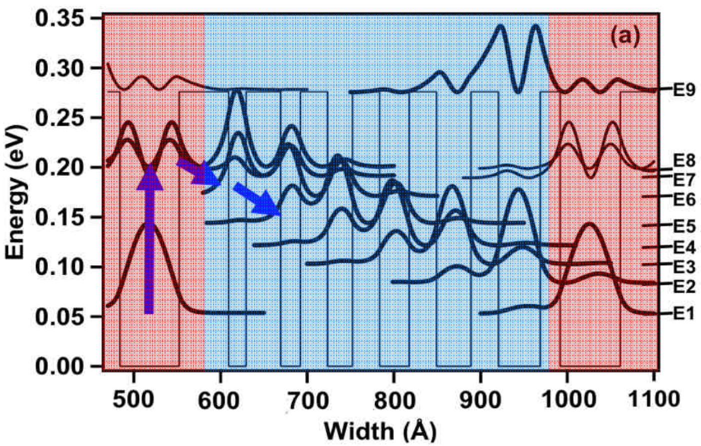
IR detectors (QWIPs or QDIPs)



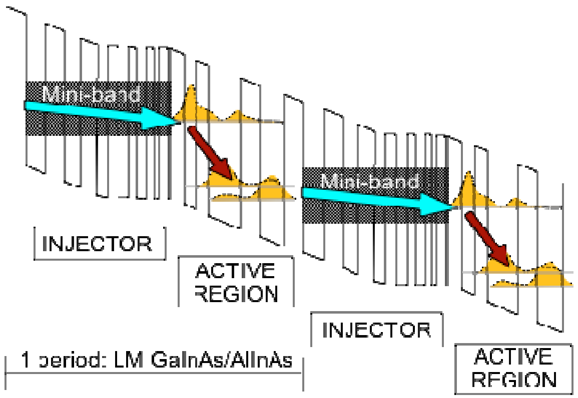
All-optical switches

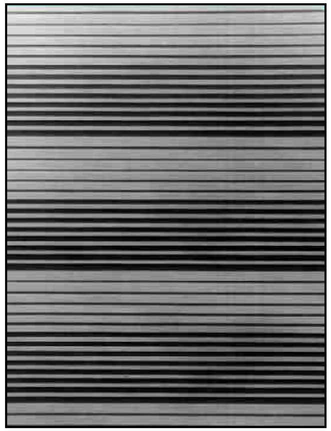


Electro-optical modulators



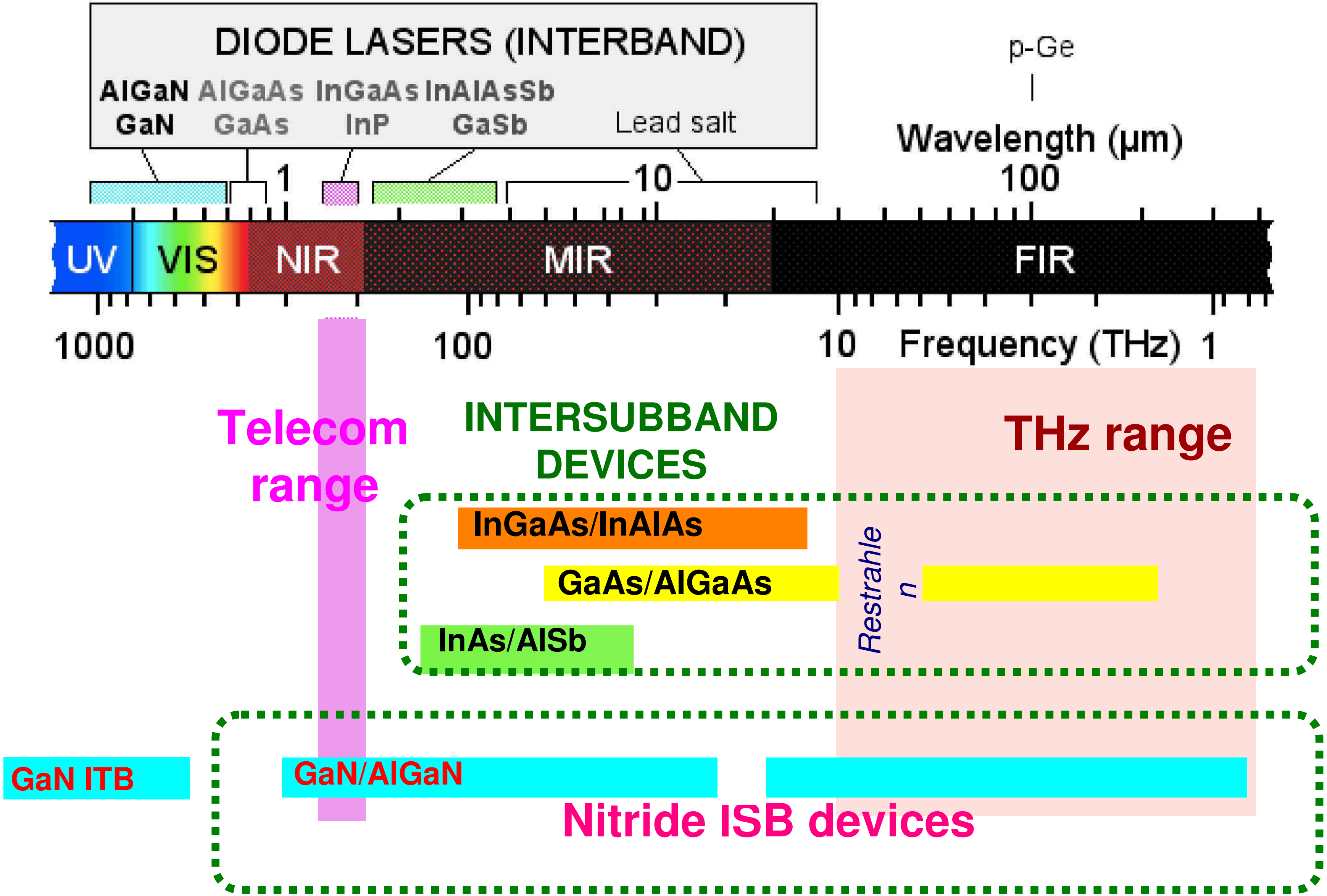
Quantum cascade detectors





Quantum cascade lasers

Spectral domain for intersubband devices

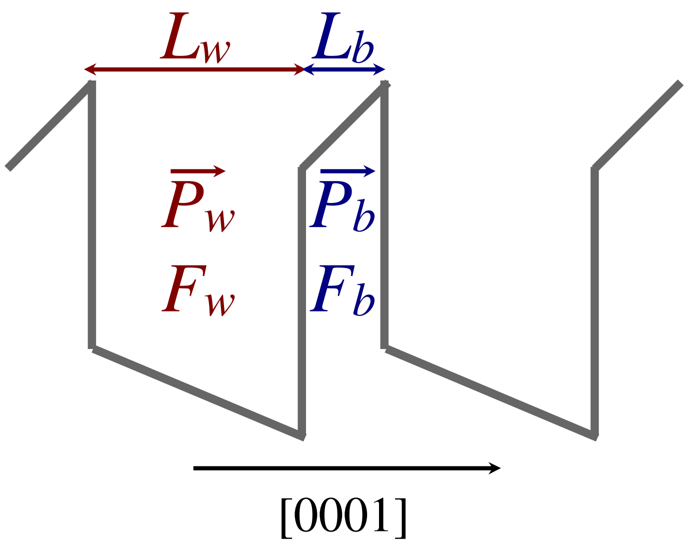


Calculation of the intersubband transition energy

Multiple GaN/AlGaN quantum wells

How to calculate the electric field?

Commonly used hypothesis of a periodic structure : zero potential drop at each period



$$F_w = \frac{P_b - P_w}{\varepsilon_0} \frac{L_b}{L_b \varepsilon_w + L_w \varepsilon_b}$$

$$F_b = -\frac{P_b - P_w}{\varepsilon_0} \frac{L_w}{L_b \varepsilon_w + L_w \varepsilon_b}$$

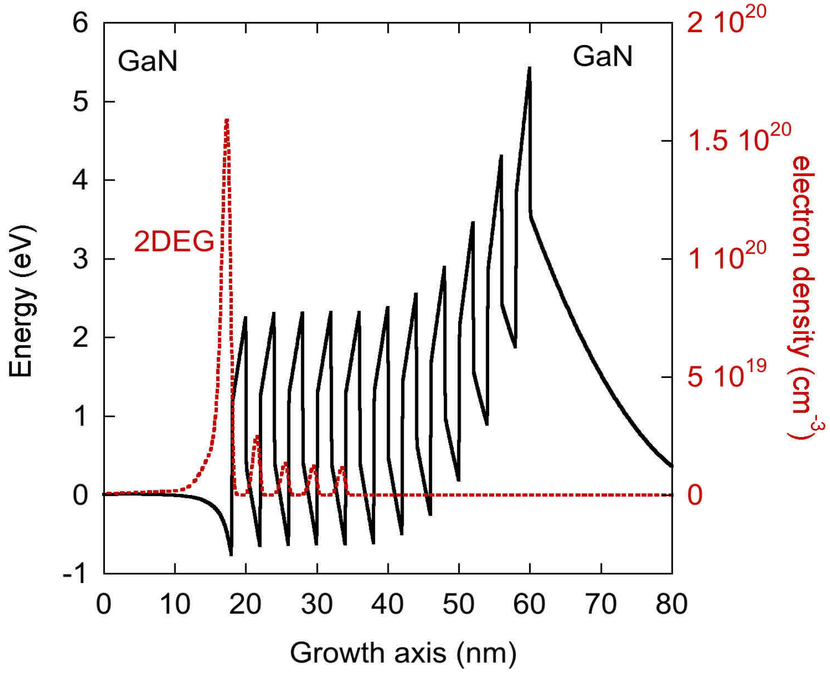
Electric field depends on

- ✓ Aluminium content in the barrier
- ✓ Barrier thickness
- ✓ Well thickness

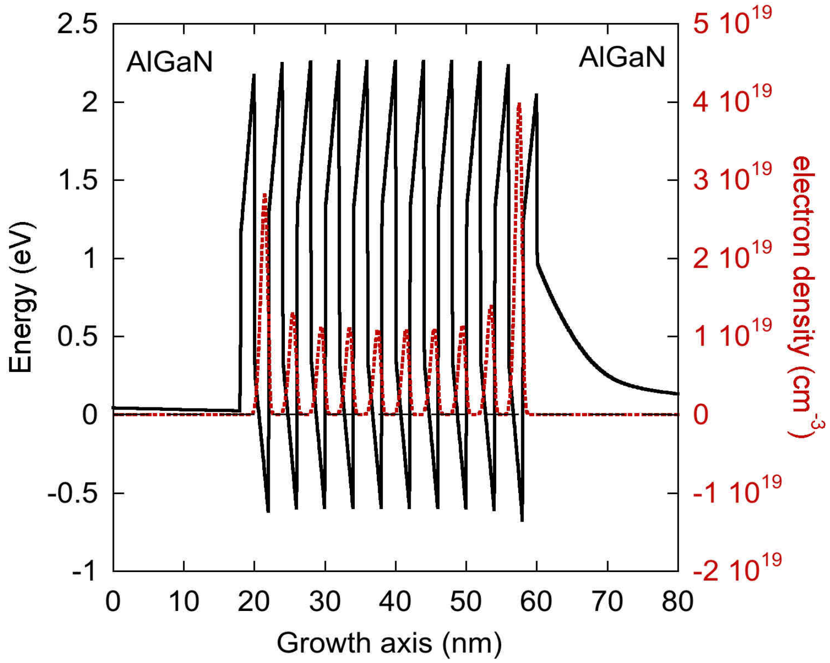
M. Leroux et al., PRB 58, R13371 (1998)

Band bending

GaN/AlN doped QWs between doped GaN claddings



GaN/AlN doped QWs between doped AlGaN claddings



- Depletion region at the upper interface and a 2D electron gas at the lower interface.
- Inhomogeneous carrier concentration

- AlGaN claddings with Al content equal to the average Al concentration
- Homogeneous carrier concentration

Conduction band non-parabolicity

Calculation is restricted to a single GaN/AlN QW

Effective mass approximation

$$\left(-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2}+U_H(z)\right)\Psi(z)=E\Psi(z)$$

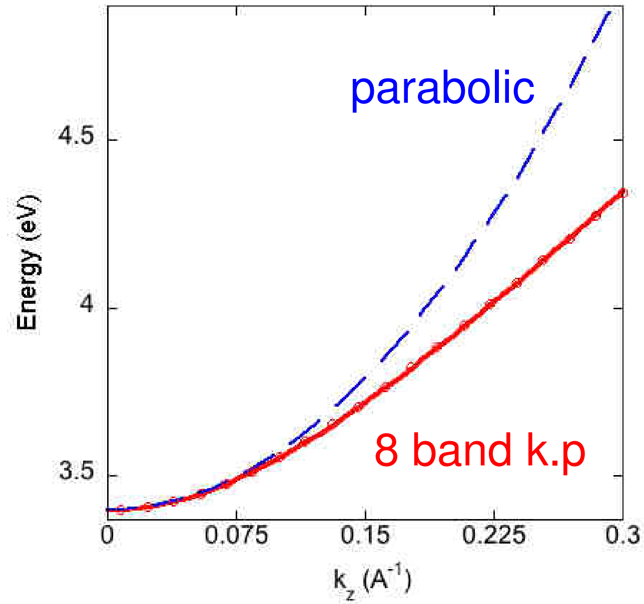
For ISB transition with high e_1-e_2 energy non-parabolicity becomes significant

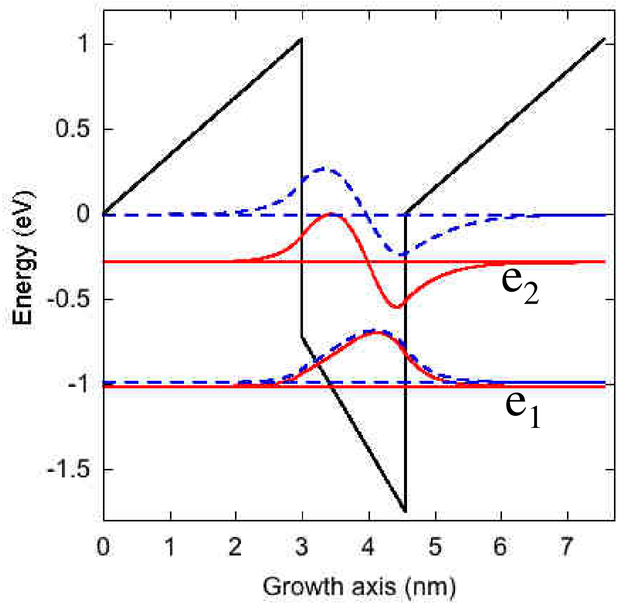
Non-parabolicity of the conduction band is taken into account using energy-dependent effective mass

$$m^*(E)=0.22m_0(1+0.068E+0.003E^2)$$

E – energy from the bottom of the conduction band

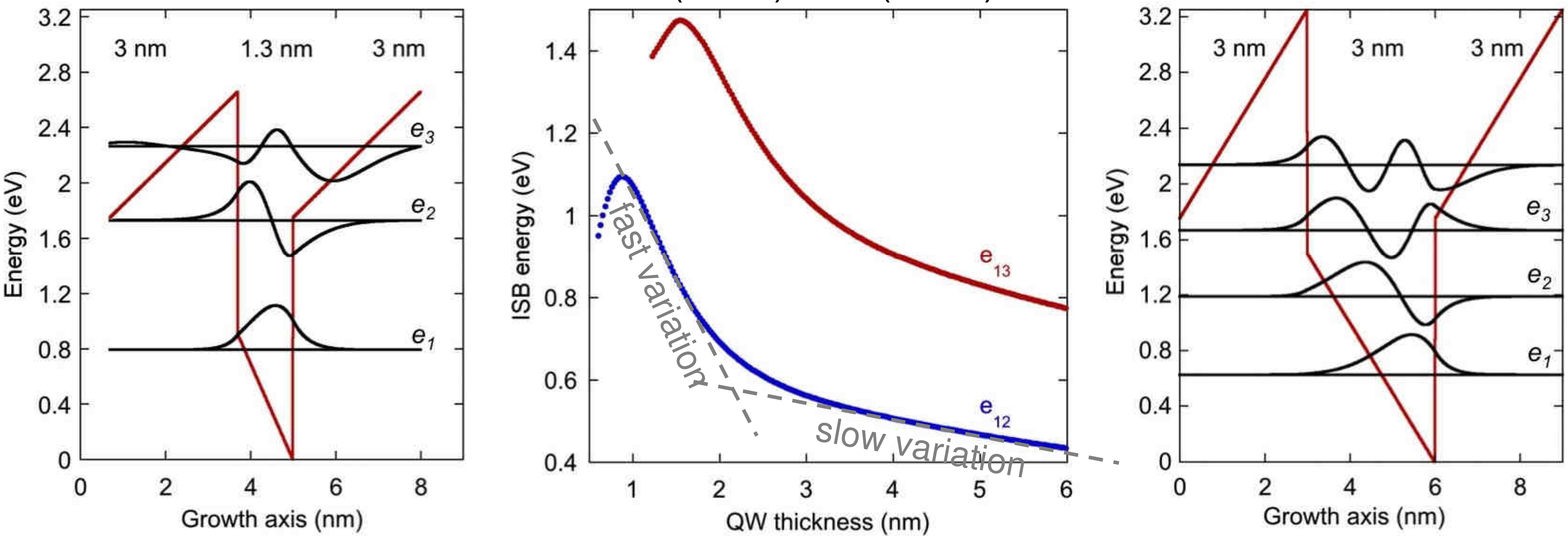
Error for e_1-e_2 energy can reach 25%





Dependence on the QW thickness

GaN (x nm)/AlN (3 nm) QW

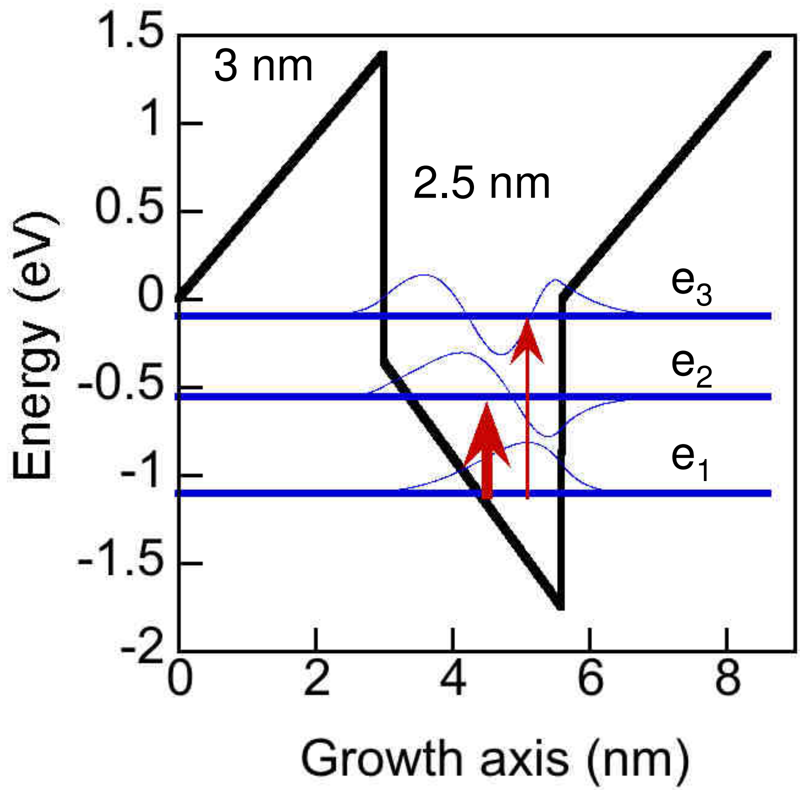


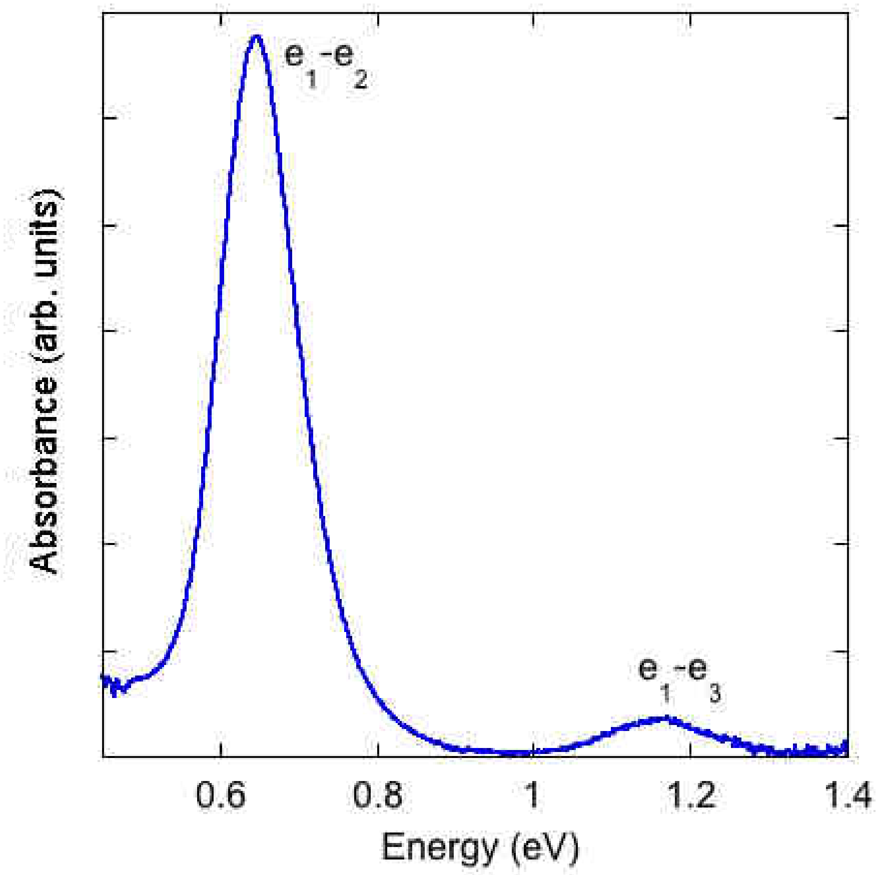
- Confinement by the QW interfaces, transition energy is determined by the well thickness
- Delocalizaion of e_2 state in the barriers for L_w<1 nm
- Confinement by the V-shaped potential, transition energy is determined by the magnitude of the internal field
- "Saturation" of the e_1-e_2 energy at ≈0.4 eV

Simulated ISB absorption spectrum

n-doped GaN/AlN 2.5 nm / 3 nm quantum well

- Strong e_1-e_2 absorption, weak e_1-e_3 absorption (5% of the e_1-e_2 amplitude)
- Absorption magnitude **0.025%** for 1 QW doped at 10^{12} cm^{-2} (2.5×10^{19} cm^{-3}) for 1 pass at 30° angle in GaN





Strongly doped heterostructures

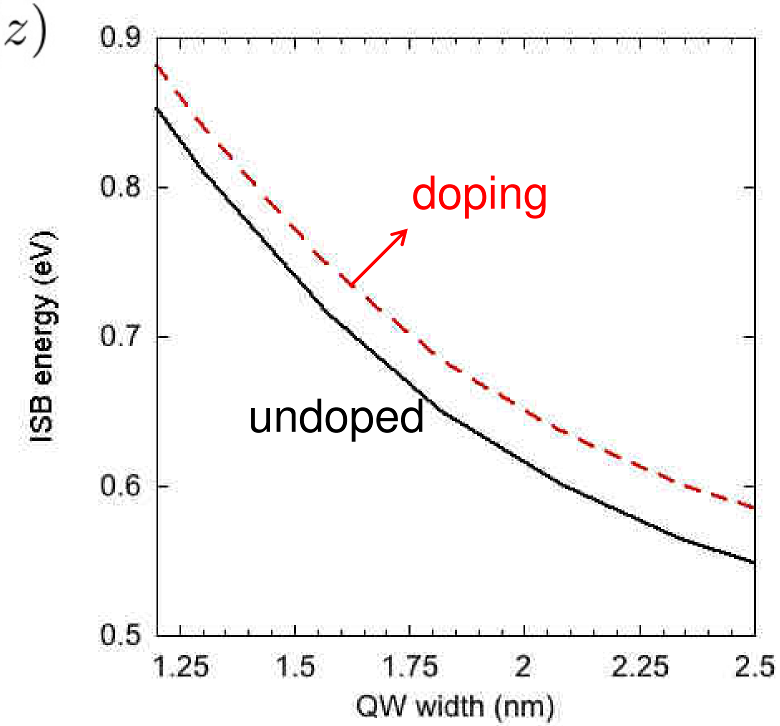
Solution of Schrödinger and Poisson equations

$$\begin{cases} \left(-\frac{\hbar^2}{2m^*}\frac{d^2}{dz^2} + U_H(z) + U_{SC}(z)\right)\Psi_i(z) = E_i\Psi_i(z) \\ \frac{d^2}{dz^2}U_{SC}(z) = \frac{e^2}{\varepsilon}(N_D^+(z) - \sum_i n_i^S|\Psi_i(z)|^2) \end{cases}$$

with surface carrier density

$$n_i^S = \frac{m^* kT}{\pi\hbar^2}\ln(1+\exp(\frac{E_F - E_i}{kT}))$$

Typical carrier concentration 10^{12} cm^{-2}



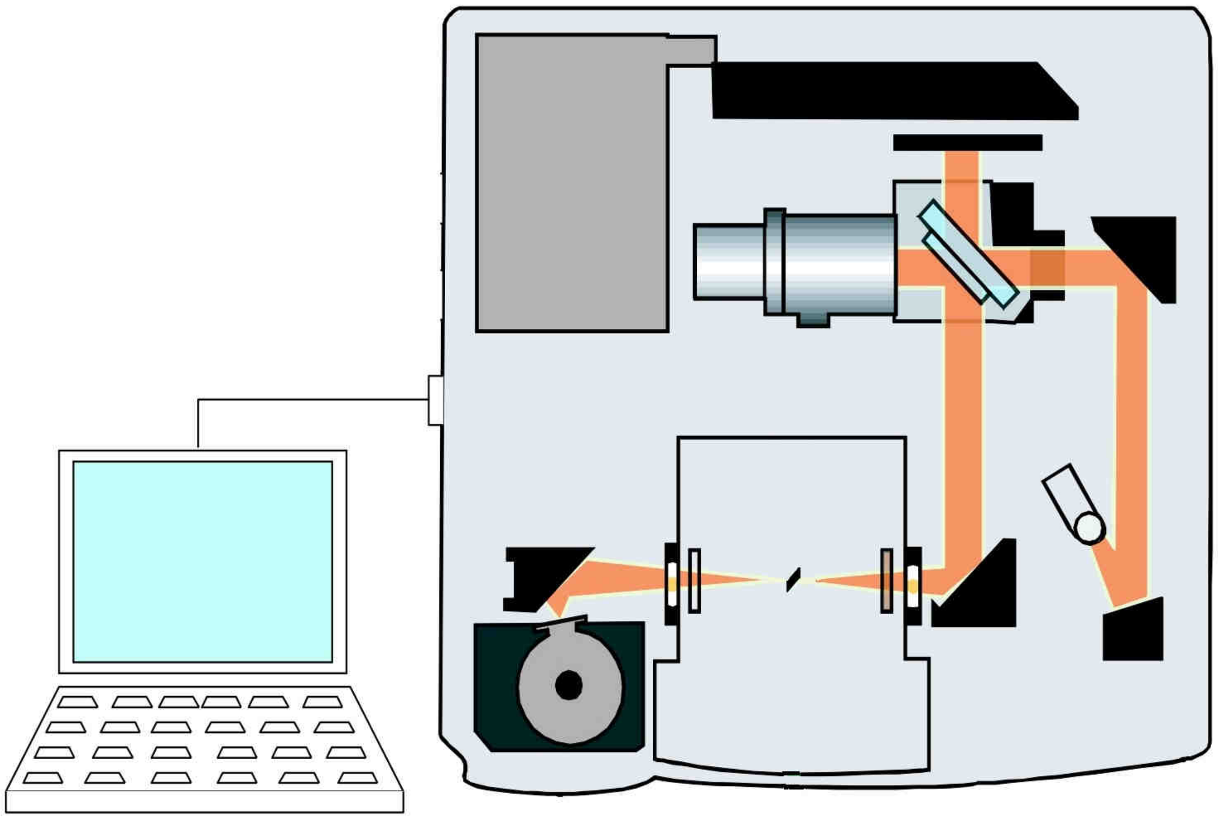
Doping induced effects :
- electric field screening (ISB redshift)
- depolarization shift (ISB blueshift)
- exchange interaction (ISB blueshift)

Resulting effect is a blueshift of the ISB transition with doping

Measurement of the intersubband absorption in GaN/AlN quantum wells and quantum dots

Detecting ISB absorption

- Main tool – Fourier Transform Infrared spectroscopy

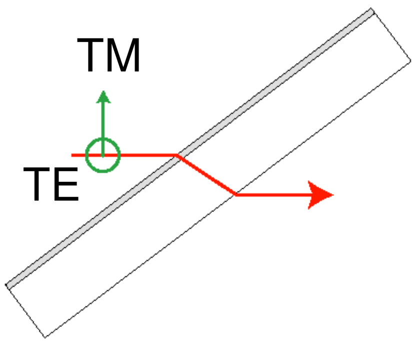


Light coupling geometry

- non-zero ε_z component is required to satisfy polarization selection rules
- For spectroscopy :

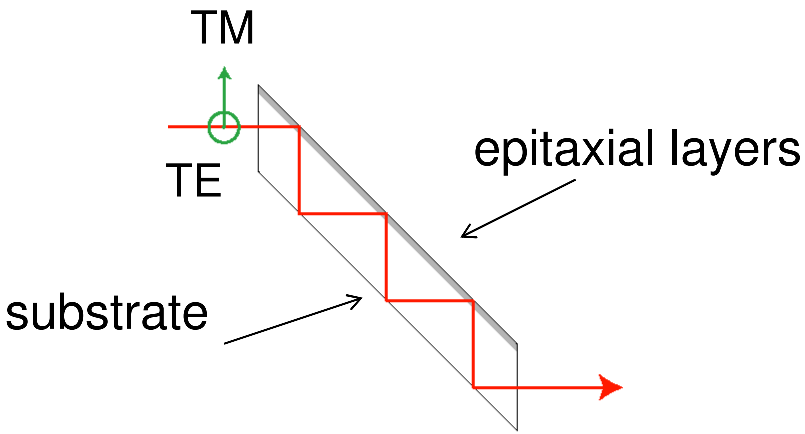
Brewster's angle

67° incidence in air
24° in GaN



Multipass waveguide

45° incidence in sapphire
31° in GaN



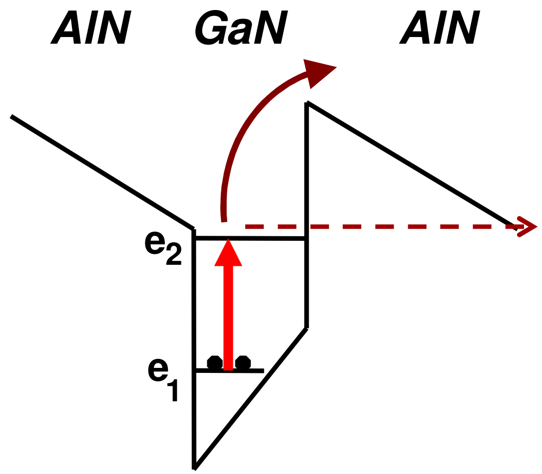
- For devices : waveguide configuration (pure TM) or normal incidence with a top grating (diffraction orders have a TM component)

Detecting ISB absorption

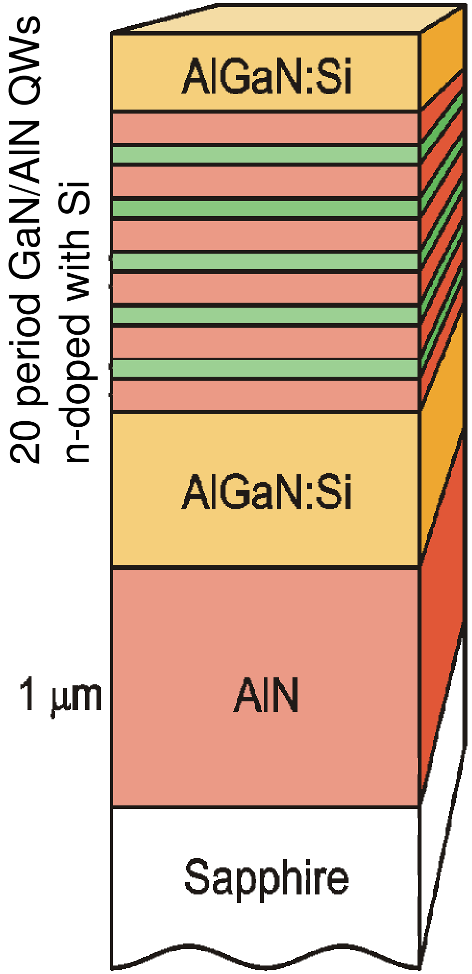
- IR transmission spectroscopy (bound-to-bound transition, possible only in doped samples)

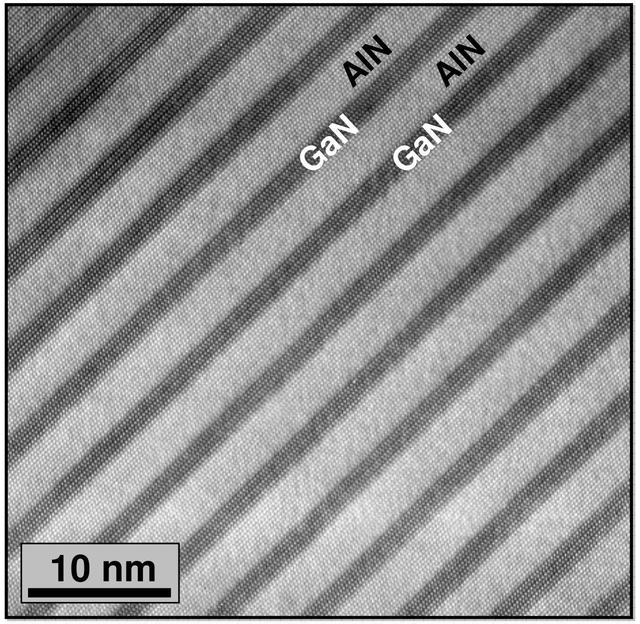
- Photoinduced absorption spectroscopy (bound-to-bound transition, possible in both doped and undoped samples)

- Photocurrent spectroscopy (bound-to-continuum or bound-to-bound transition, possible only in doped samples)



Near infrared spectroscopy of GaN/AlN quantum wells



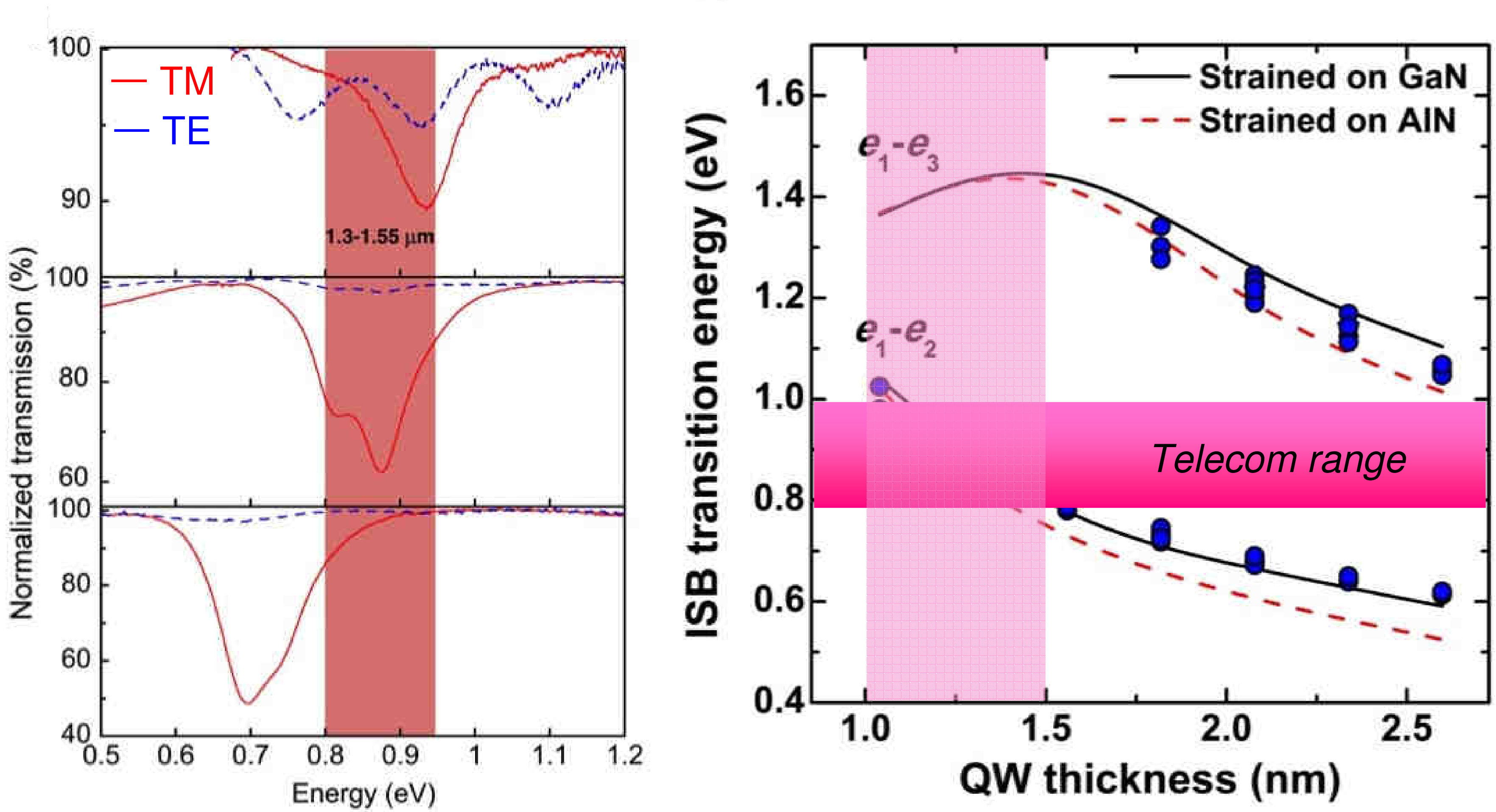


PA-MBE growth, TEM CEA-Grenoble

PA-MBE growth of GaN/AlN quantum wells

- ✓ Metal-rich conditions
- ✓ Low growth temperature (~720° C) to prevent GaN/AlN interaction – abrupt and smooth GaN/AlN interfaces at the monolayer scale
- ✓ Low growth rate for thickness control
- ✓ AlN-on-sapphire substrates: crack-free growth (compressive strain)

Near infrared spectroscopy of GaN/AlN quantum wells



- ISB absorption in 1.3-1.55 µm range for quantum wells with thickness **1-1.5 nm**
- Thickness control down to 1 atomic layer is required – MBE technique

*M. Tchernycheva et al., Phys. Rev. B **73**, 125347 (2006), Kandaswamy et al. JAP, 104, 093501 (2008)*

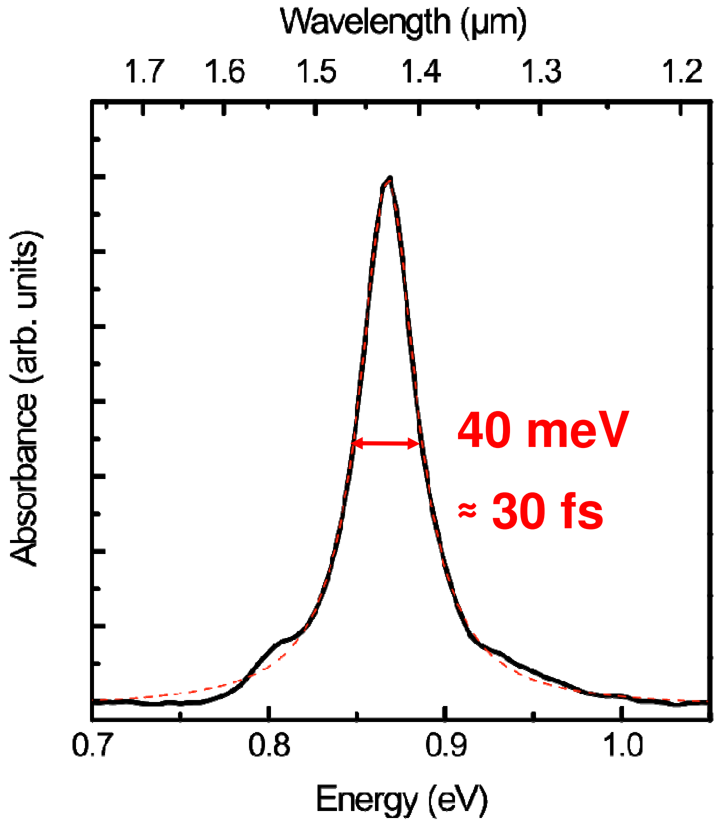
ISB lineshape and broadening in GaN/AlN QWs

- Lorentzian shape or multi-peak lineshape
- Typical ISB broadening at 0.8 eV is 40-70 meV (undoped) or 60-100 meV (doped)
  $\Delta E/E \approx 5\text{-}10\%$
- Homogeneous broadening in a two-level system :

$$\Delta E = 2\hbar/\tau \quad \text{with} \quad \frac{1}{\tau} = \frac{1}{2\tau_1} + \frac{1}{\tau_2}$$

population relaxation

phase relaxation

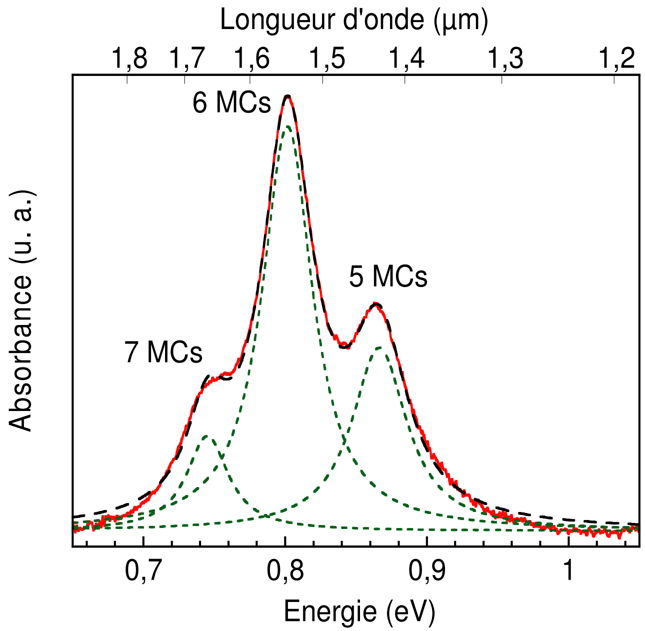


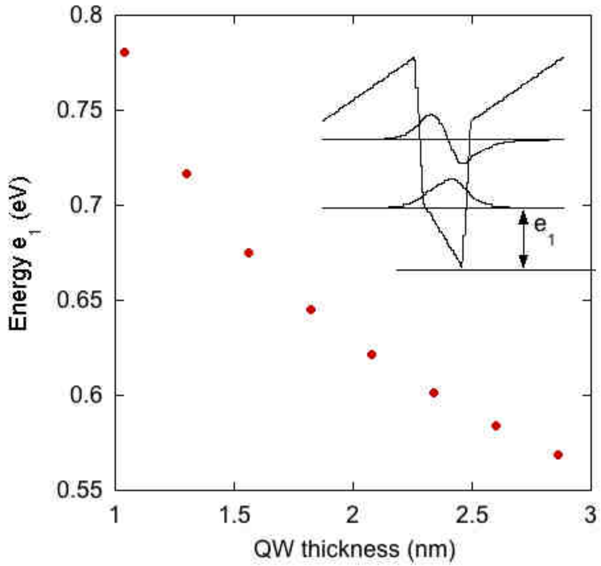
F. Julien et al., PSS 204, 1987 (2007)

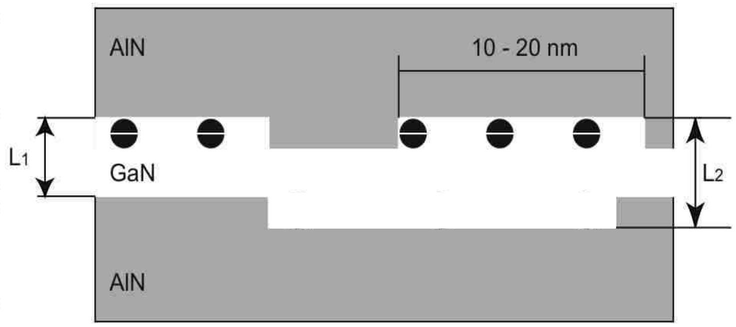
- GaN/AlN QWs intersubband relaxation 0.15-0.4 ps
- Dephasing time is much shorter (tens of fs)
- Processes responsible for relaxation :
  - electron - LO-photon interaction
  - electron-electron interaction (for doped QWs)
  - electron-impurity interaction (for QWs doped above 5×10^{19} cm^{-3})

N. Suzuki, et N. Iizuka, Jpn. J. Appl. Phys. 37, L369 (1998)

Origine of the multi-peak ISB lineshape

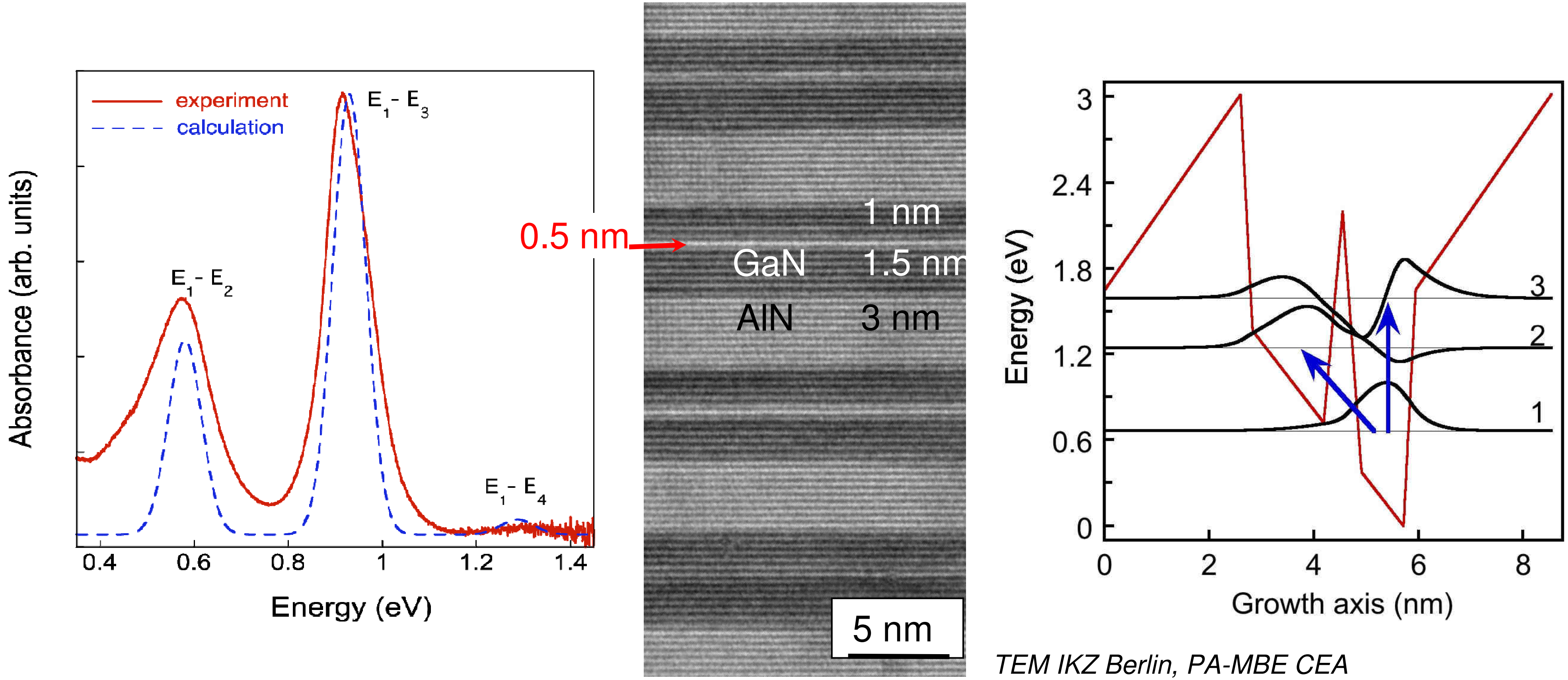






- Narrow QWs (< 2nm) : 1 ML thickness fluctuation induces a large energy shift > 25 meV
- Carrier localization at room temperature
- The peaks correspond to QWs with a well thickness equal to an integer number of monolayers
- Different from GaAs/AlGaAs system, where large QWs are used and the ML fluctuation induces a small spectral shift resulting in an inhomogeneous broadening

ISB transitions in coupled quantum wells

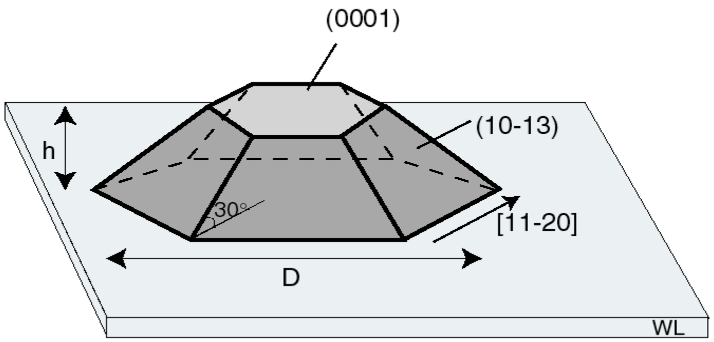


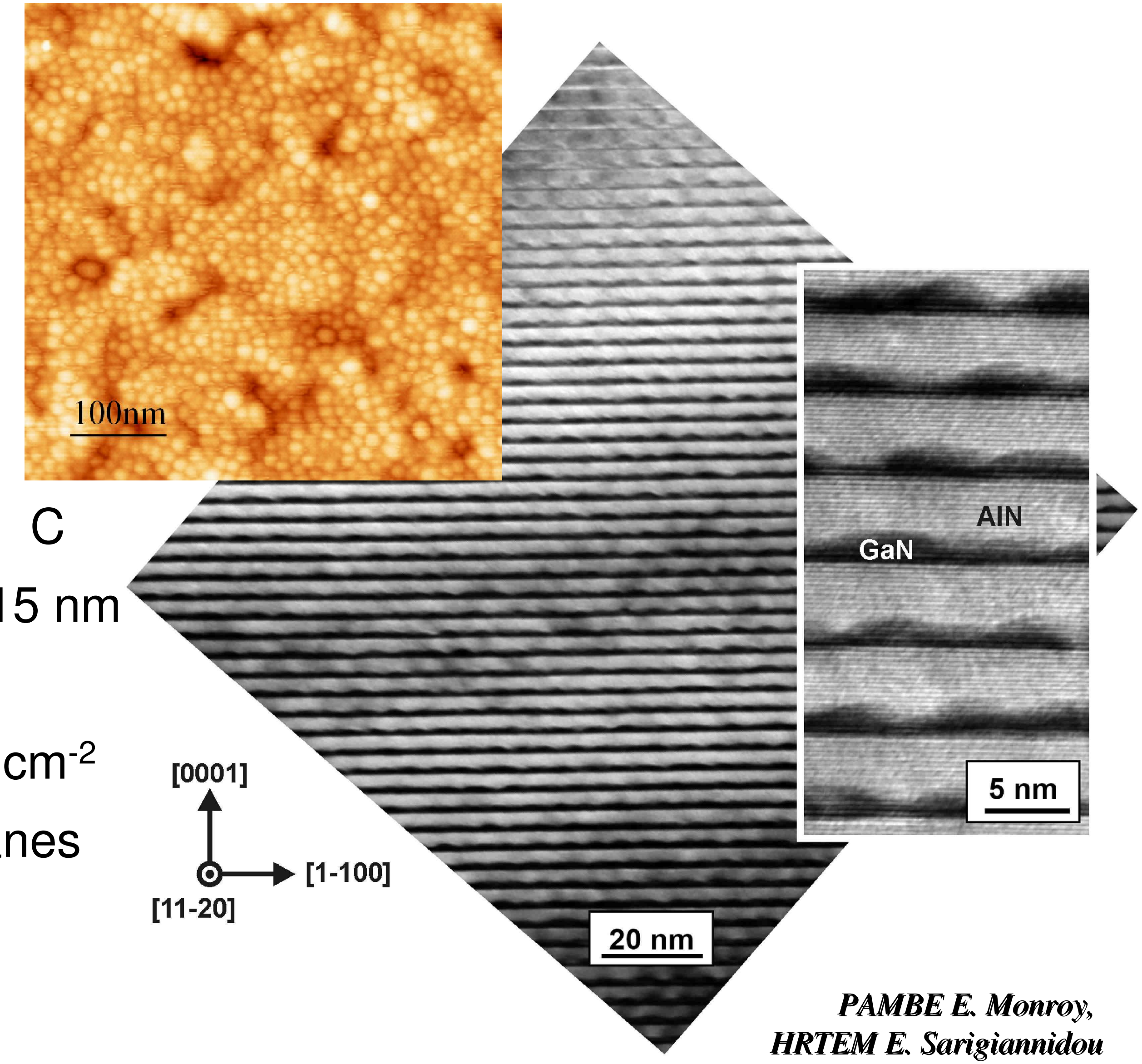
TEM IKZ Berlin, PA-MBE CEA

- Intersubband absorption e_1-e_2 and e_1-e_3 between the ground state and the excited states delocalized in two quantum wells
- Transition energy depends on the applied electric field

M. Tchernycheva et al., APL 88, 153113 (2006)

GaN/AlN quantum dots



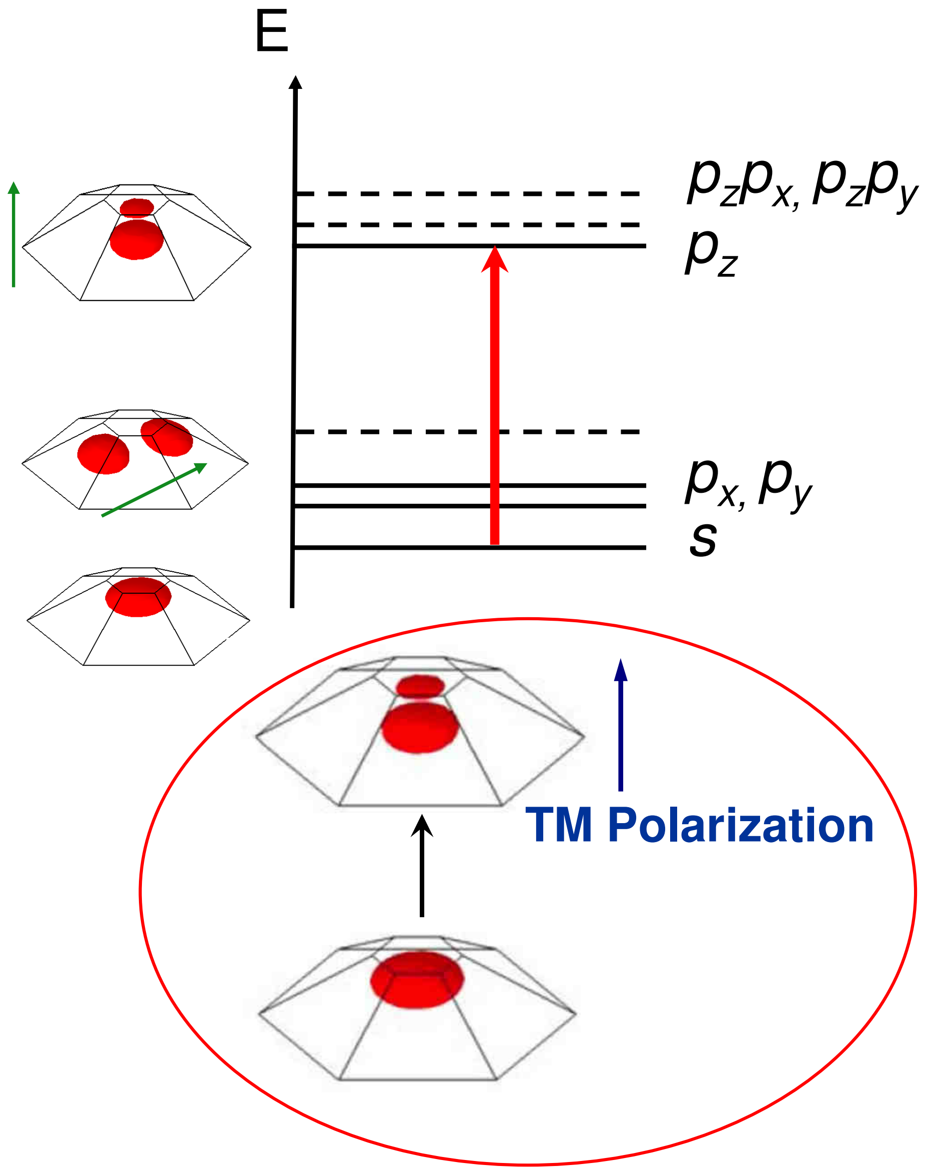


- ✓PA-MBE growth N-rich T= 700° C
- ✓Small QDs h = 1-1.5 nm, d= 6-15 nm
- ✓High Si doping in QDs
- ✓High density up to several 10^{12} cm^{-2}
- ✓ Homogeneous stack of QD planes can be achieved

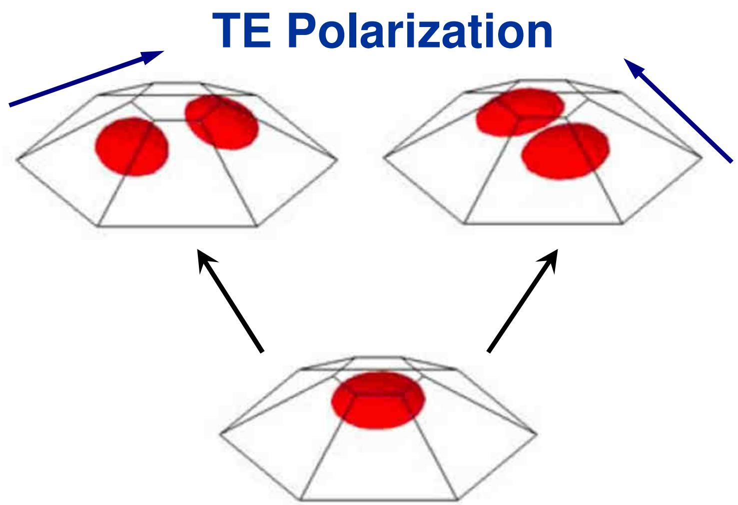
PAMBE E. Monroy,
HRTEM E. Sarigiannidou

F. Guillot et al., JAP 100, 044326 (2006)

Quantum confinement in GaN/AlN QDs

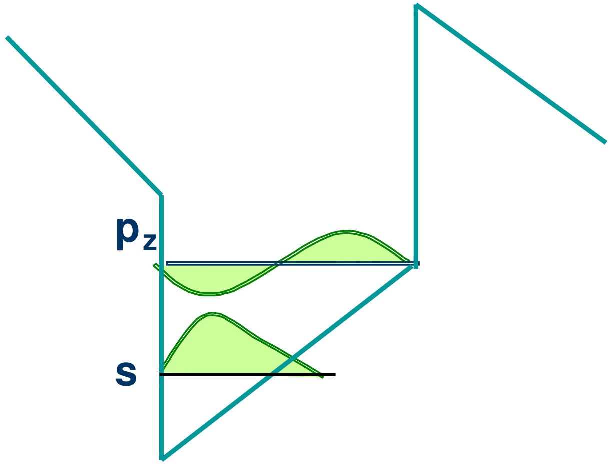


- ✓ Excited state both with in-plane and vertical confinement
- ✓ Strong TM-polarized s-p_z transition in the near-IR



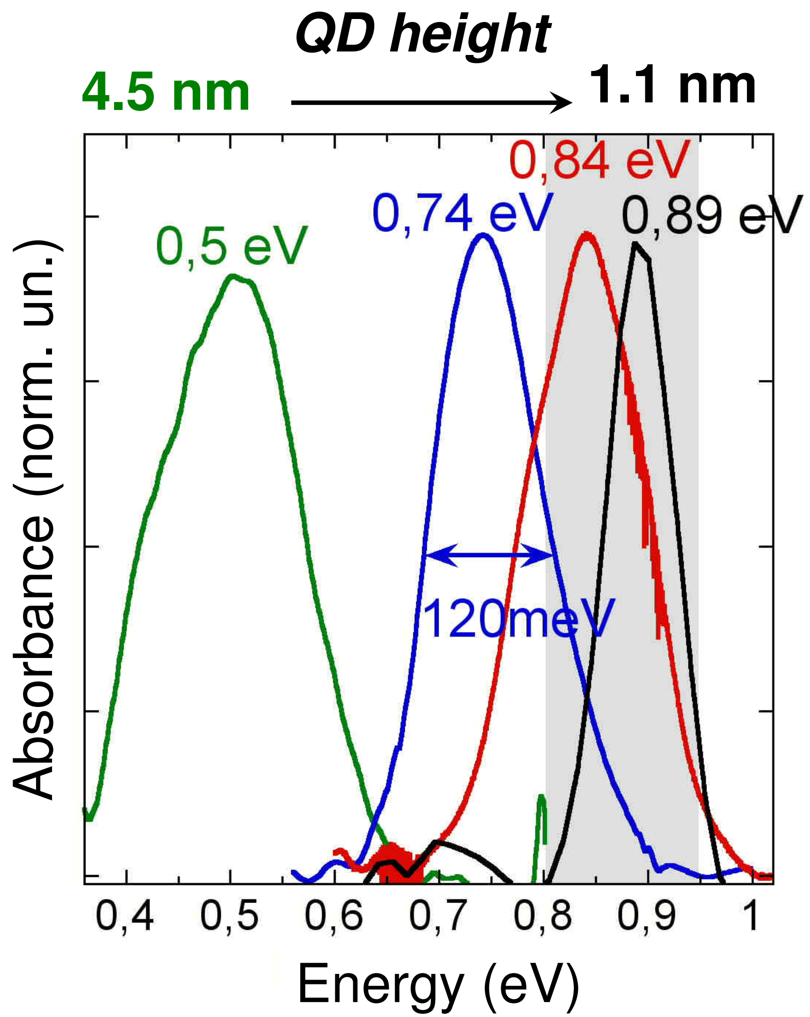
A.D.Andreev et al., Phys. Rev. B 62, 15851, (2000); APL.79, 521 (2001)

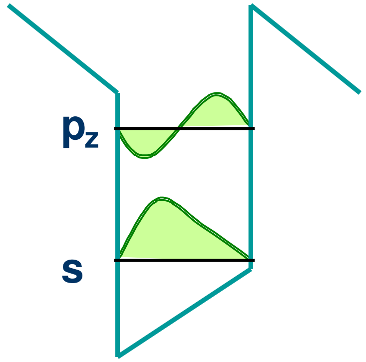
s-p$_z$ intraband transition in GaN QDs



Big QD

Internal electric field





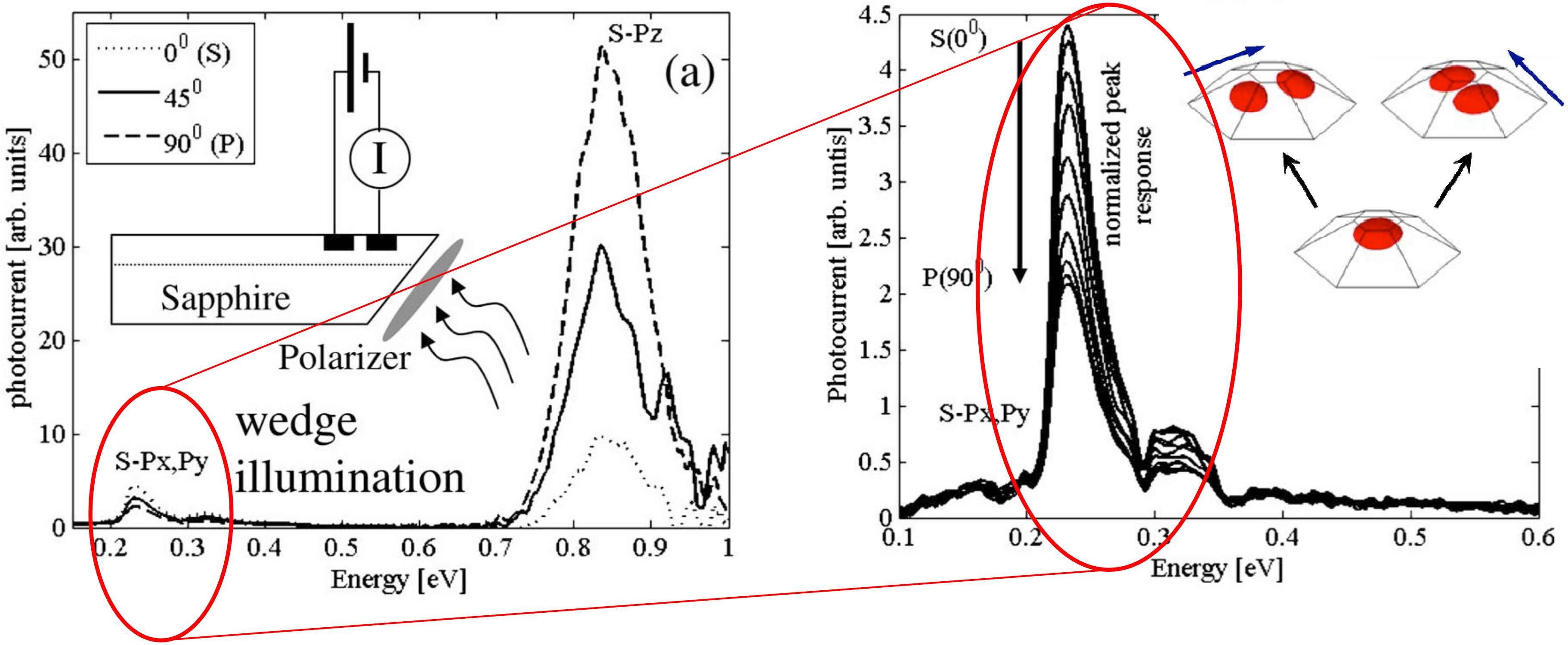
Small QD

QD height

- *s-p$_z$* transition TM-polarized transition is tunable from 2.5 µm to 1.3 µm
- Gaussian lineshape due to the diameter fluctuations

M. Tchernycheva et al., APL 87, 101912 (2005); F. Guillot et al., JAP 100, 044326 (2006)

In-plane intraband transitions in GaN QDs



- Photocurrent measurement to probe in-plane s-p_x and s-p_y transitions
- s-p_x and s-p_y TE-polarized transitions are detected at 0.15 - 0.25 eV depending on the dot diameter (10-16 nm)

A. Vardi et al., PRB 80, 155439 (2009)

Nitride near-IR ISB devices

- ✓ **IR photodetectors**
  - ✓ **Quantum well IR photodetector**
  - ✓ **Quantum cascade detectors**
  - ✓ **Quantum dot IR photodetector**
- ✓ Modulators
- ✓ Light emitters

Photodetectors: D. Hofstetter et al. APL 2006; Vardi et al. APL 2008

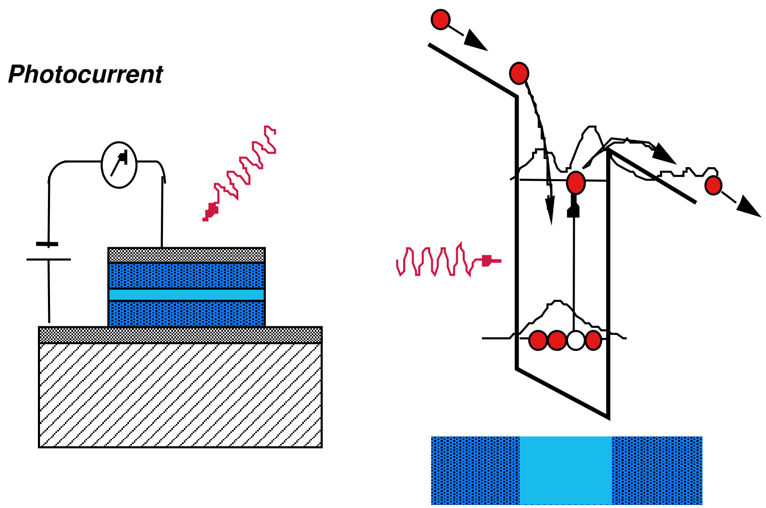
Fast electro-optical modulators: Bauman et al. APL 89, 101121 (2006); Nevou et al. APL 2007; Kheirodin et al. IEEE PTL 2008, Lupu et al., Optics Express (2012)

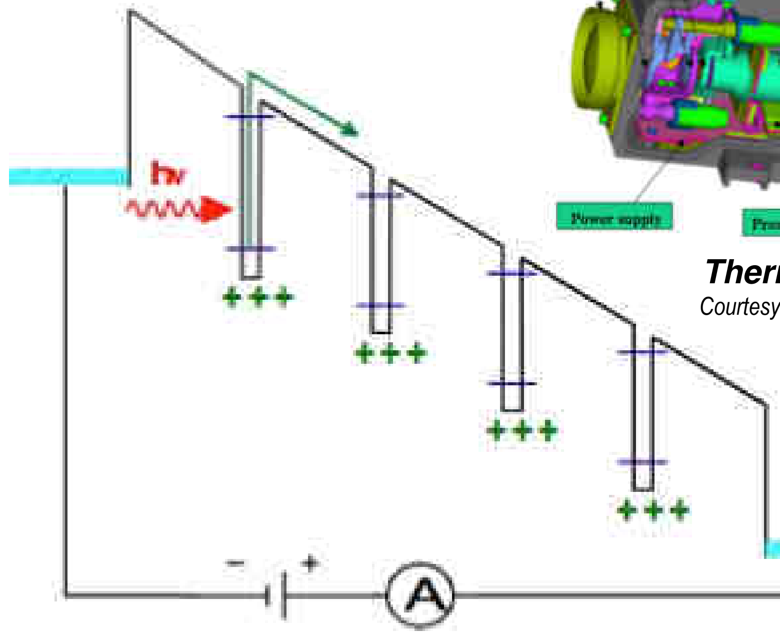
All-optical switches: Iizuka et al., Opt. Expr. 2005; Li et al., Opt. Expr. 2007

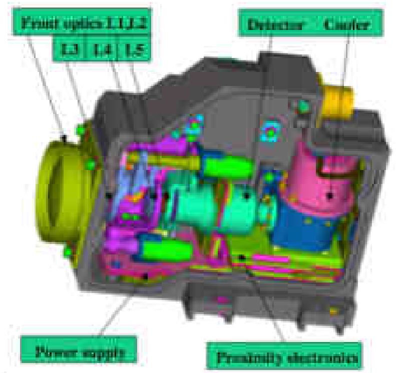
ISB light emission: Nevou et al., Electron. Lett. 2006, APL 2007; Driscoll et al. APL 2009

Quantum well infrared photodetectors

IR photoconductive detectors (QWIPs or QDIPs) in conventional III-V semicoductors (Mid-IR range, thermal imaging)







Thermal imagers

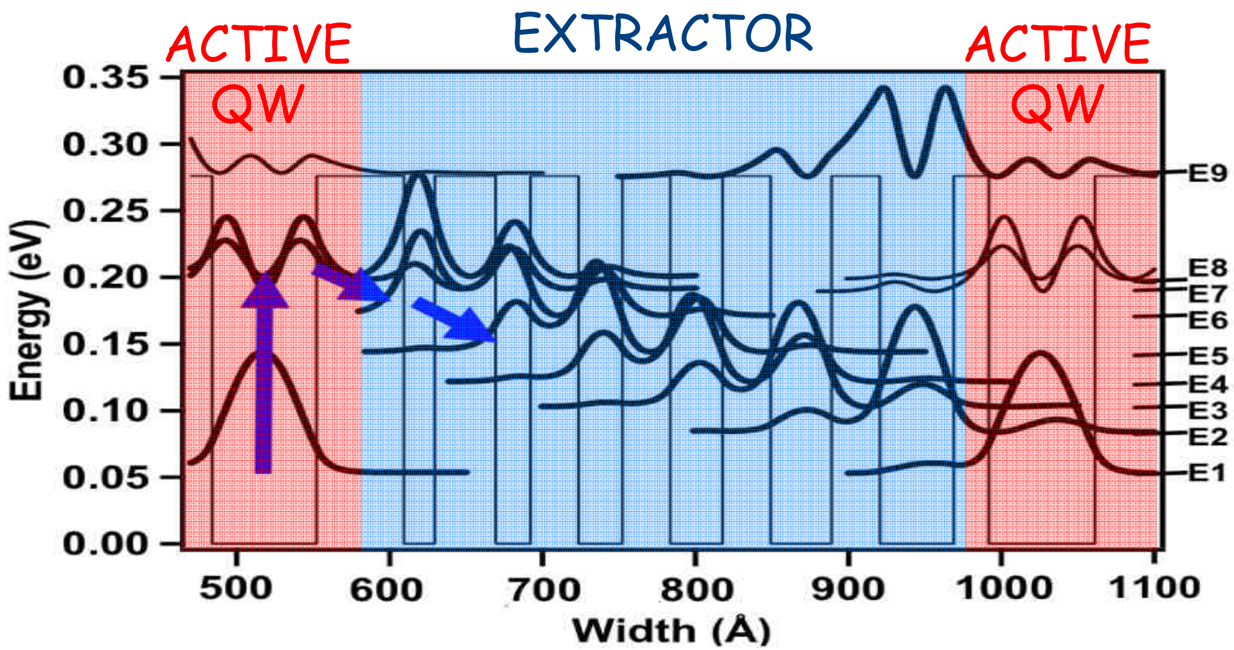
Courtesy P. Bois, Thales R&T

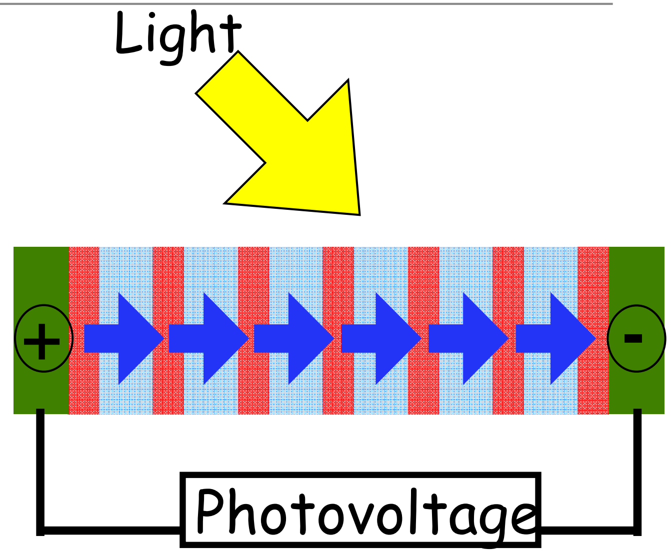
Electron is promoted to the excited state, tunnel to the continuum and creates the photocurrent

Commercial devices used for IR imaging

Levine et al., APL 16, 1092 (1987)

Quantum cascade detectors





- ✓QCDs are photovoltaic devices operated at zero bias : **no dark current**
- ✓QCDs rely on ISB absorption in an active QW and LO-phonon-assisted relaxation in an extractor region
- ✓Electron transfer in each period results in a macroscopic photovoltage across the QCD stack
- ✓Potentially extremely fast (low capacitance devices)

L. Gendron et al., APL 85, 2824 (2004)

QWIPs versus QCDs

Photoconductive gain : $g = \frac{\tau_{capture}}{\tau_{transit}}$

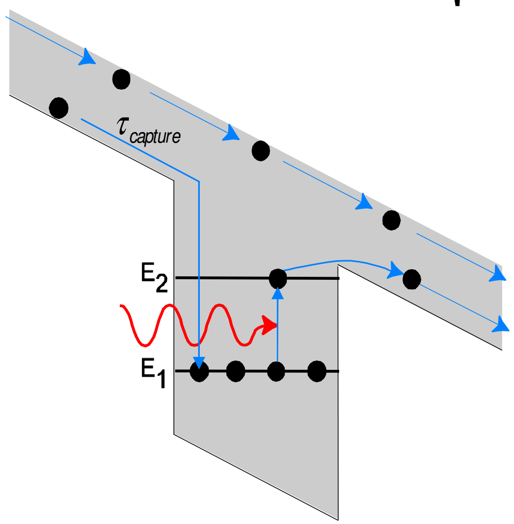
Quantum efficiency : η

Responsivity = e $\frac{\eta g}{h\nu}$

Thermally-limited detectivity :

$$D^* = \frac{\eta}{2h\nu}\sqrt{\frac{\tau_{capture}}{n_t L}}$$

BLIP detectivity : $D^*_{BLIP} = \frac{1}{2}\sqrt{\frac{\eta}{h\nu F_B}}$



Responsivity in A/W independent of number of periods (N):

$$R(\lambda) = a \times \eta \times \frac{1}{E(eV)}$$

a light absorption per period

η electron transfer efficiency per period

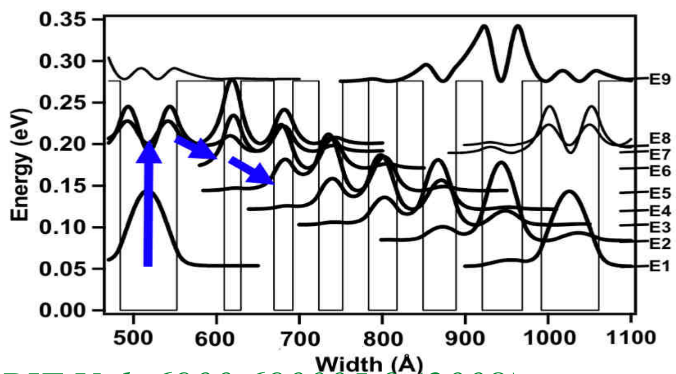
$E(eV)$ ISB transition energy in eV

Photoconductive gain = 1/N (≤ 1)

Detectivity limited by Jonhson noise

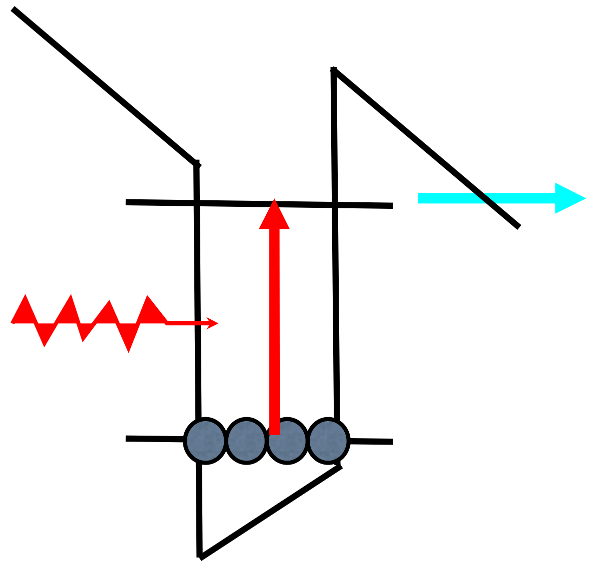
$$D^* = R(\lambda)\sqrt{\frac{R_0 A}{4kT}}$$

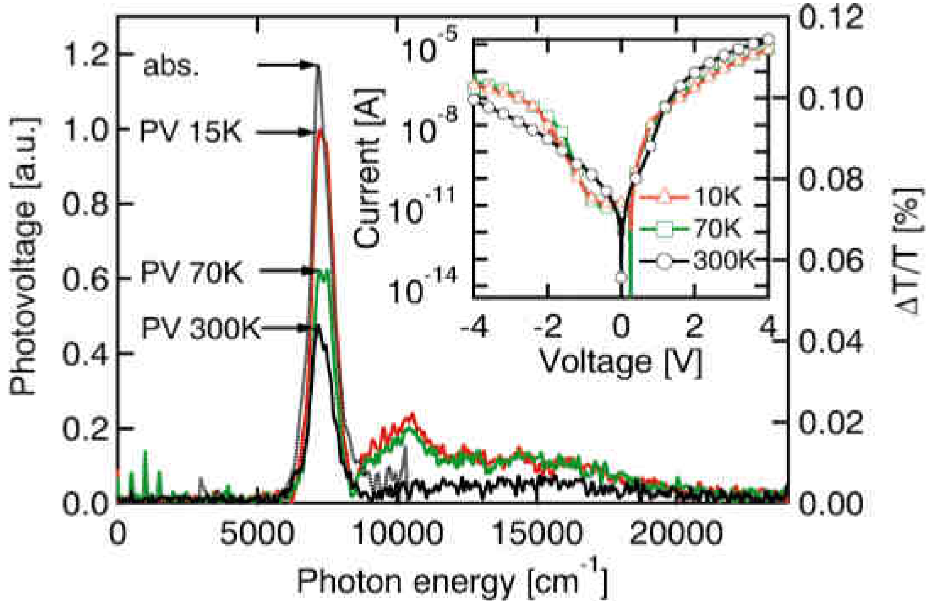
R_0 internal resistance at zero bias, A device area



V. Berger et al., Proc. of SPIE Vol. 6900 69000J-9 (2008)

GaN/AlN QW infrared photodetectors



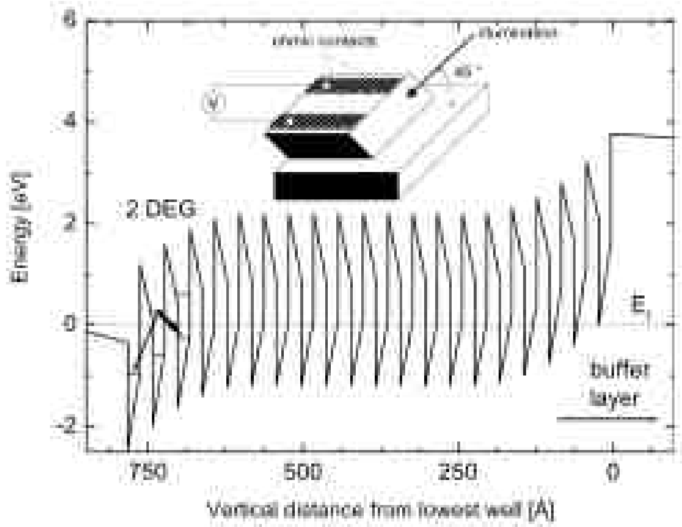


Photoconductive QWIP:

- excess dark current due to dislocations

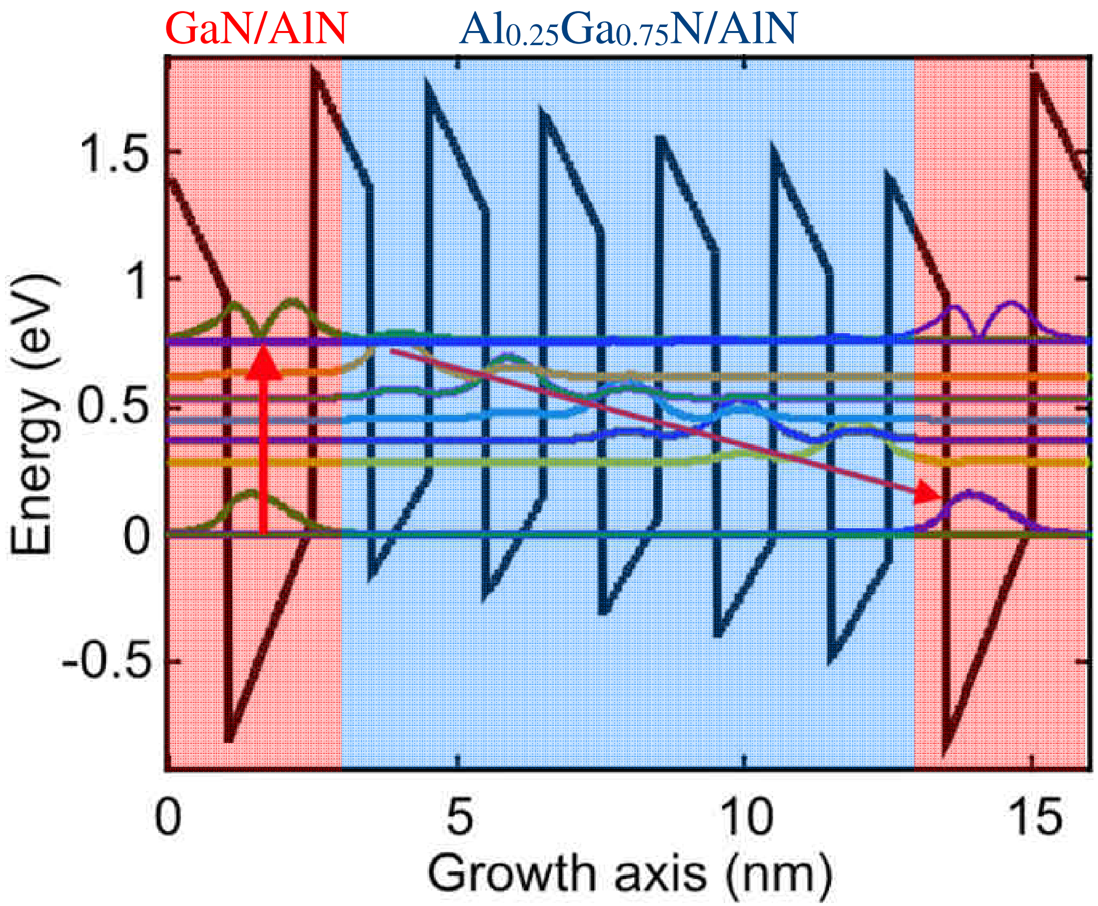
Photovoltaic QWIP :

- Low responsivity (3 mV/W @ 150 K)



Hoffstetter et al. APL 88, 121112 (2006)

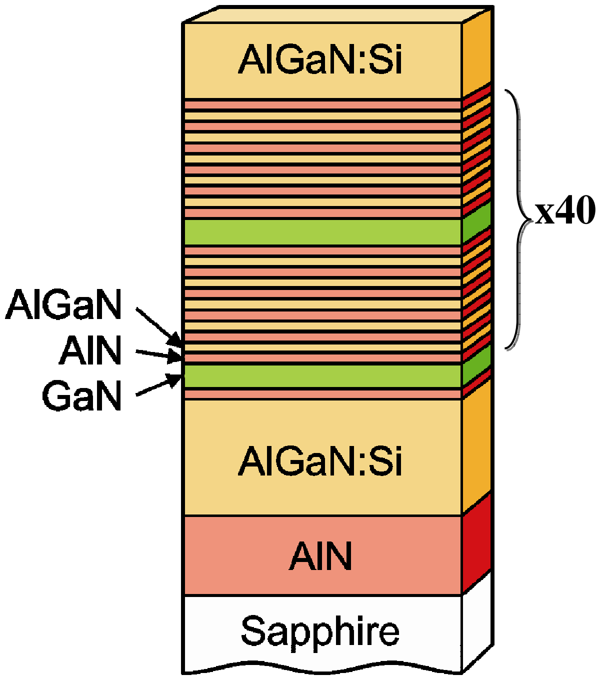
The GaN/AlGaN quantum cascade detector

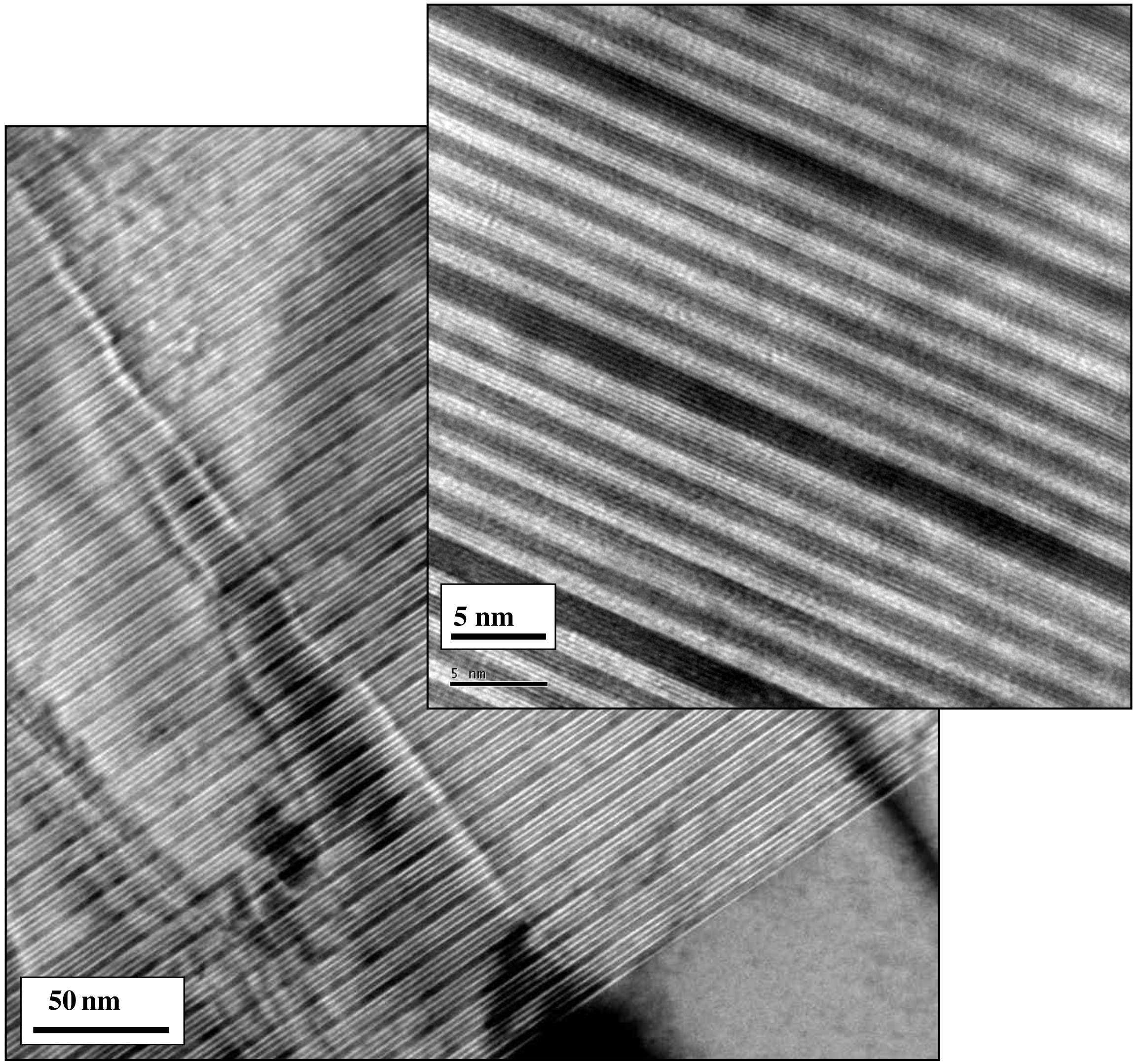


- ✓Design making use of spontaneous/piezoelectric polarization
- ✓Active QW: 1.5 nm thick (6 ML) GaN/AlN QW
- ✓Extractor region: 4 ML thick $Al_{0.25}Ga_{0.75}N$/4 ML thick AlN multiple QWs

A. Vardi et al., APL ***92****, 011112 (2008)*

Nitride quantum cascade detector – sample structure



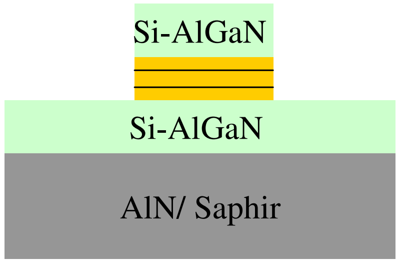


- ✓ Cascade structure with 40 periods
- ✓ $Al_{0.25}Ga_{0.75}N$ contact layers with $n = 1 \times 10^{19}\ cm^{-3}$

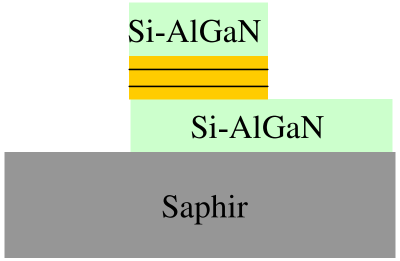
PAMBE E. Monroy, HRTEM E. Sarigiannidou

Device processing

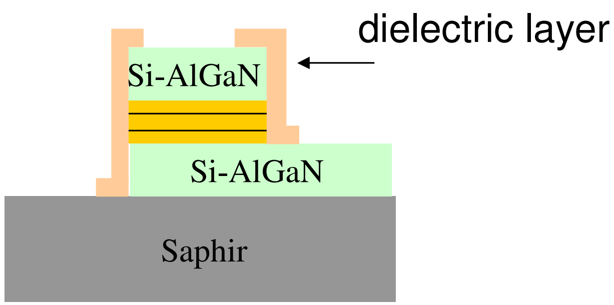
1. ICP mesa etching



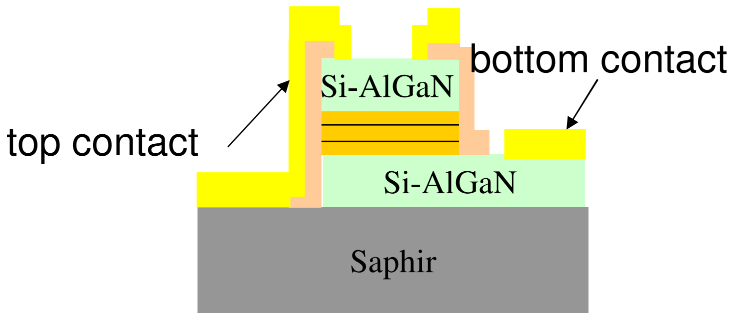
2. Second etching down to sapphire substrate



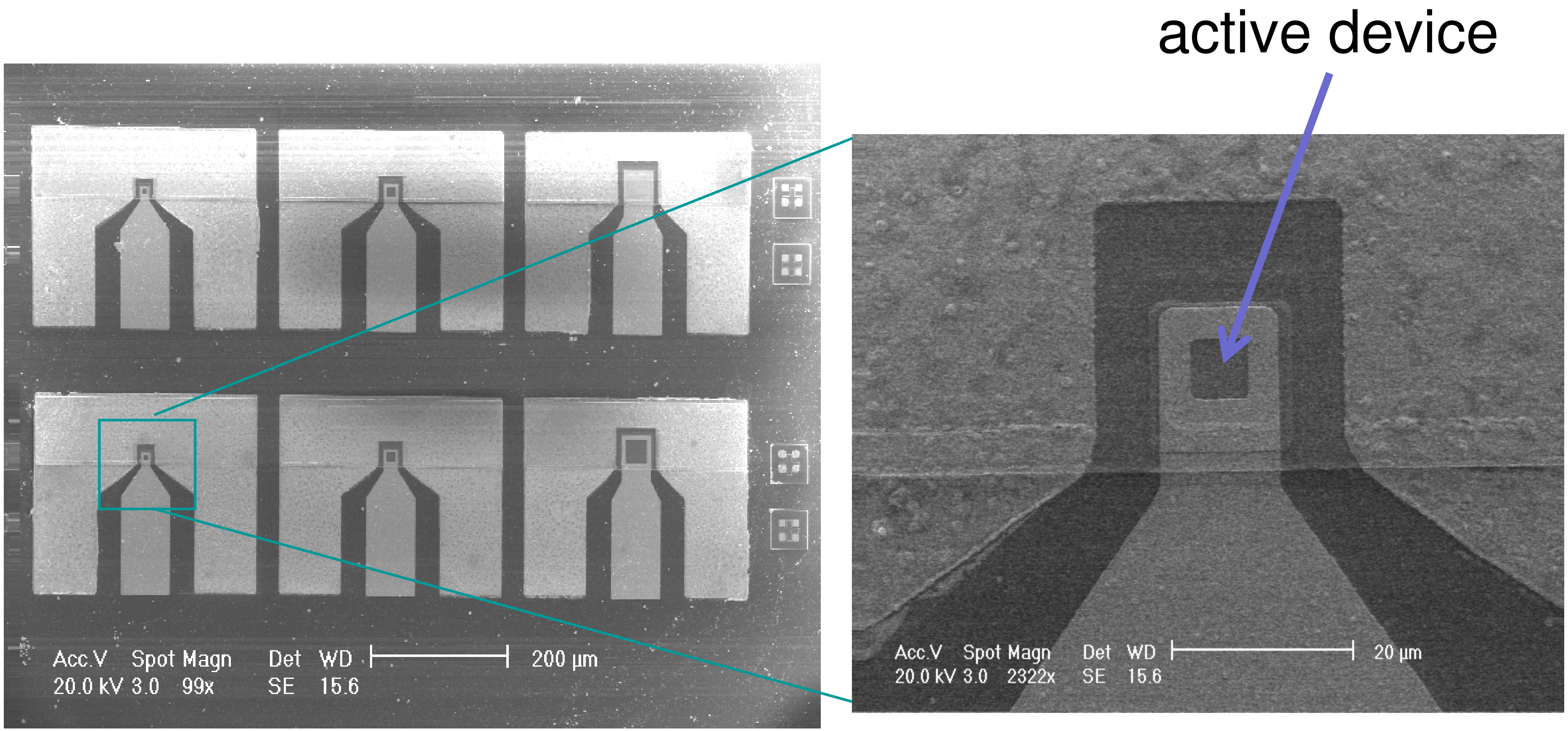
3. Dielectric ensulation



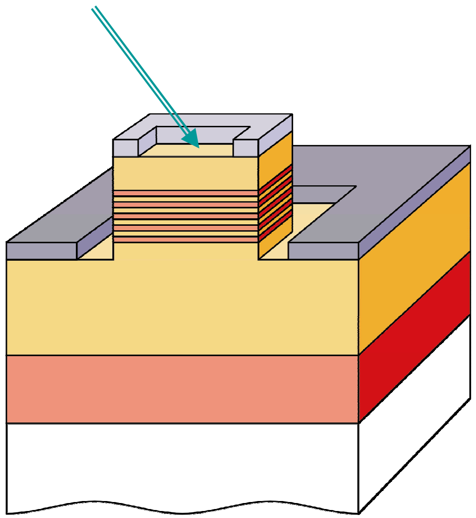
4. Bottom contact deposition + annealling
5. Top contact deposition (no annealing to avoid metal defusion)

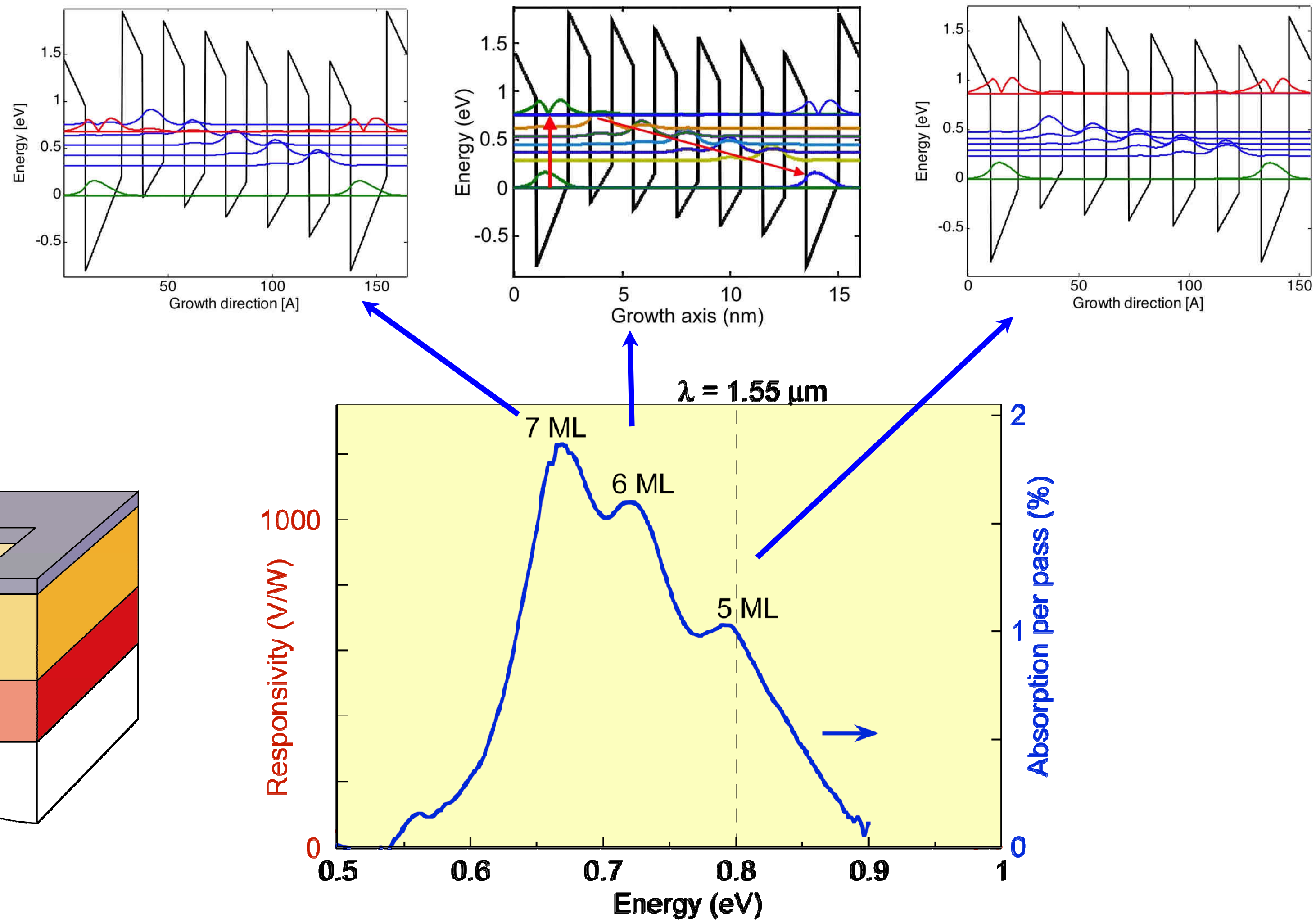


Example of a QCD with RF contact lines



Spectral response

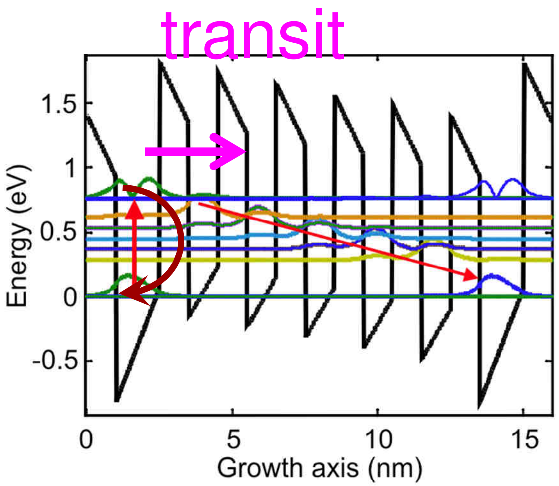


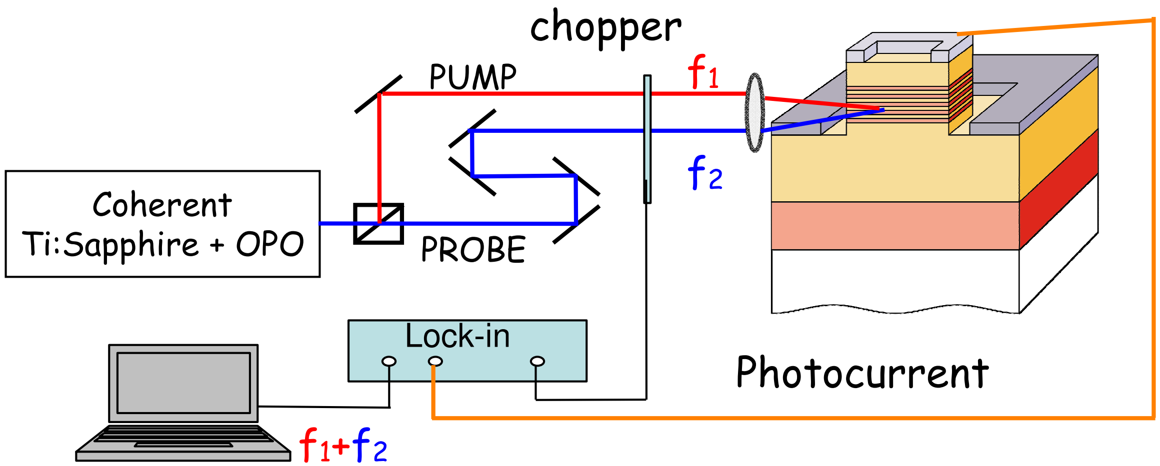


- Peak responsivity at 300 K: 1000 V/W, 10 mA/W
- Internal quantum efficiency: number of electrons per absorbed photons 14%

*A. Vardi et al., APL **92**, 011112 (2008); APL **93**, 193509 (2008)*

Intrinsic speed of GaN QCD



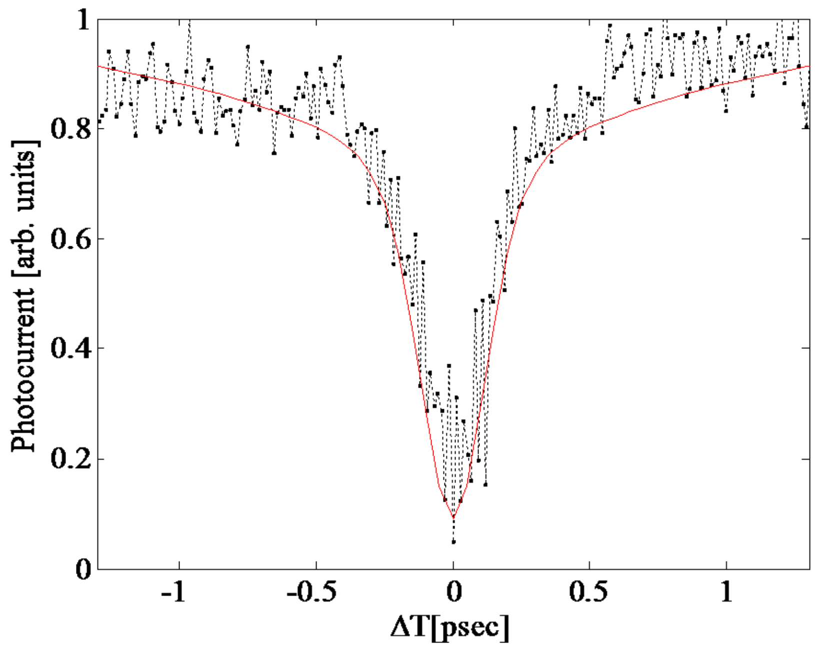


ISB relaxation time

$$R = \eta \times \frac{\tau_{21}}{\tau_{21} + \tau_t} \times \frac{1}{E_{21}}$$

η extraction efficiency

Transit time (tunneling + cascade relaxation)



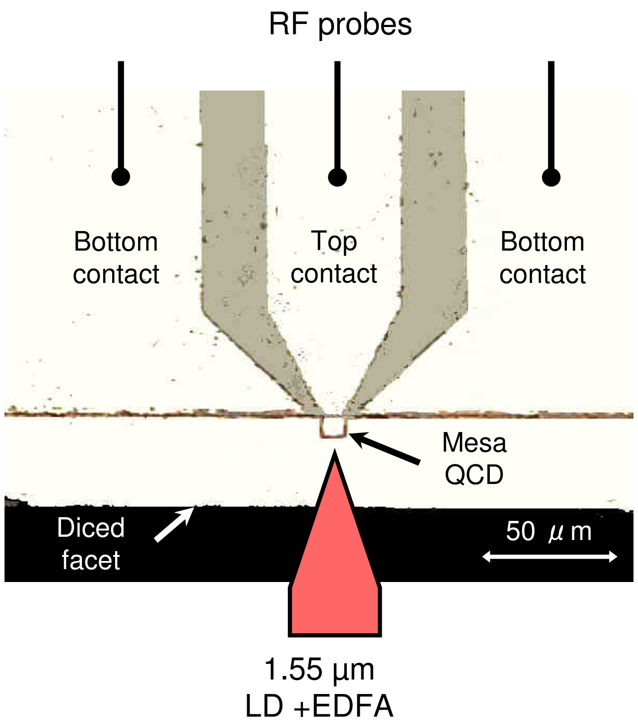
The transit time is the intrinsic speed and response limitation

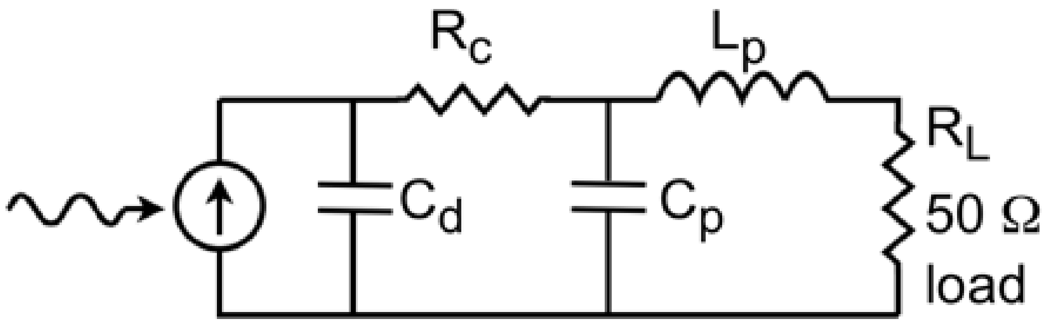
Time-resolved measurements: transit time ≤ 1 ps

Available bandwidth above 100 GHz

A. Vardi, et al., Appl Phys Lett 99, 202111 (2011).

Frequency response of 1.55 µm GaN QCD



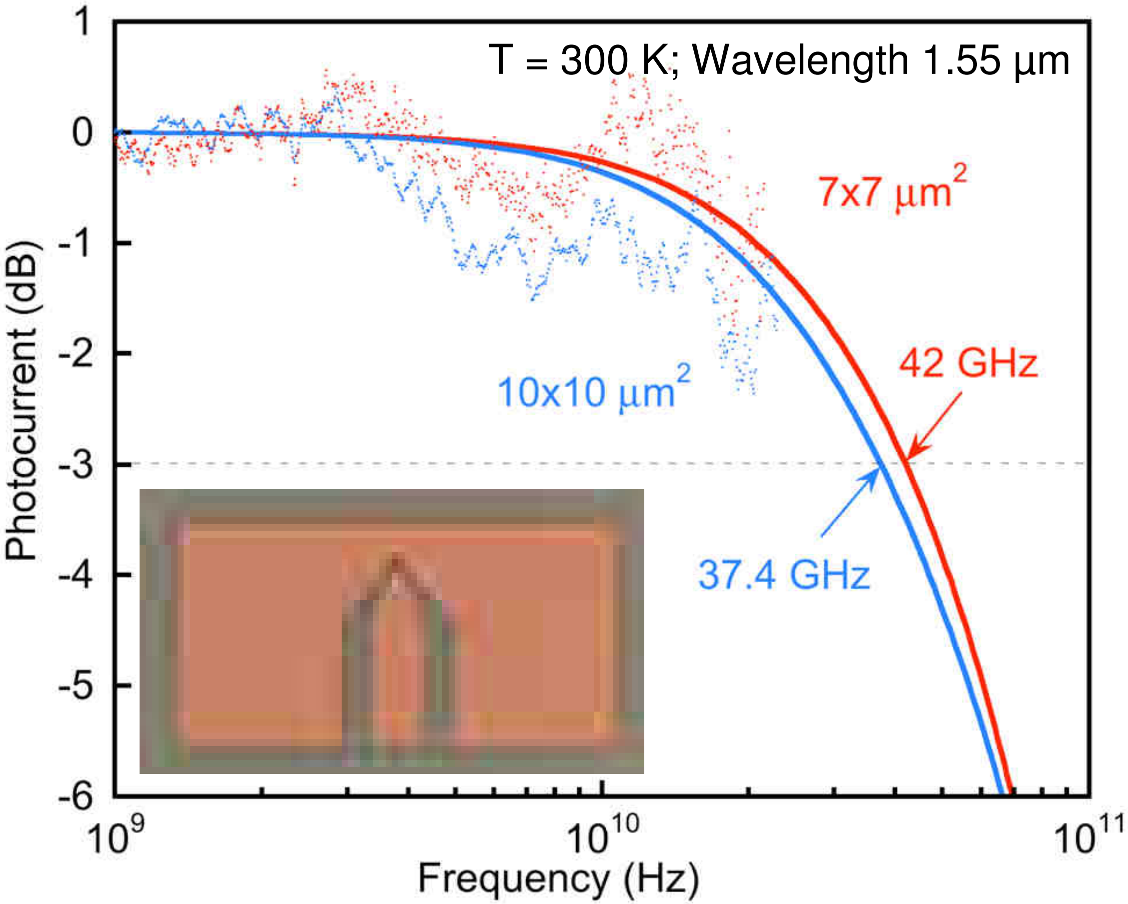


Mesa size	RC
25x25 µm^2	180 Ω 97 fF
17x17 µm^2	210 Ω 97 fF
10x10 µm^2	56 Ω 72 fF
7x7 µm^2	74 Ω 52 fF

- Impedance-matched RF access lines. Top contact fully metallized
- Agilent component analyzer and S-parameter measurements at 300 K

S. Sakr et al. Appl. Phys. Lett. 102, 011135 (2013)

Frequency response of 1.55 µm GaN QCD



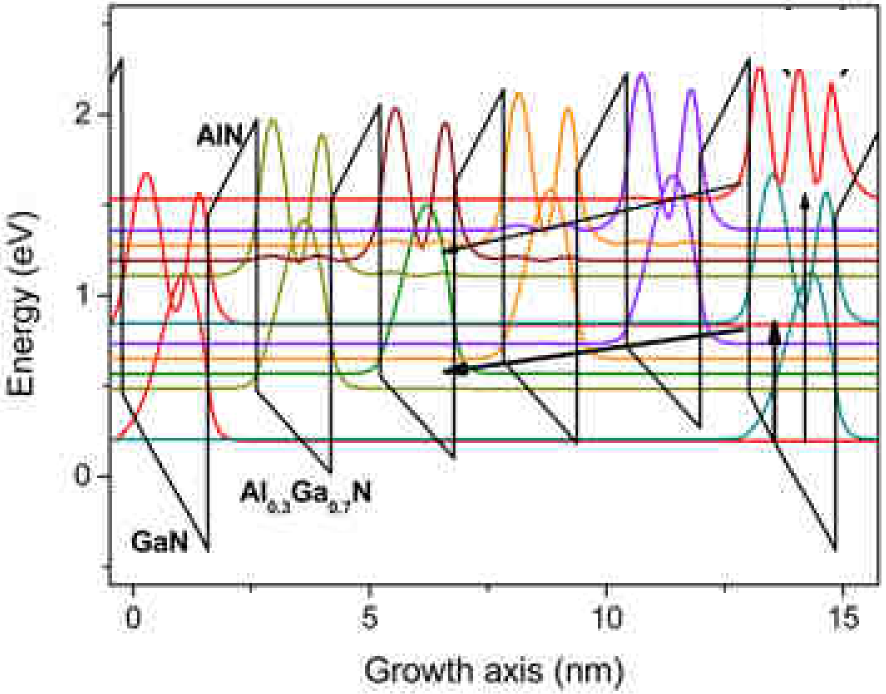
Mesa size	RC	- 3 dB frequency cut-off
25x25 µm²	180 Ω 97 fF	6.5 GHz
17x17 µm²	210 Ω 97 fF	11.4 GHz
10x10 µm²	56 Ω 72 fF	38 GHz
7x7 µm²	74 Ω 52 fF	42 GHz

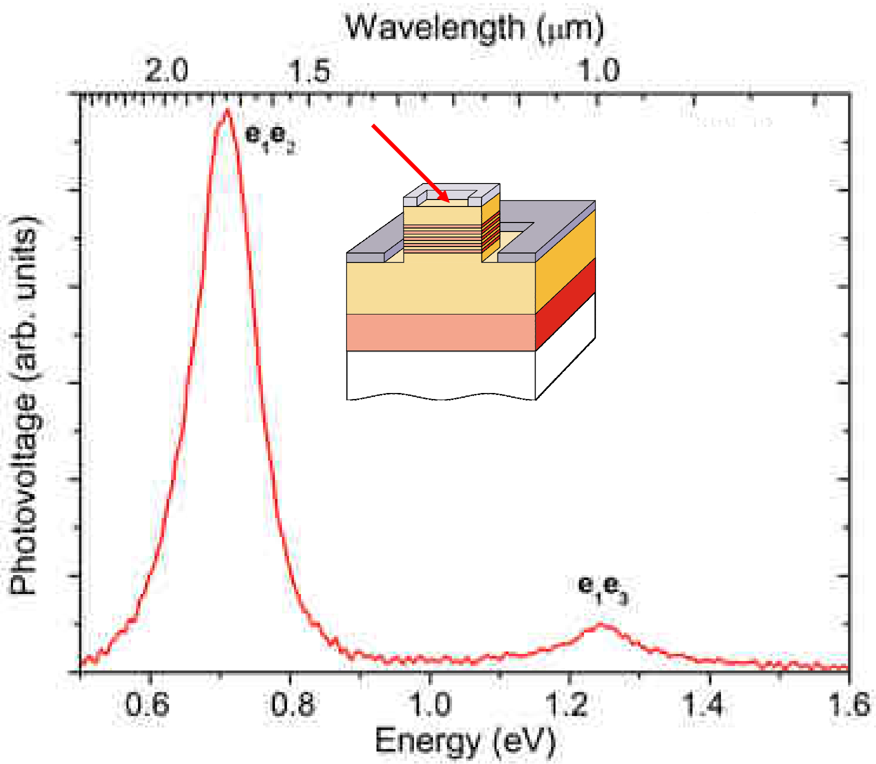
Frequency response is RC limited

Bandwidth in excess of 40 GHz achievable

*A. Vardi et al., APL **93**, 193509 (2008); S.Sakr et al. (2013)*

Other designs : two-color QCD

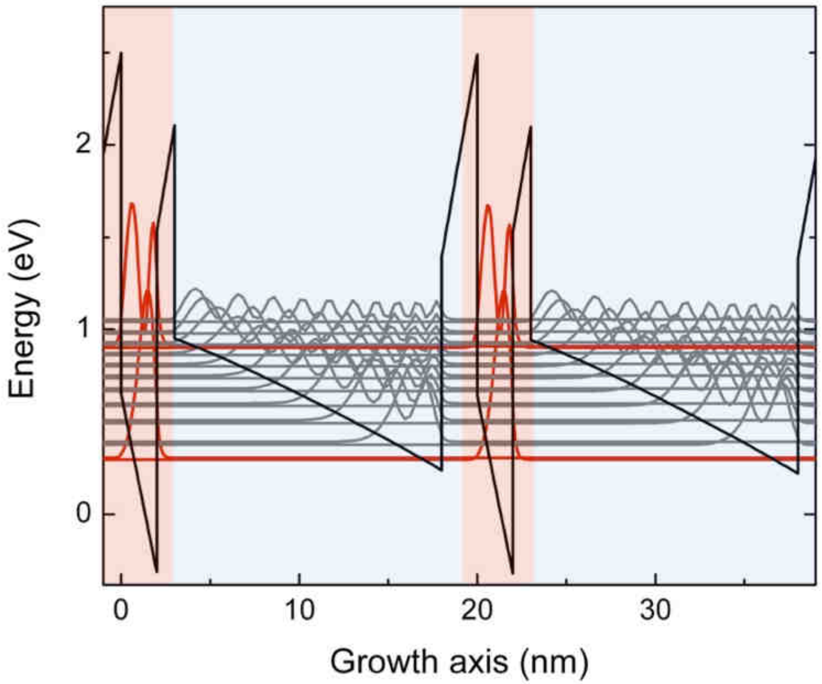


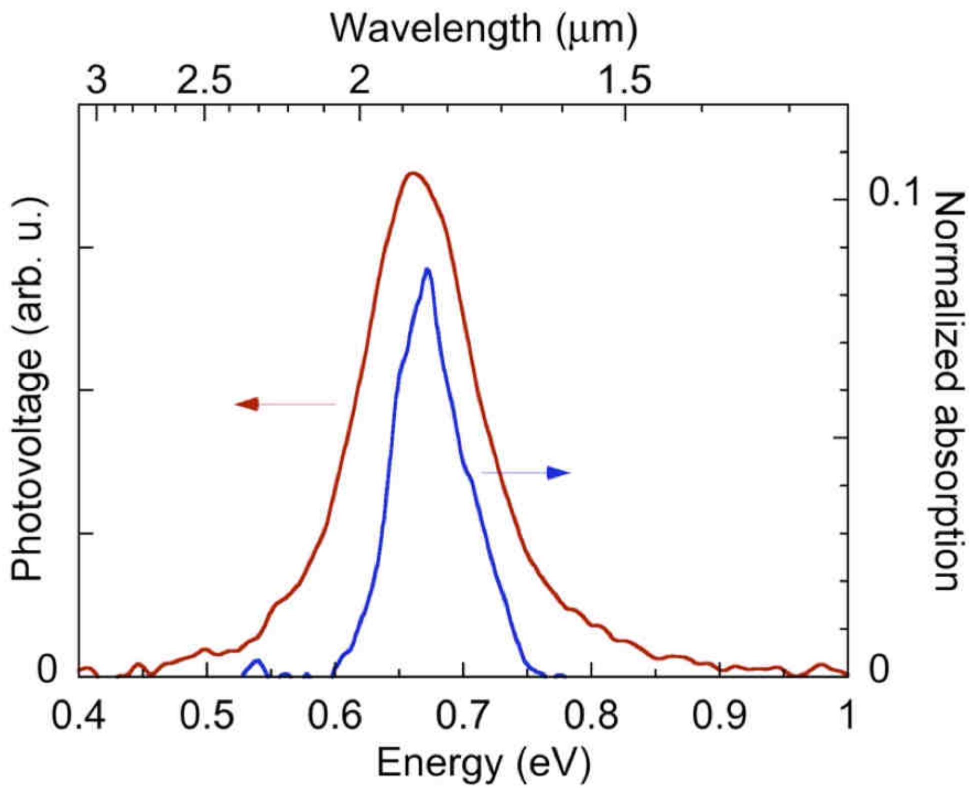


- Peak detection wavelength of 1.7 and 1 µm
- Shortest wavelength intersubband detector

S. Sakr et al., APL 100, 181103 (2012)

Other designs : alloy extractor QCD

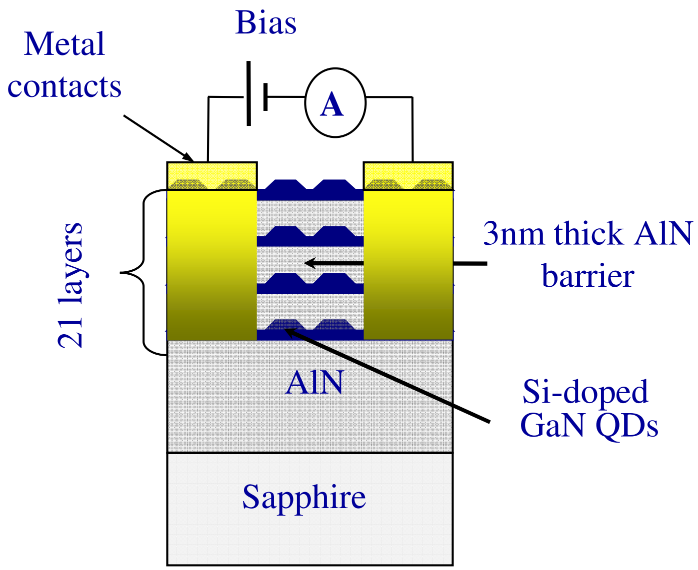


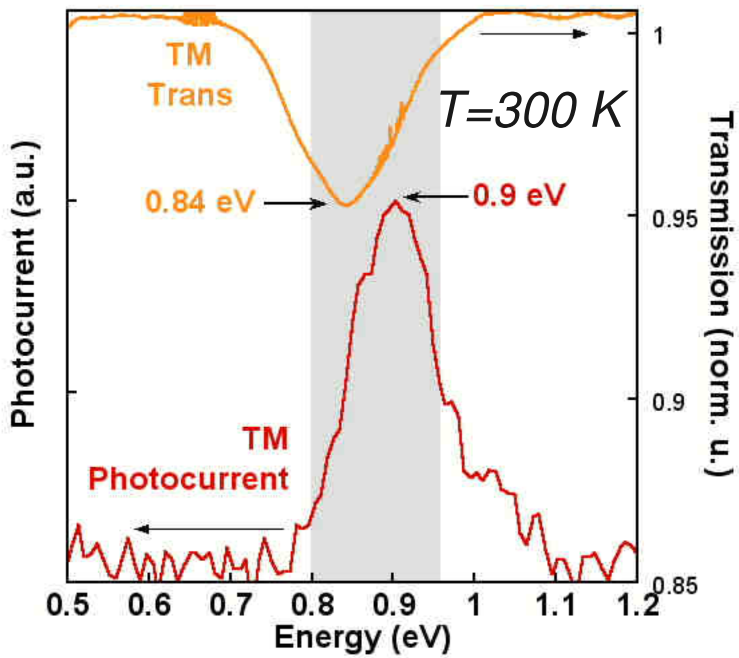


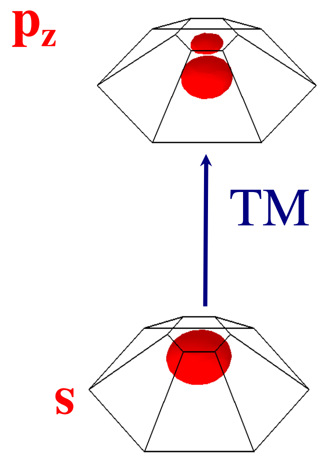
- Simplified and flexible design
- Interesting and robust design for GaN-based far infrared QCDs

S. Sakr et al., APL 101, 251101 (2012)

Quantum dot intraband photodetector







✓ Absorption involves the s-p_z intraband transition

✓ p_z electrons transfer to the WL ground state via phonon absorption

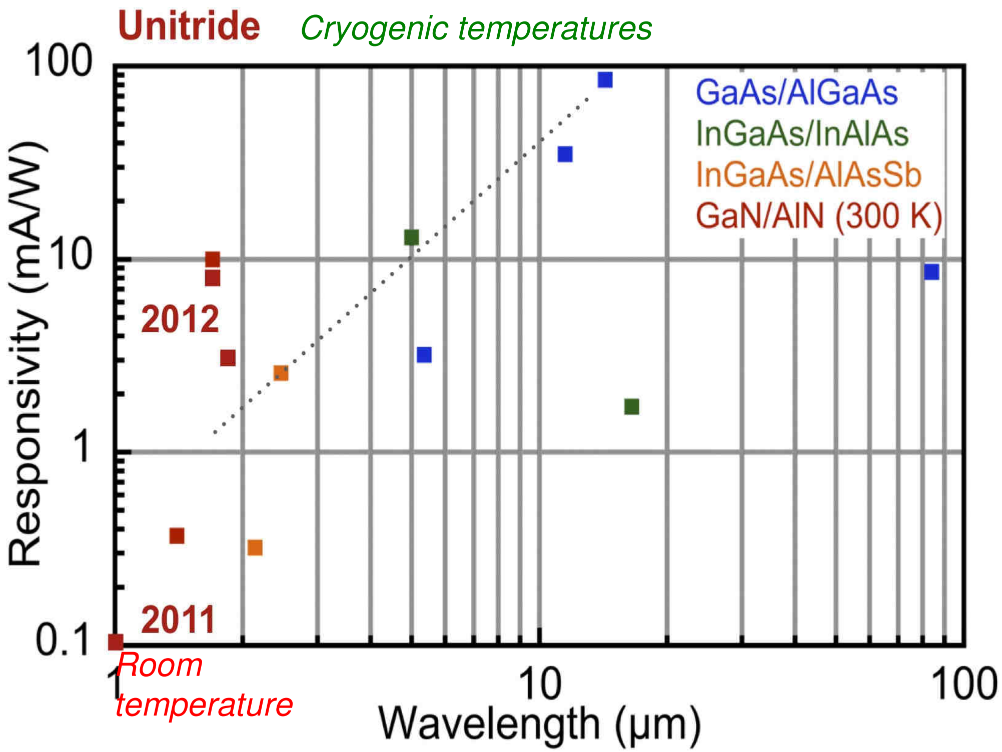
✓ In-plane transport in the WL generates the photo-current.

✓ Responsivity 12 mA/W at 1.3 µm at room temperature

L. Doyennette et al., Electron. Lett., 41, 1077, (2005)
A. Vardi et al., Appl. Phys. Lett., 88, 143101, (2006)

Comparison of nitride QCDs with state-of-the-art

- Infrared QCDs:



GaN/AlGaN QCDs offer superior responsivity at room temperature and allow for photodetection at record-short near-infrared wavelengths.

- High-speed telecom photodiodes:

Waveguide detectors at λ=1.55 µm	InGaAs photodiode	Ge/Si photodiode	Unitride GaN QCD
Size (μm^2)	60	78	49
f_{-3dB} (GHz)	100 @ -1 V	42 @ -4 V	42 @ 0 V
Responsivity (A/W)	0.58	1	0.01
D* (Jones)	$5x10^{12}$	$1x10^{11}$	$>1x10^{11}$

QCDs are the fastest ISB detectors developed so far, whatever the material system. The frequency performance of QCDs is comparable to that of current-technology waveguide InGaAs or Ge p-i-n photodiodes at λ =1.55 μ m regarding the device size.

Nitride near-IR ISB devices

- ✓ IR photodetectors
- ✓ **Modulators**
  - ✓ Coupled QW modulator
  - ✓ Depletion modulator
  - ✓ All-optical switches
- ✓ Light emitters

Electro-optical modulators : Motivations

Potential **advantages of ISB electro-optical modulators**

- intrinsically very fast - large spectral bandwidth
- possibility to obtain negative chirp parameter
- insensitive to saturation
- potentially low drive voltage (symmetric around zero bias)

Theoretical paper by *P. Holmström, IEEE J Quant Elec, 42, 810 (2006)*

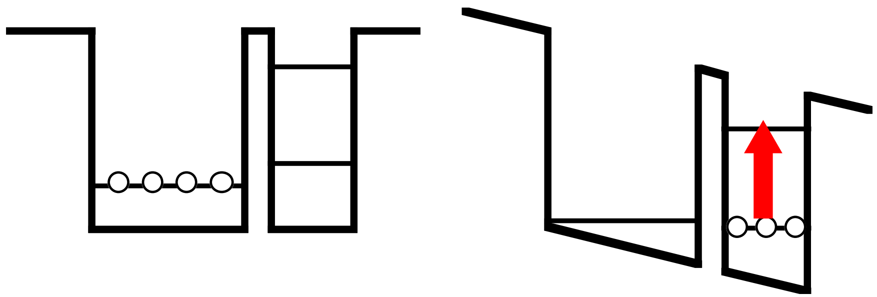
First proposal by *N. Vodjdani et al., APL 59, 555 (1991)* in GaAs/AlGaAs coupled quantum wells operating at ~10 µm

Further optimization in Mid-IR :

H. C. Liu, et al., J. Appl. Phys., 70, 7560 (1991)

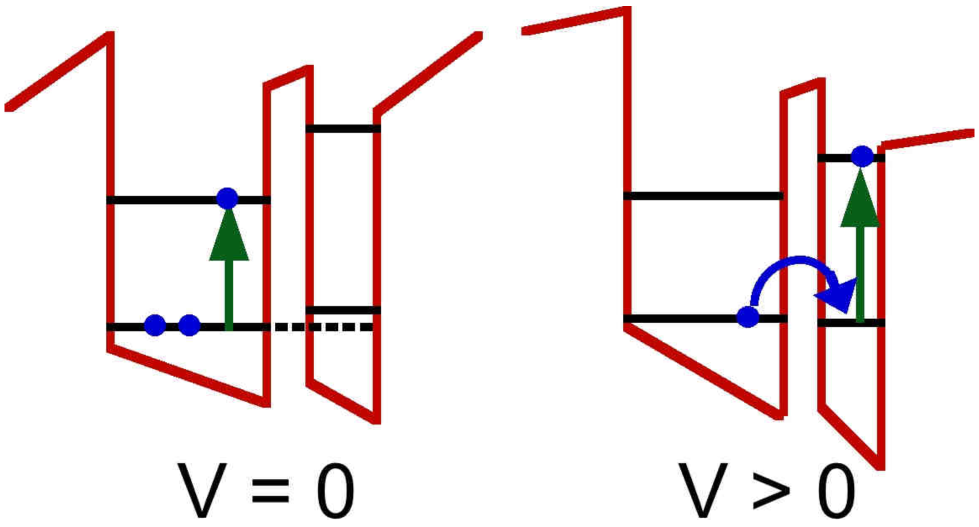
E. Dupont, et al., Appl. Phys. Lett. 62, 1907 (1993)

J. Y. Duboz, et al., Appl. Phys. Lett. 70, 1569 (1997)



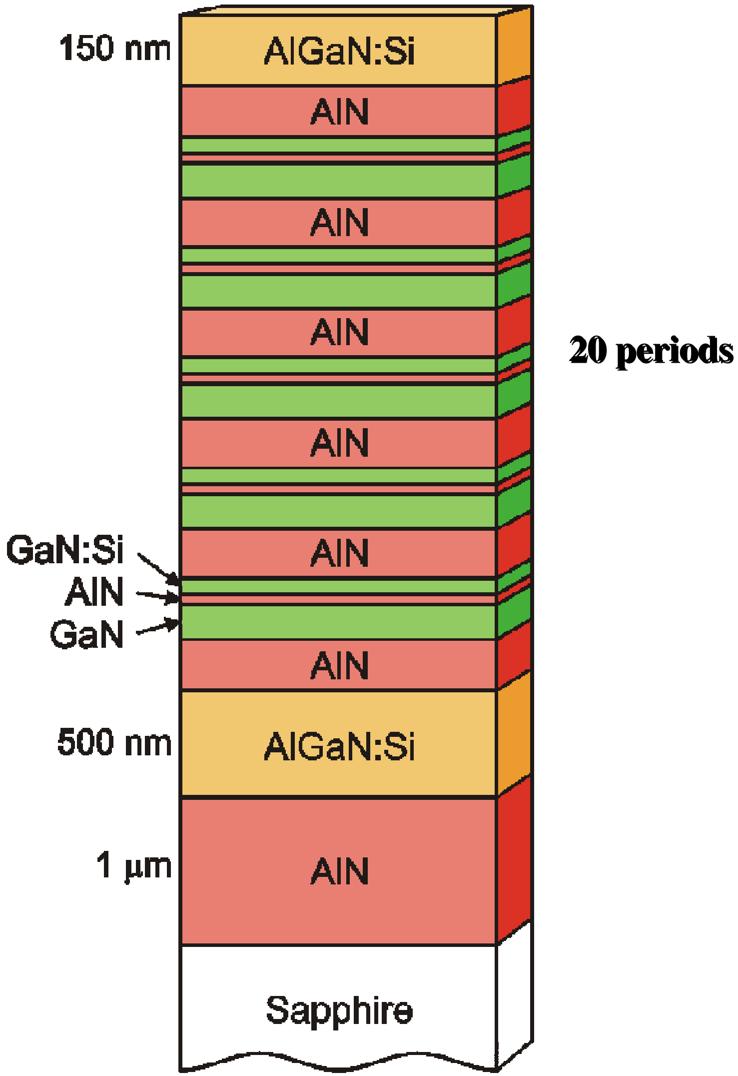
Charge-transfer electro-optical modulator based on GaN/AlN coupled QWs

Operation principle



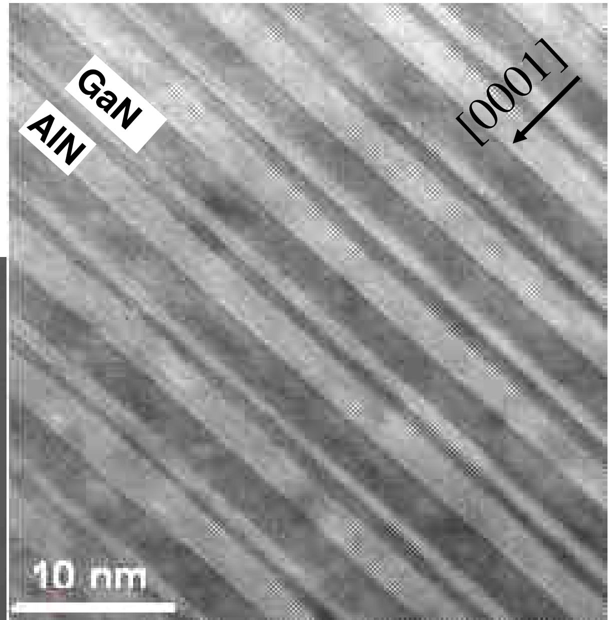
Electron transfer between two wells

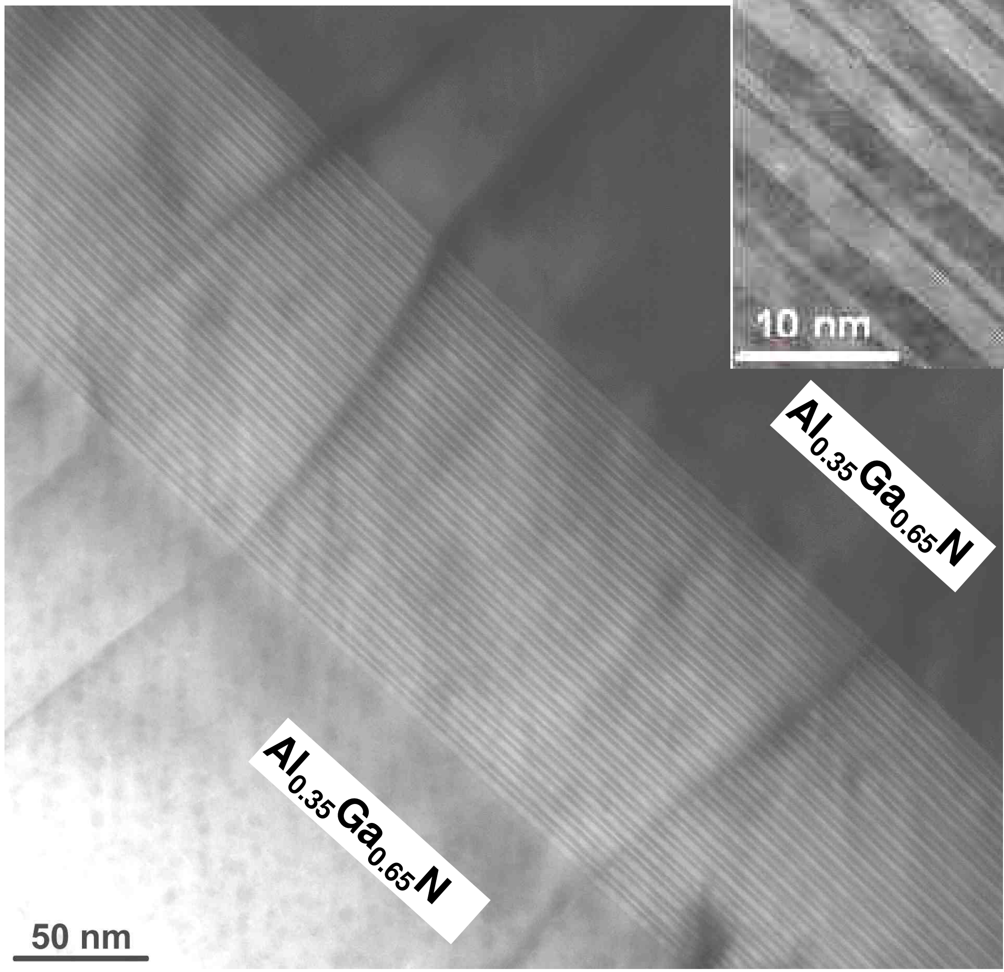
Structure



Structural characterization

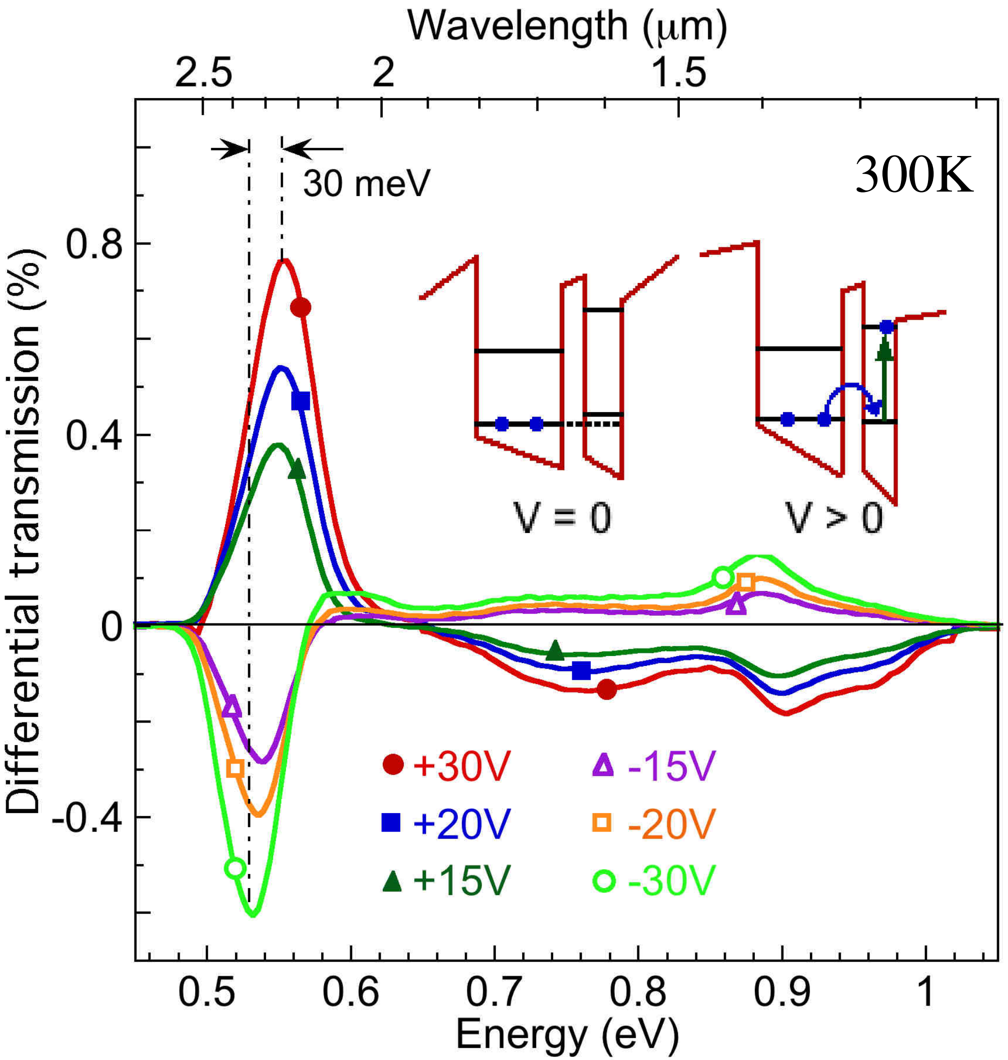
- ✓ No cracks
- ✓ Sharp GaN/AlN interfaces
- ✓ Good periodicity

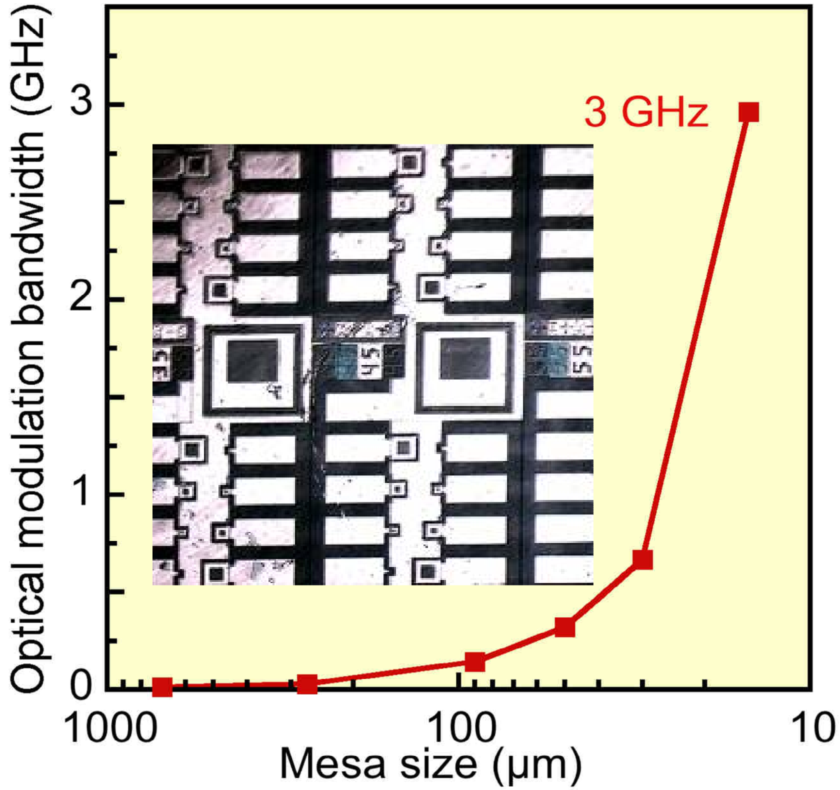




PA-MBE E Monroy CEA,
HRTEM images by M. Albrecht

Spectroscopy and bandwidth





*L. Nevou et al., APL **90**, 121106 (2007)*

*N. Kheirodin et al., IEEE PTL **20**, 724 (2008)*

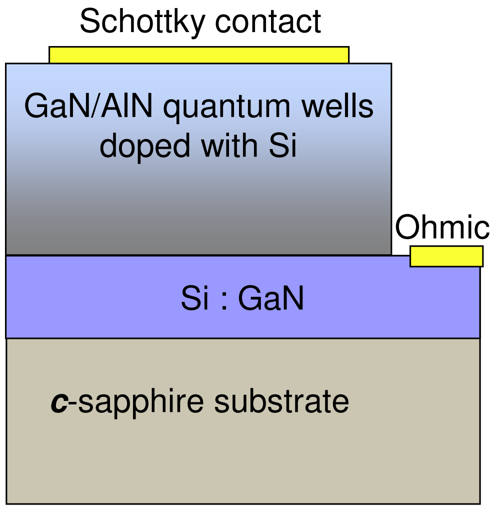
✓ Optical modulation bandwidth 3GHz @ 1.55 μm limited by RC constant

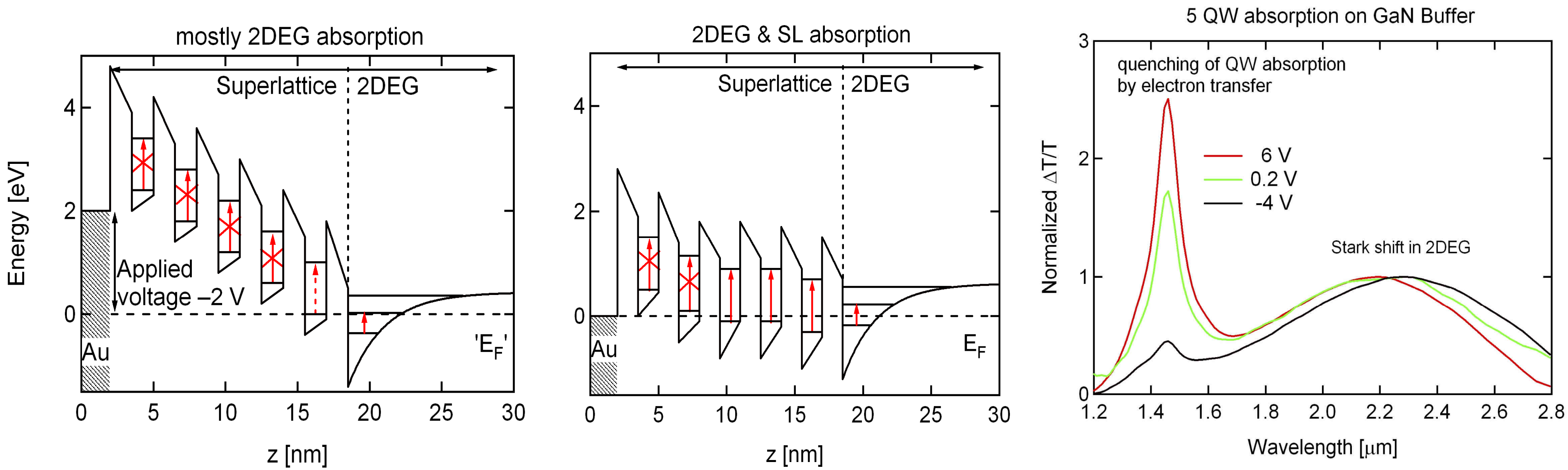
GaN/AlN depletion modulator

Depletion of quantum wells by applying bias to the Schottky contact

Quenching of the QW absorption

Stark shift of the 2DEG absorption

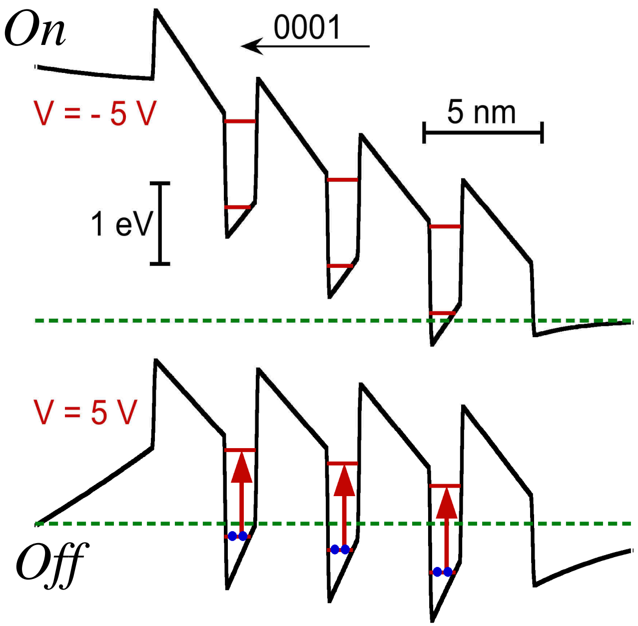


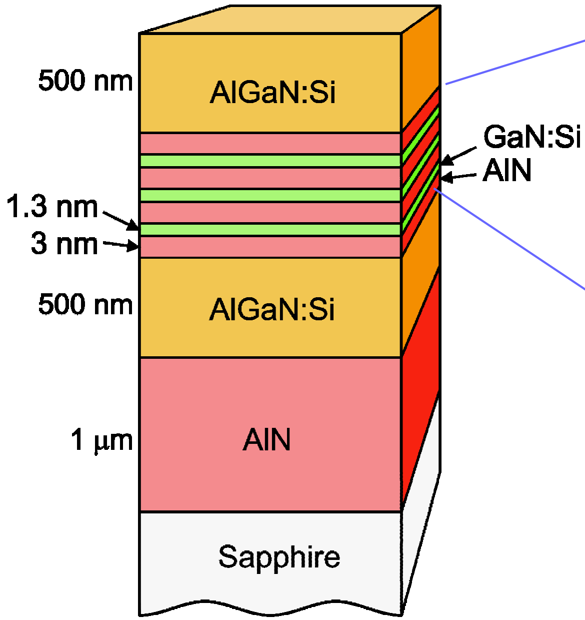


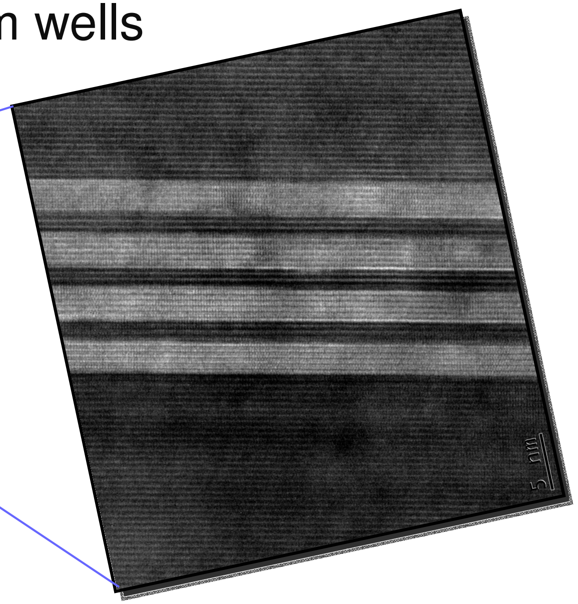
Bauman et al. APL 89, 101121 (2006)

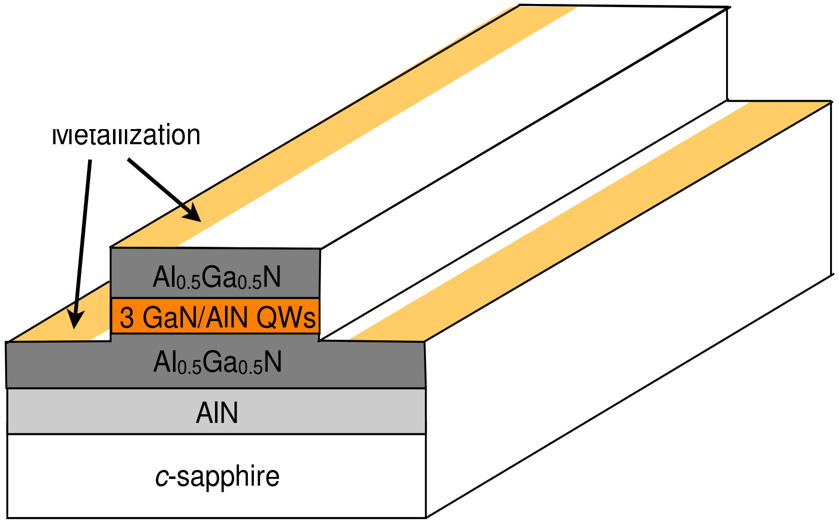
GaN/AlN waveguide depletion modulator

Depletion modulator structure with 3 active GaN/AlN quantum wells



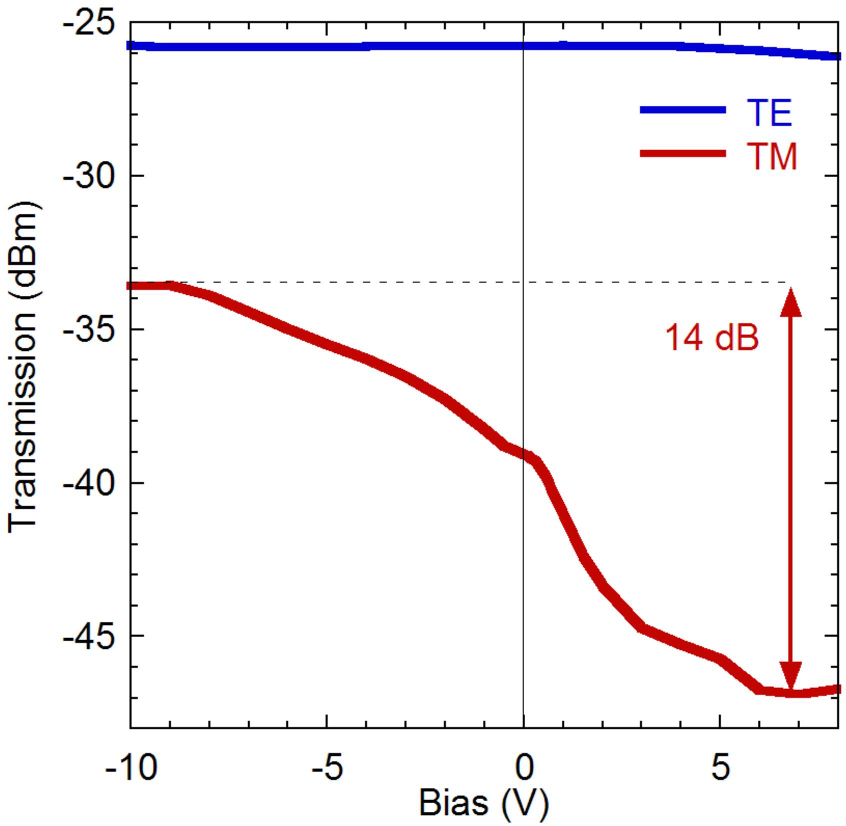


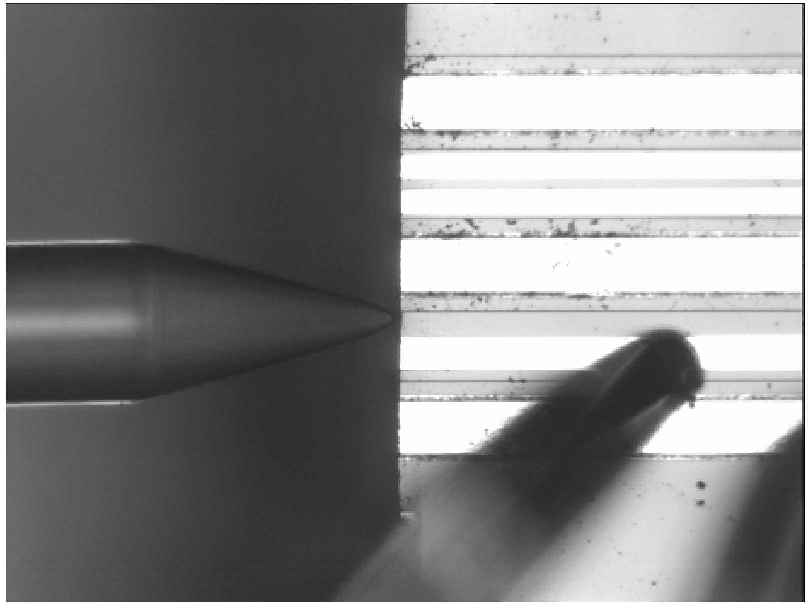




Waveguide coupling configuration

Modulation depth





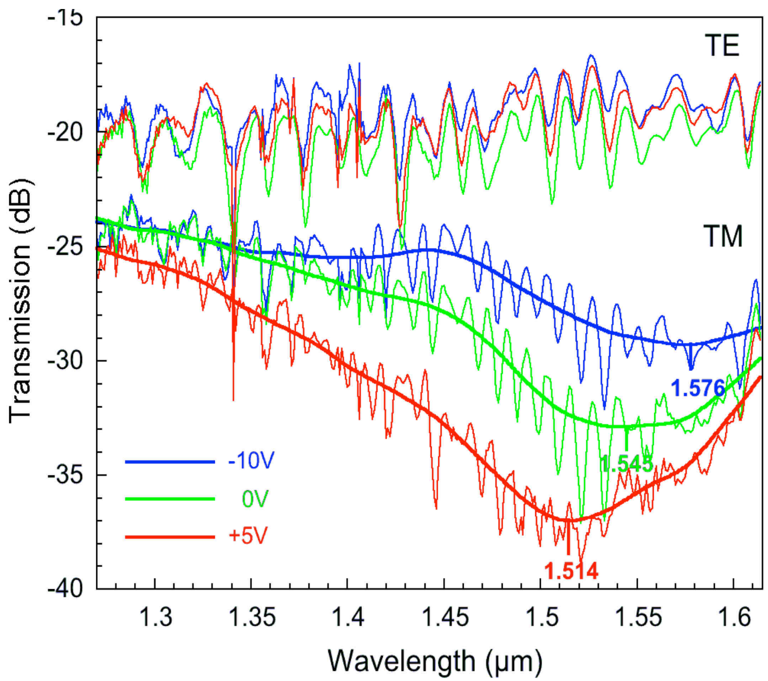
✓Modulation depth at λ =1.5 µm of 14 dB (10^{-14} bit error rate)

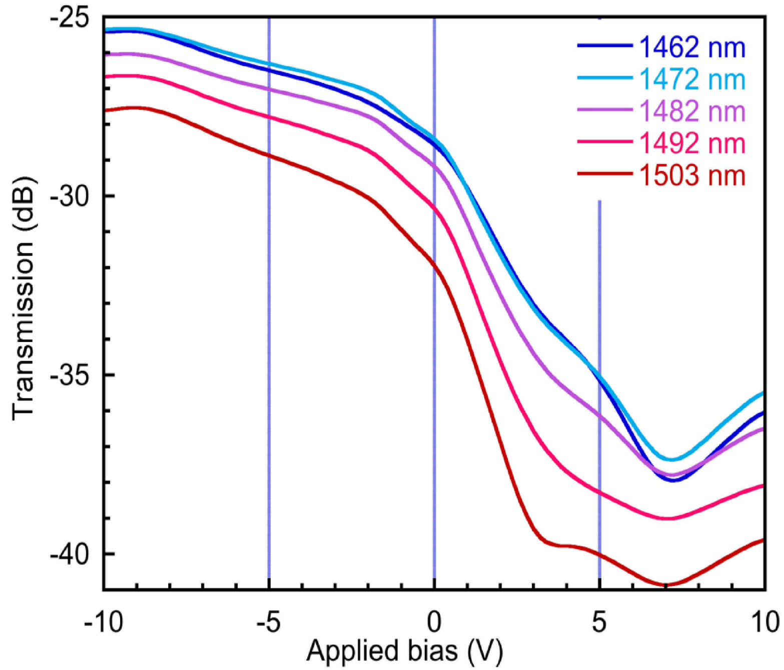
✓Wide spectral width: 1.35 to 1.6 µm

H. Machhadani et al., New J Phys. 11, 125023 (2009)

Demonstration of waveguide amplitude and phase modulation

- Waveguide depletion modulator transmission at RT versus wavelength and bias.



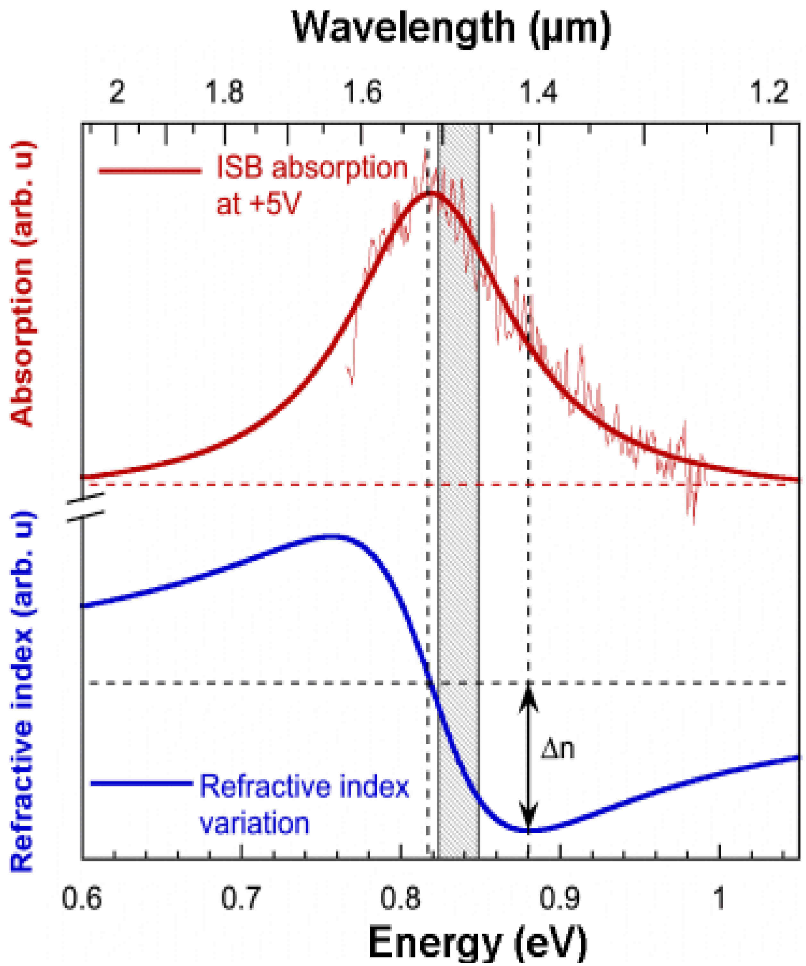


- Demonstration of ISB absorption modulation due to population/depletion of active QWs and to the quantum confined Stark effect.
- Modulation depth as large as 14 dB.

A. Lupu et al., Optics Express (2012)

Phase modulation with ISB transitions

PM is directly used for phase shift encoding or can be converted to amplitude modulation with a Mach-Zehnder intorferometer

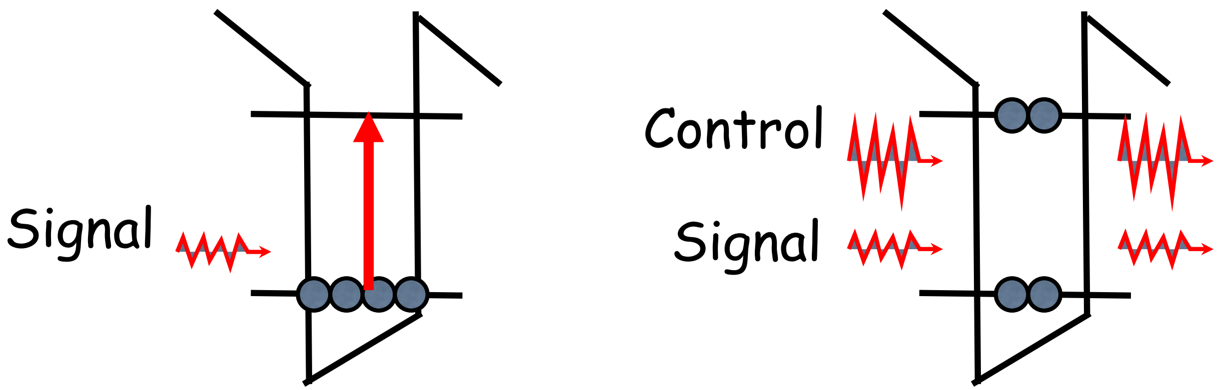


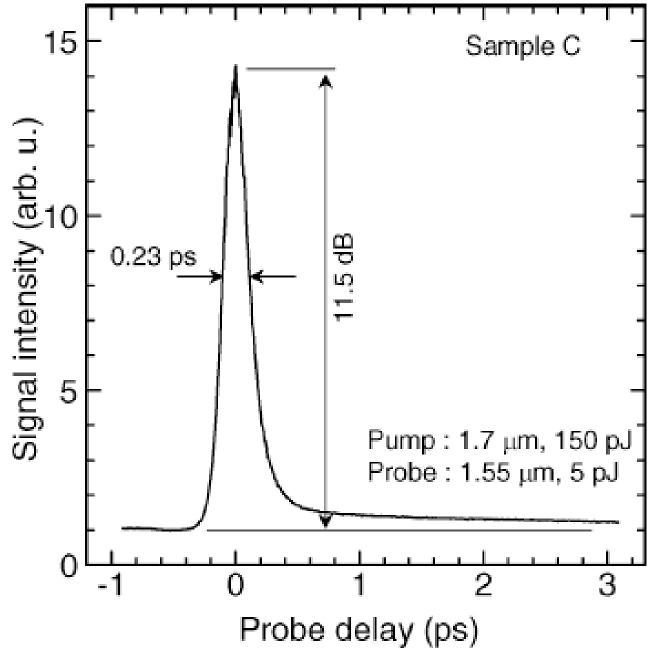
- Fourier analysis of mode beating interferences in the transmission spectrum.
- The maximum refractive index variation in the –5 V to 5 V bias range is found to be **: Δn/n ~5x10^{-3}** at 1.46 µm.
- This value achieved with only 3 QWs is comparable to the state-of-the-art value reported for InP-based phase modulators

@ 10 µm – E. Dupon et al., APL 62, 1907 (1993)
@ 1.5 µm – A. Lupu et al., Optics Express (2012)

Ultrafast all-optical switches based on GaN/AlN quantum wells

Absorption saturation





*Iizuka et al., IEEE JQE **42**, 765 (2006).*

- ✓Absorption recovery time 150-400 fs @ 1.5 µm
- ✓Key device for multi-Tbit/s all-optical processing
- ✓Intense work dedicated to GaN/AlN QWs
- ✓Switching energy 20-150 pJ

N. Iizuka et al., Appl. Phys. Lett. 77, 648 (2000)

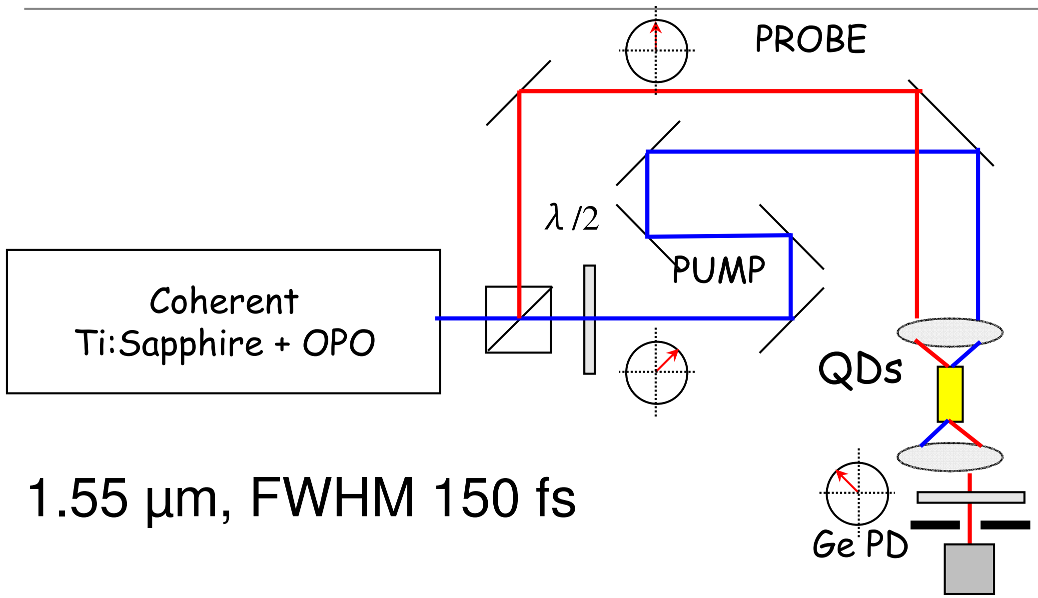
J. D. Heber et al., Appl. Phys. Lett. 81, 1237 (2002)

J. Hamazaki et al., Appl. Phys. Lett. 84, 1102 (2004)

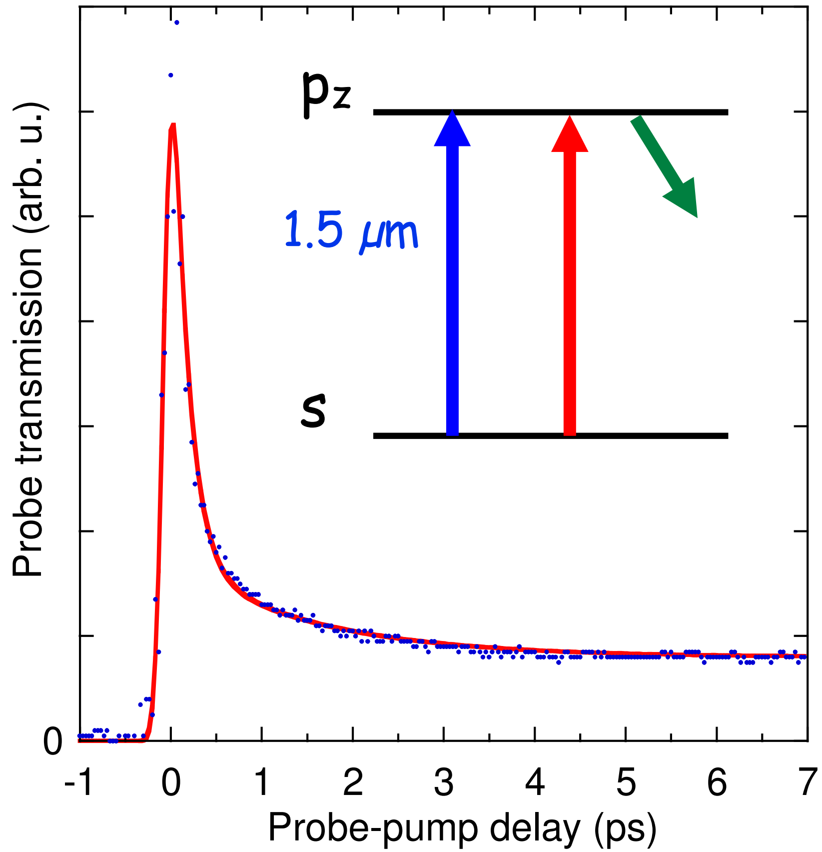
N. Iizuka et al., J. Appl. Phys. 99, 093107 (2006)

Yang Li et al., Optics Express, 15, 17922 (2007)

Carrier relaxation in GaN/AlN QDs



1.55 µm, FWHM 150 fs

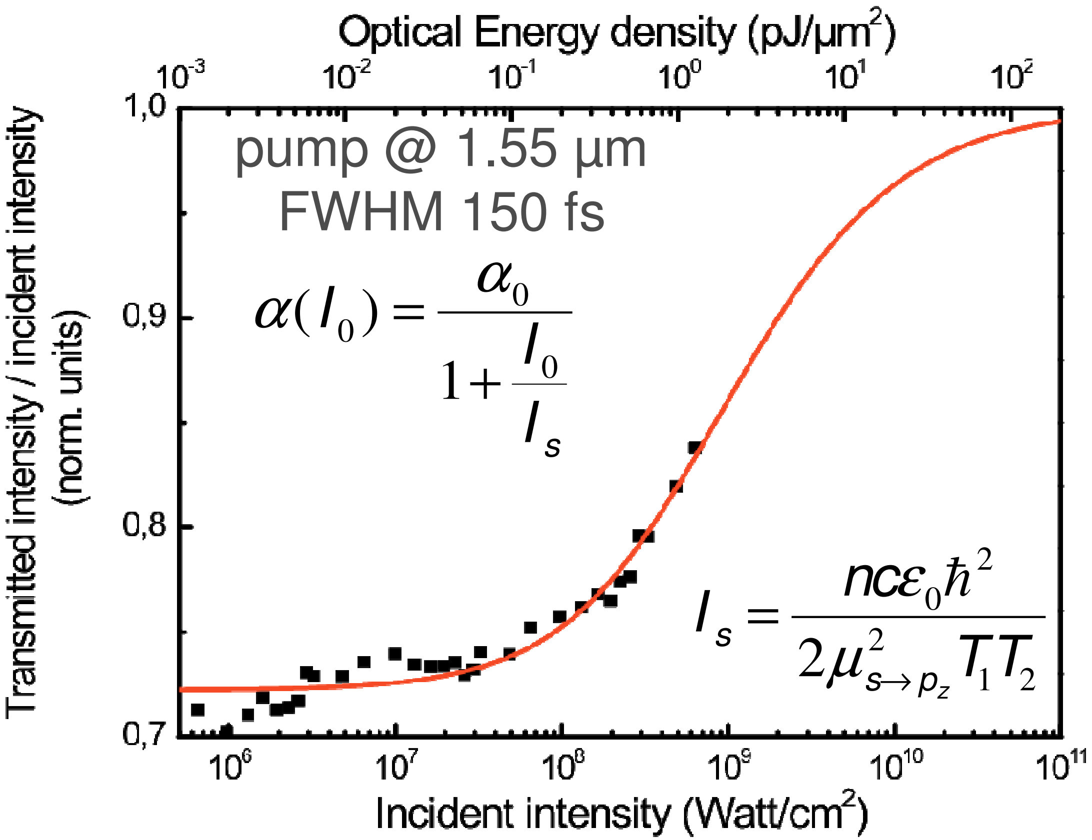


Intraband absorption recovery exhibits two-exponential decay

- ✓ Electron lifetime in p_z state T_1=165 fs
- ✓ Thermalisation of electrons in the ground state 1.5 ps

*L. Nevou et al., APL **94**, 132104 (2009)*

Intraband absorption saturation of GaN/AlN QDs



✓Saturation intensity <130 MWatt/cm^2 (saturation energy density <0.27 pJ/µm^2) is smaller than for QWs and comparable with IB devices on InP

✓Simulation for a single quantum dot I_s =9 MW/cm^2

✓QD-based all-optical switches: as fast as QWs, but with low control energy

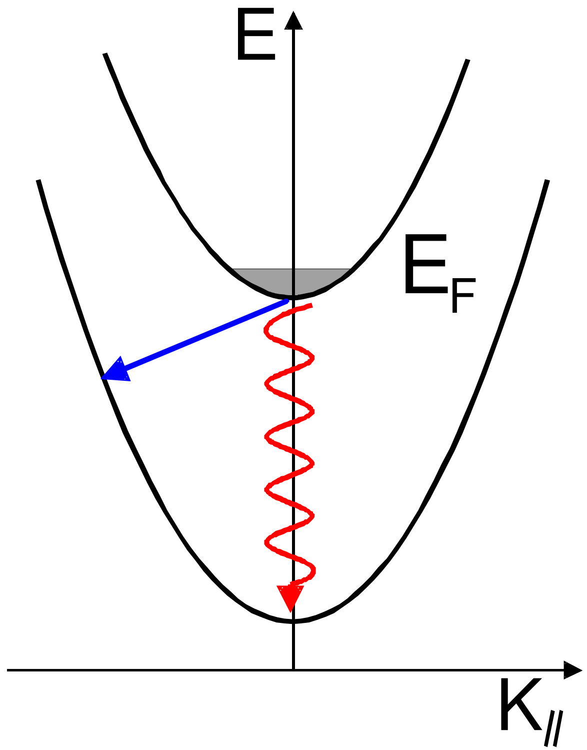
*L. Nevou et al., APL **94**, 132104 (2009)*

Nitride near-IR ISB devices

- IR photodetectors
- Modulators
  - Coupled QW modulator
  - Depletion modulator
  - All-optical switches
- **Light emitters**

ISB light emission in nitrides

- ✓ Internal quantum efficiency τ_{nr}/τ_r is very weak (radiative lifetime τ_r ~20-30 ns, non-radiative scattering time τ_{nr} ~100-400 fs)
- ✓ ISB transitions make bad LEDs but good lasers (high oscillator strength ➔high gain)



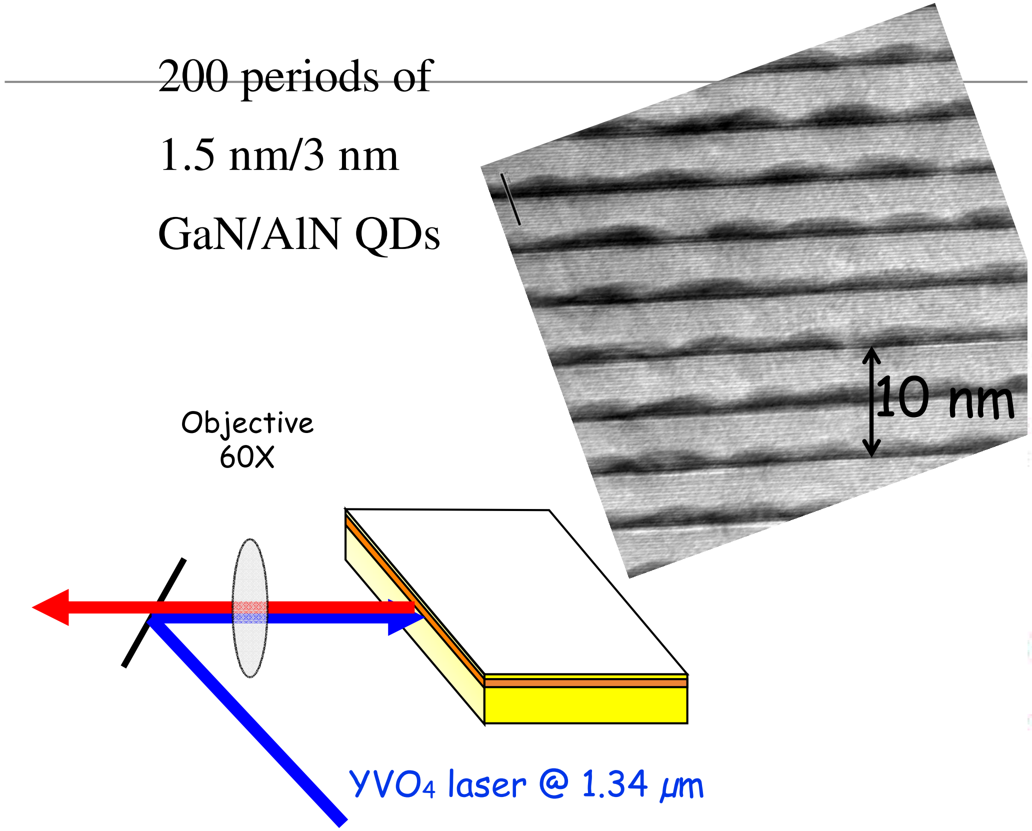
Photon emission (20 - 30 ns)

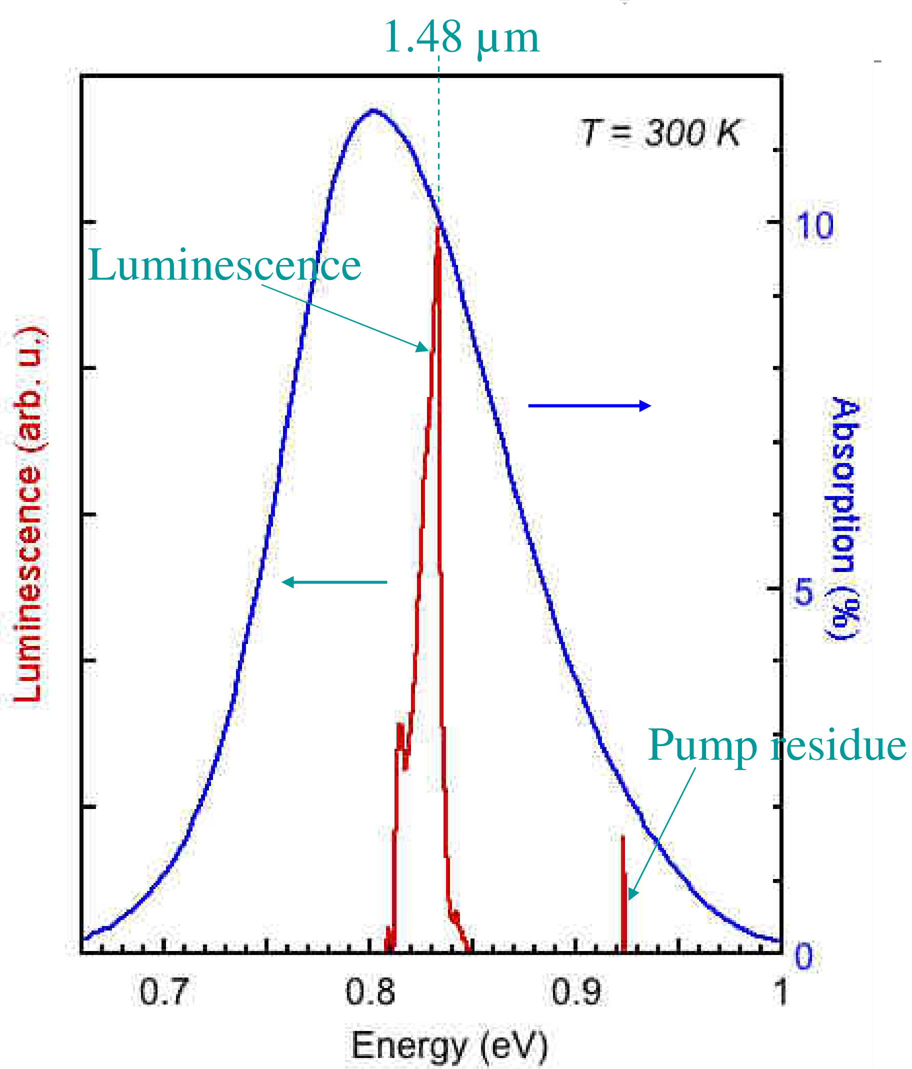
Phonon emission (0.1 – 0.4 ps)

Radiative efficiency ~ 10^{-5}

GaN/AlN quantum dot intraband emission

200 periods of
1.5 nm/3 nm
GaN/AlN QDs

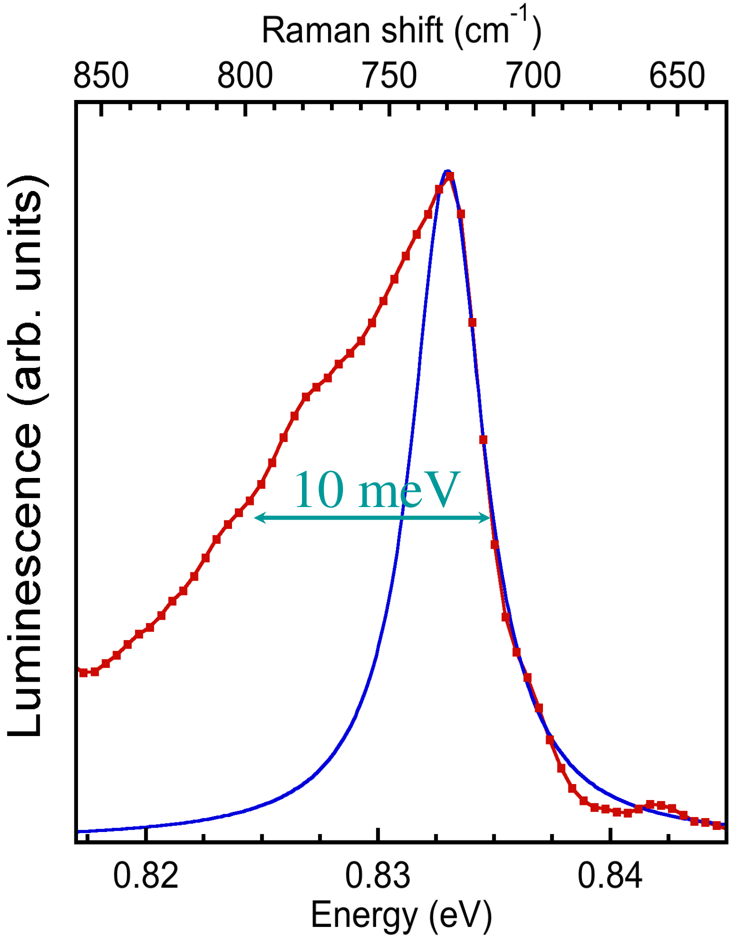


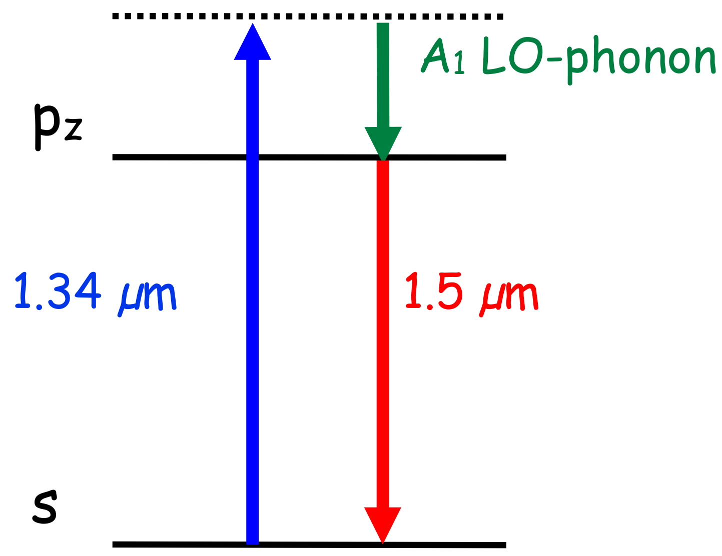


- TM-polarized p_z-s emission at **1.48 µm** only under TM-polarized excitation
- Energy shift 90 meV - GaN LO phonon
- T = 300 K

L. Nevou et al., APL ***92****, 161105 (2008)*

Intraband emission mechanism

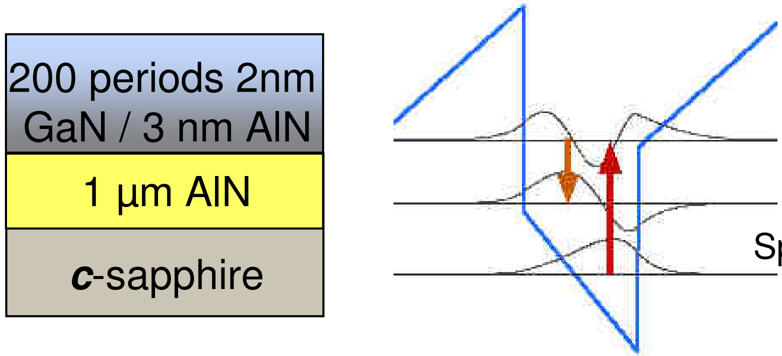


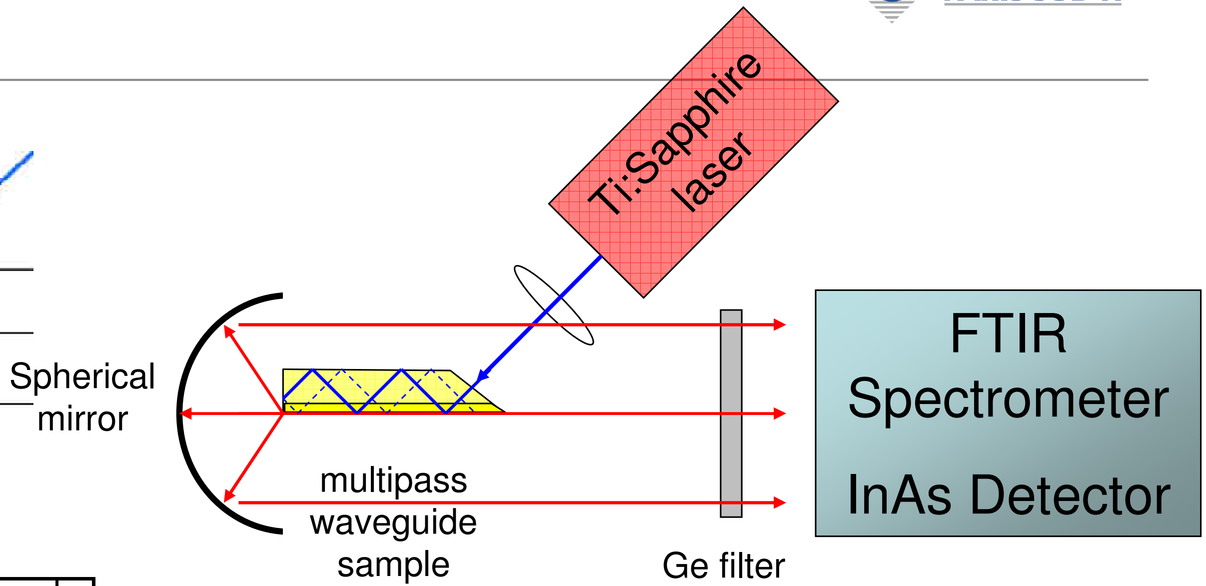


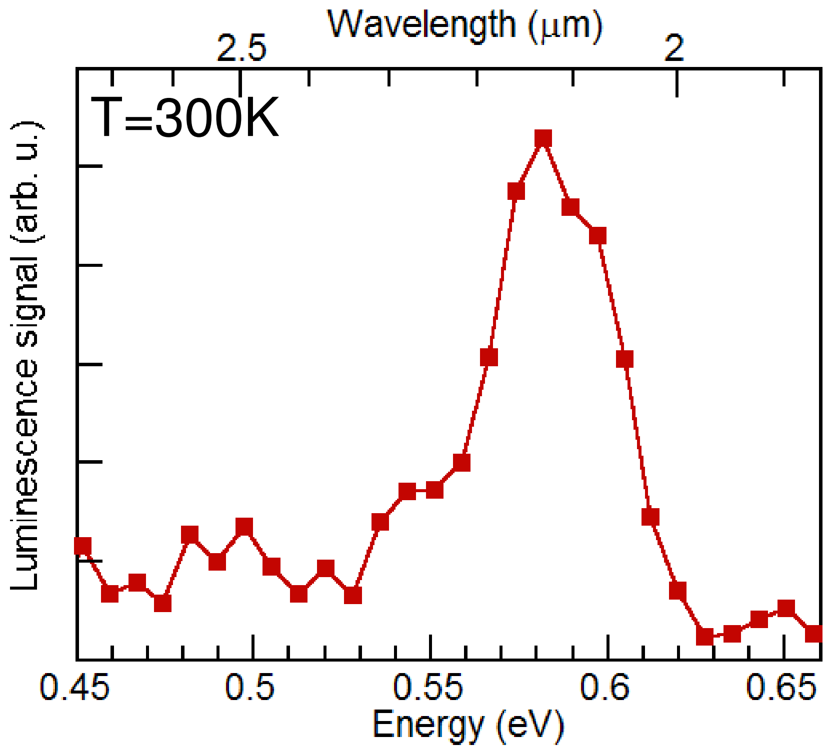
- ✓ Emission process is selective in terms of dot size
- ✓ FWHM for a single GaN QD < 10 meV (hole-burning experiments by *G. Cassabois et al.* ~15 meV at 300K, FWHM QWs 40 meV)
- ✓ Population inversion is achievable

*L. Nevou et al., APL **92**, 161105 (2008)*

ISB luminescence from GaN/AlN QWs







- ✓ Excitation resonant with e_1e_3 ISB absorption
- ✓ ISB emission at record short wavelength 2.13 µm
- ✓ Room temperature
- ✓ Internal quantum efficiency 0.3 µW /Watt of pump power

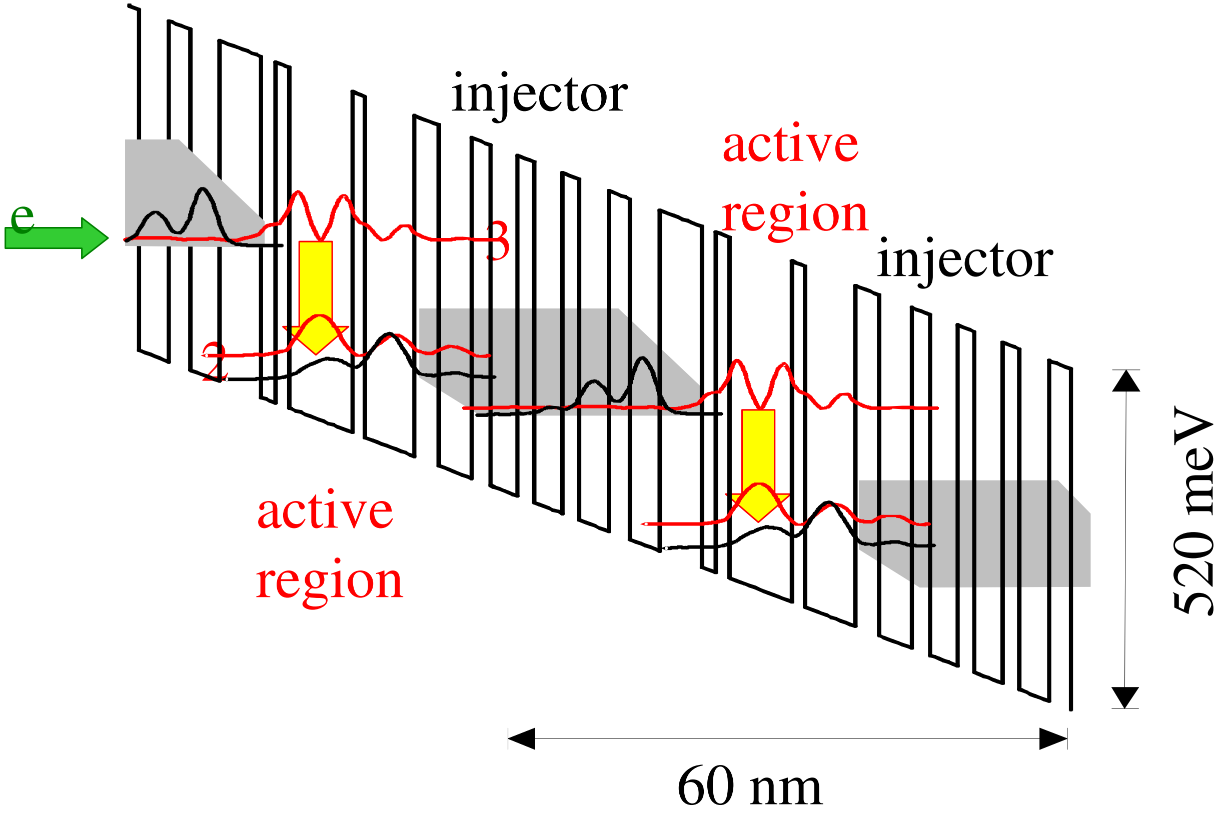
*L. Nevou et al., Electron. Lett. **42**, 1308 (2006); APL **90**, 121106 (2007); Driscoll et al. APL 2009*

Why nitrides can make high temperature THz Quantum Cascade Lasers ?

Quantum cascade laser

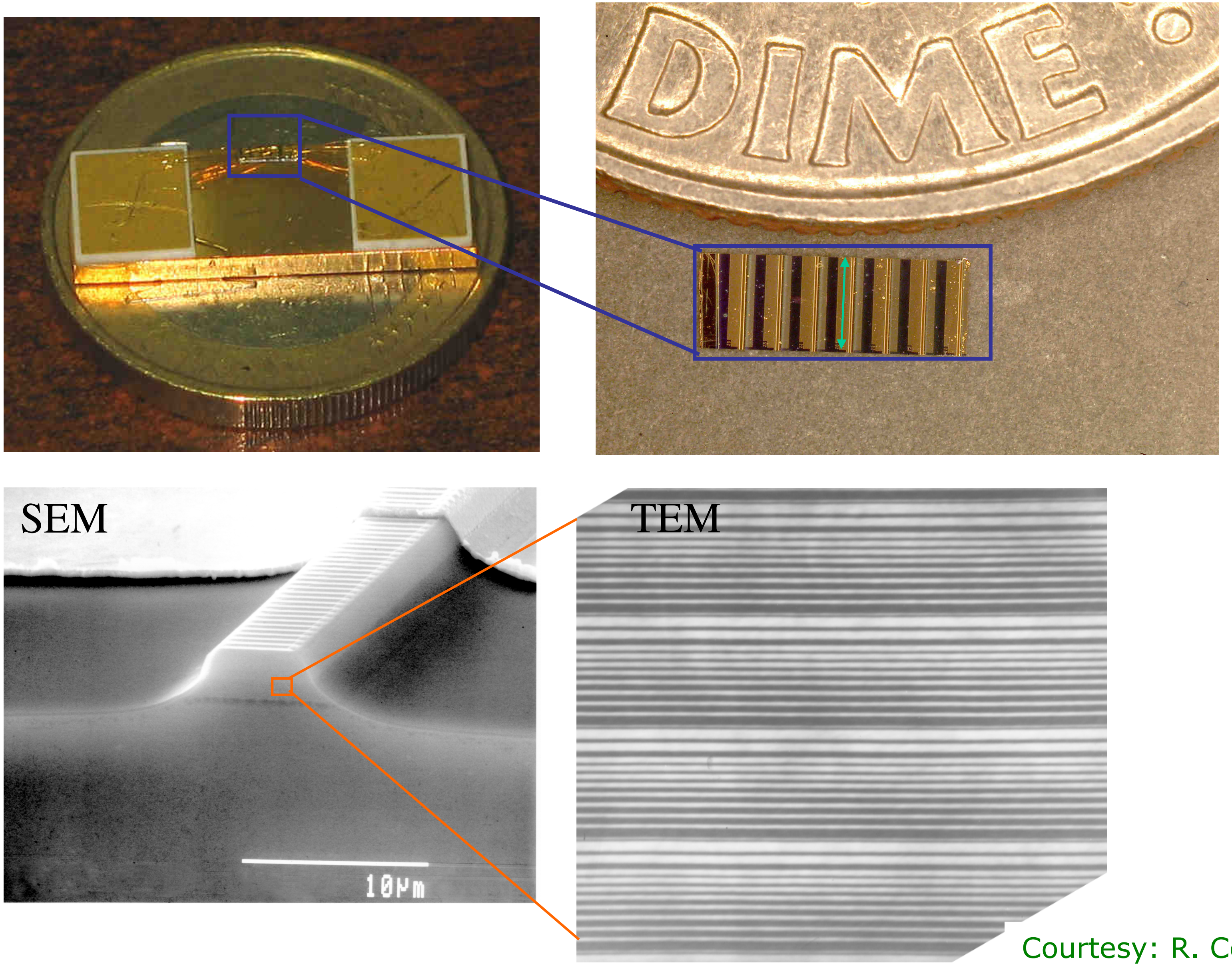
QCL materials: InGaAs/AlInAs on InP and GaAs/AlGaAs on GaAs

Operating λ : mid-IR ($\lambda \approx 3.5$ - 24 μm) and THz ($\lambda \approx 60$ – 160 μm)



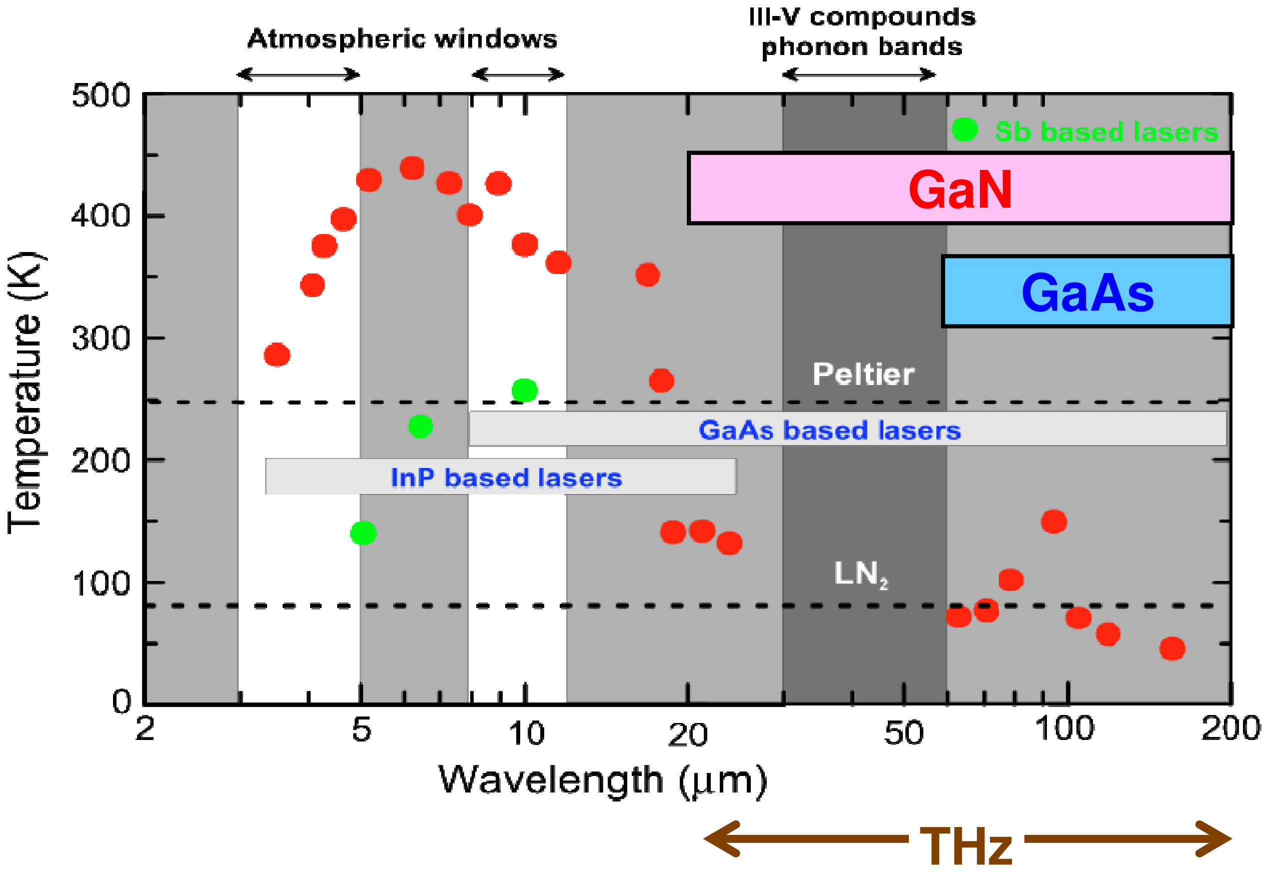
Courtesy: R. Colombelli

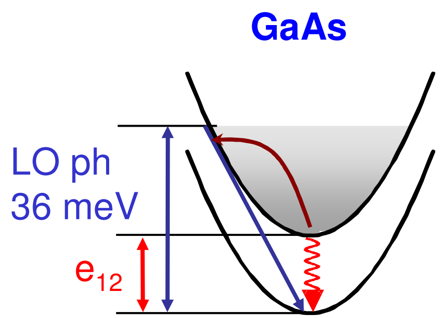
Quantum cascade lasers



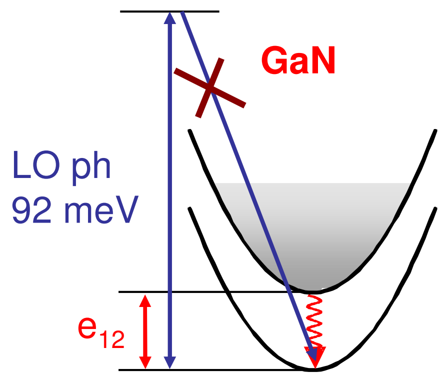
Courtesy: R. Colombelli

Why GaN THz QC lasers





LO phonon emission kills the population inversion



THz QC lasers above 300 K

Taking benefit from the large LO-phonon energy

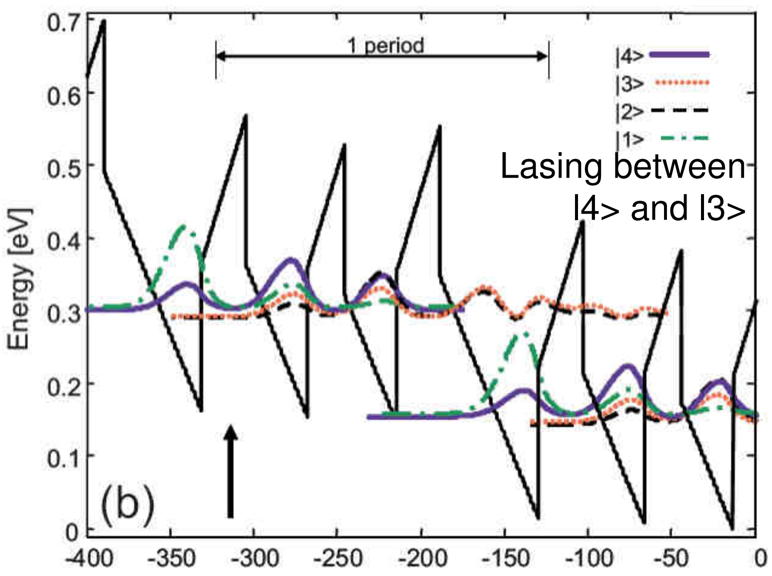
- ✓ Lasers at wavelengths inaccessible to GaAs-based QCLs
- ✓ Increase operating temperature above 300 K

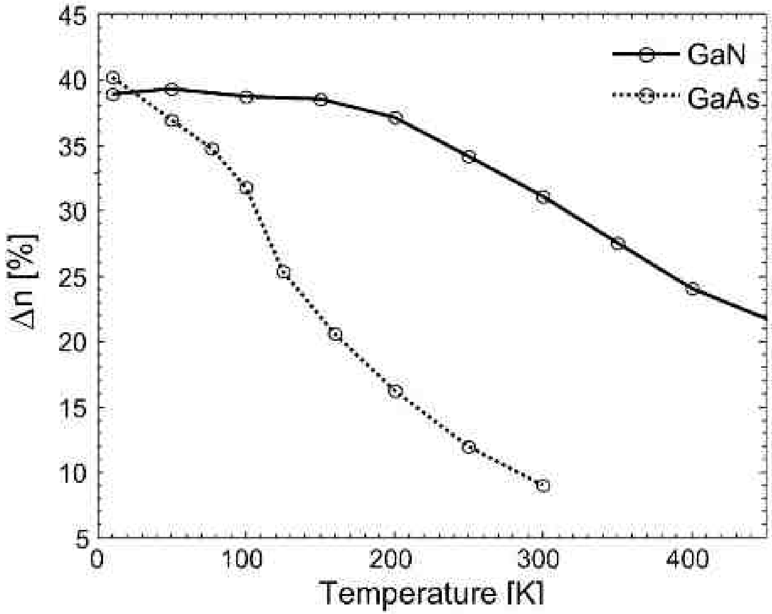
Nitride THz QCLs – theoretical proposals

Only theoretical proposals

Bellotti et al., "Monte Carlo study of GaN versus GaAs THz QCL structures", Appl Phys Lett 92, 101112 (2008)

Bellotti et al., "Monte Carlo simulations of THz QCL structures based on wide-bandgap semiconductors", J. Appl Phys 105, 113103 (2009)



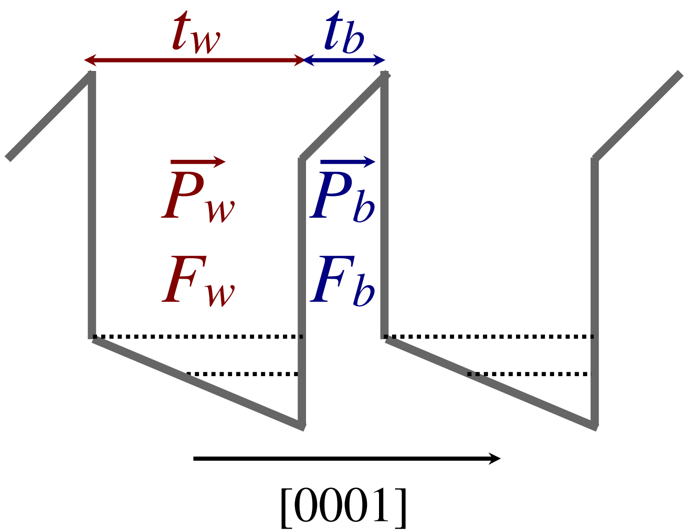


Present challenges

- ✓ to control resonant tunelling (injector fabrication)
- ✓ to tune the ISB absorption to the THz region

How to increase the ISB wavelength?

Reduce the internal electric field in the GaN well

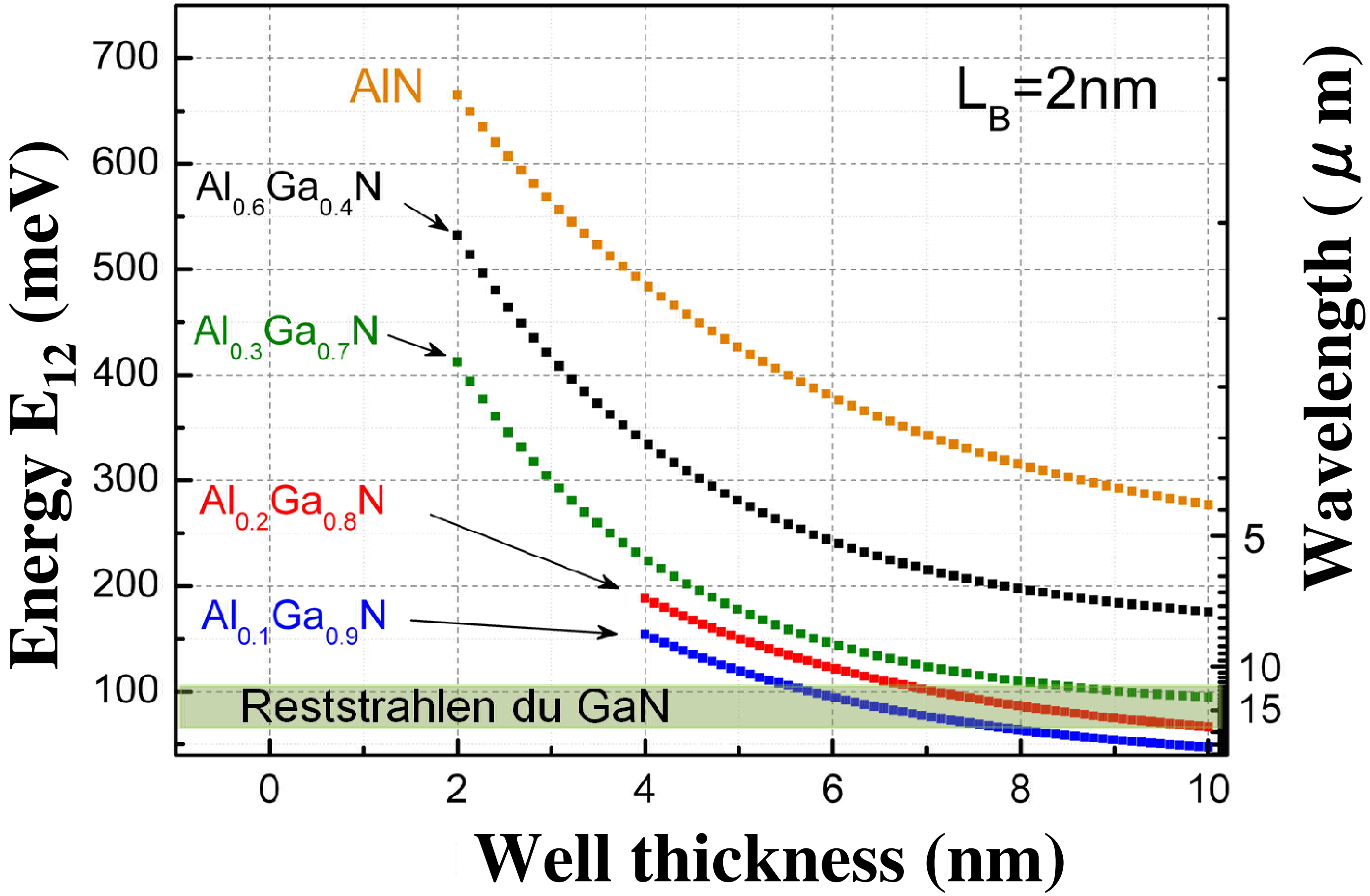


$$F_w = \frac{P_b - P_w}{\varepsilon_0}\frac{L_b}{L_b\varepsilon_w + L_w\varepsilon_b}$$

$$F_b = -\frac{P_b - P_w}{\varepsilon_0}\frac{L_w}{L_b\varepsilon_w + L_w\varepsilon_b}$$

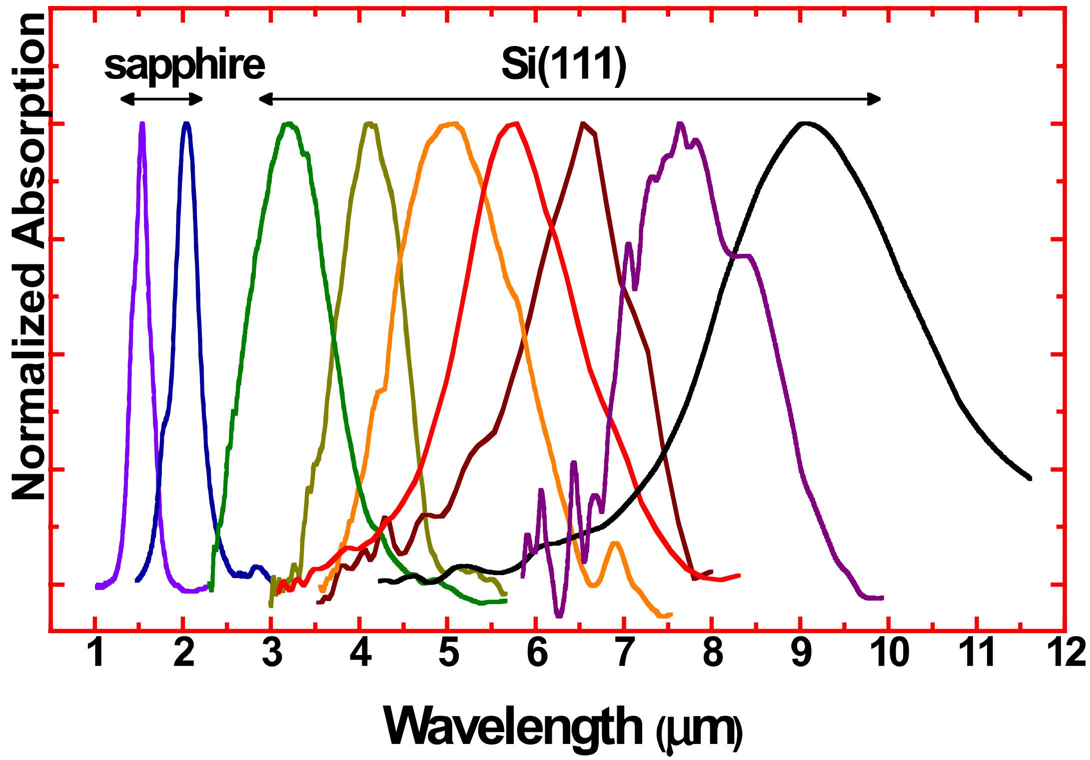
✓ Reducing the Aluminium content in the barrier
✓ Decreasing the barrier thickness
✓ Increasing the well thickness

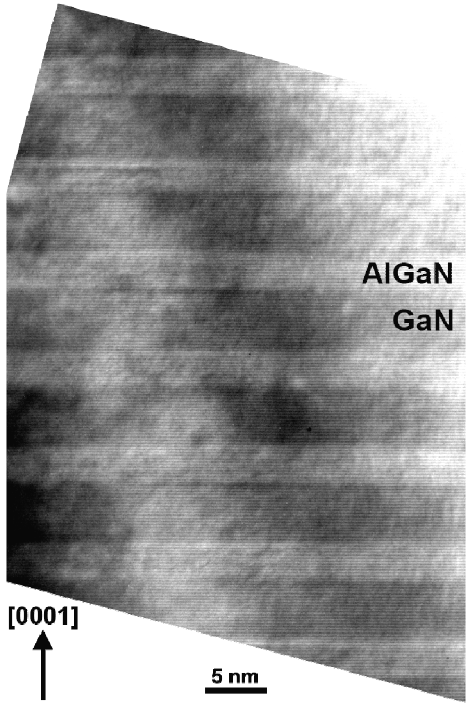
Tunability in the mid-infrared spectral range



- ISB absorption can be easily tuned in the MIR
- ISB can go below the GaN Reststrahlen band for $Al_{0.1}Ga_{0.9}N/GaN$ QWs with thickness > 9 nm

MID-IR absorption in GaN/AlGaN QWs

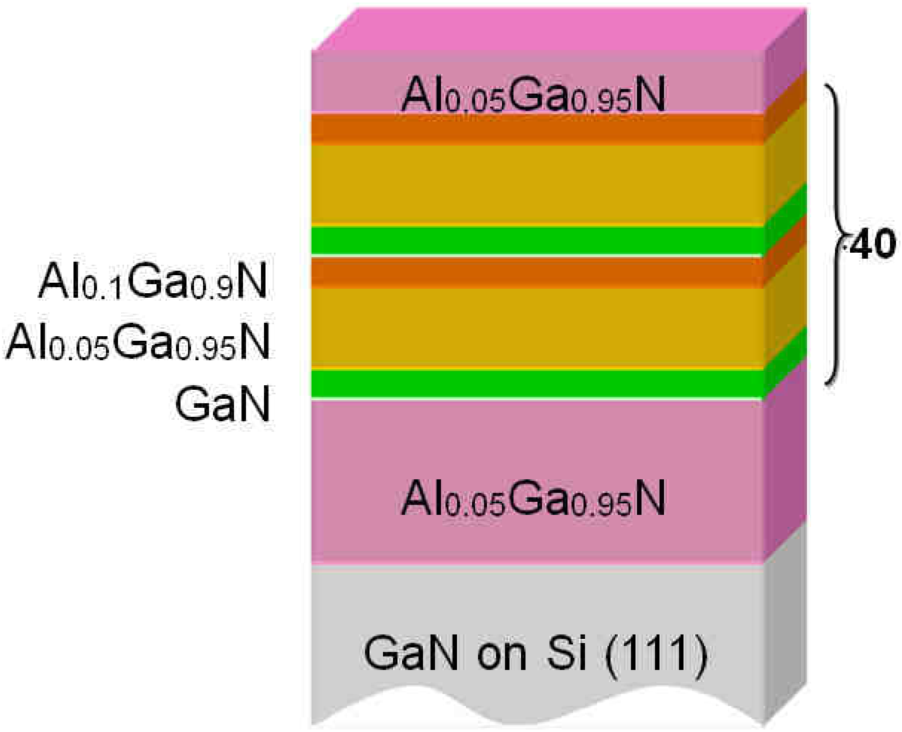


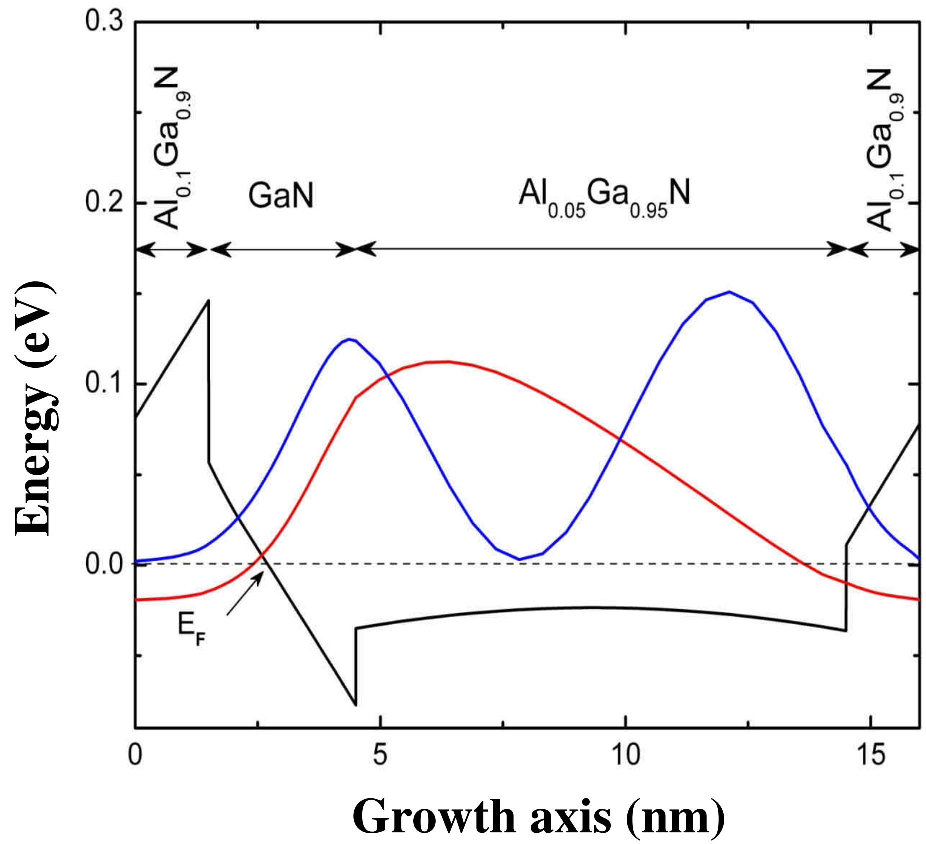


- ✓ Room-temperature ISB absorptions up to ~ 9.5 µm
- ✓ Parameters: barrier Al content (**10**-100%), barrier width (~3 nm) well width (1.5-**8 nm**), doping ($1x10^{19}$ cm^{-3})

P. Kandaswamy et al., Appl. Phys. Lett. 96, 141903 (2010)

Going to far-infrared – step quantum well

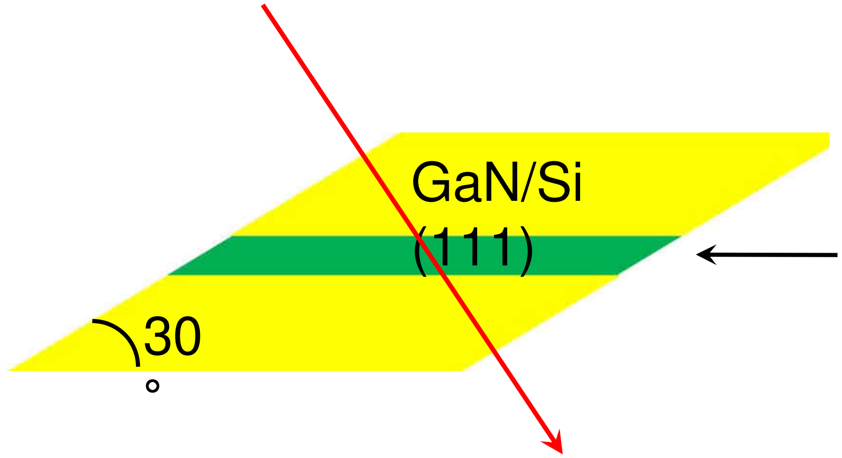


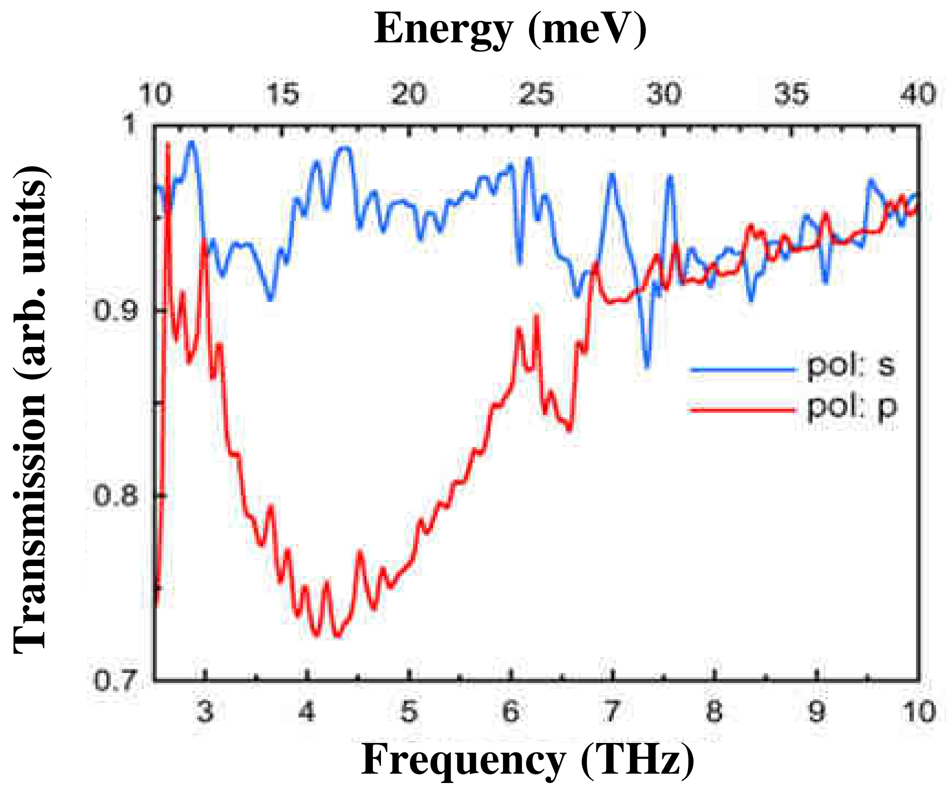


✓ Design of a step quantum well with an AlGaN insertion having an intermediate Al content

✓Almost flat potential profile in the AlGaN step

Observation of far - IR absorption in GaN quantum wells



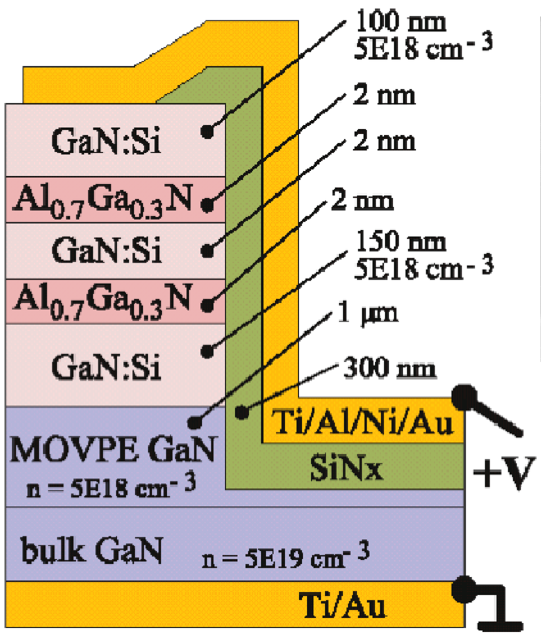


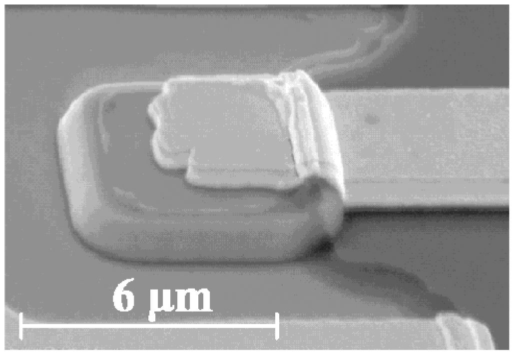
Low temperature (4K) transmission measurements

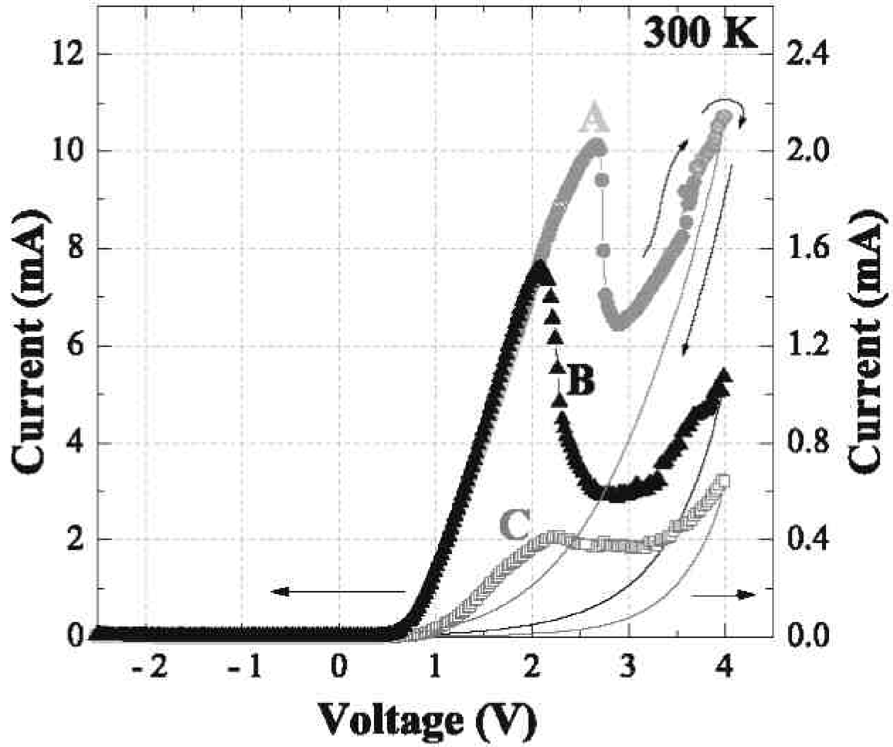
Step 10 nm : e_1-e_2 = 17 meV (4.2 THz)

H. Machhadani et al., APL ***97****, 191101 (2010)*

Tunneling in III-N thin film heterostructures



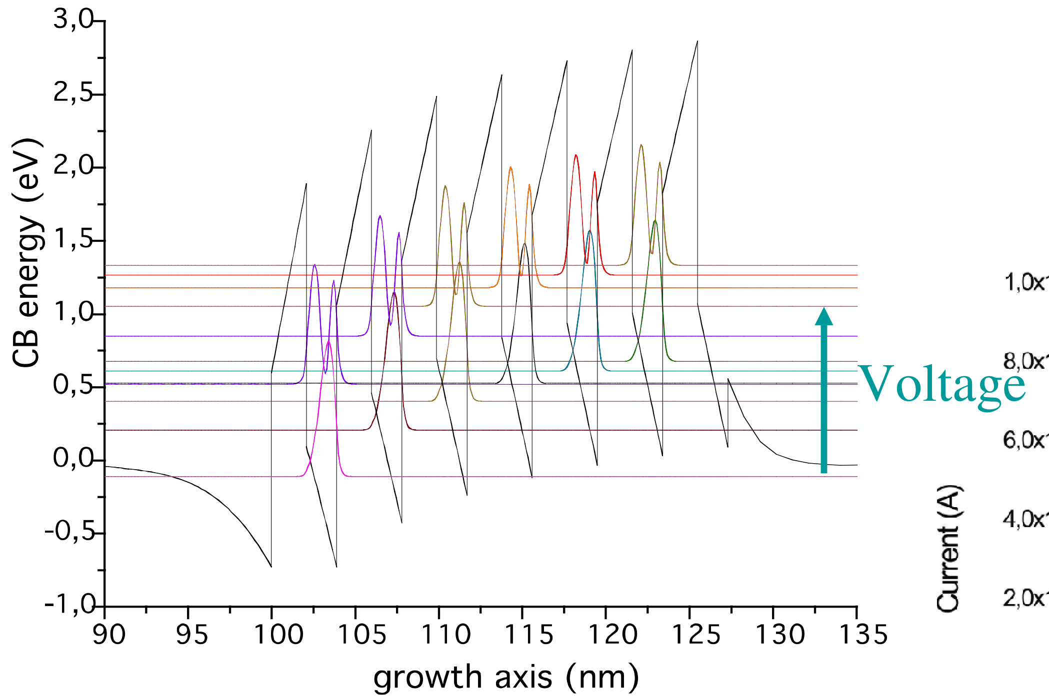


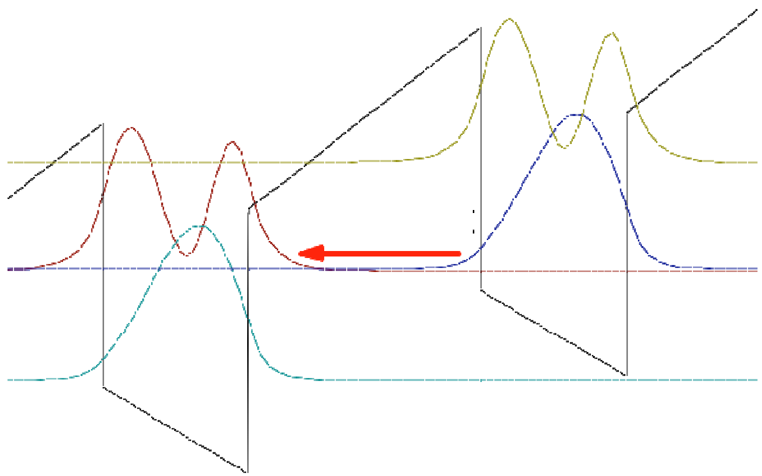


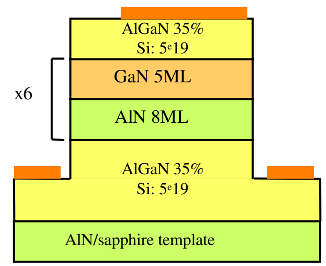
Negative differential resistance observed in I-V characteristics at 300K
But appears only once for forward bias scan
Problem of non-reproducibility attributed to material defects

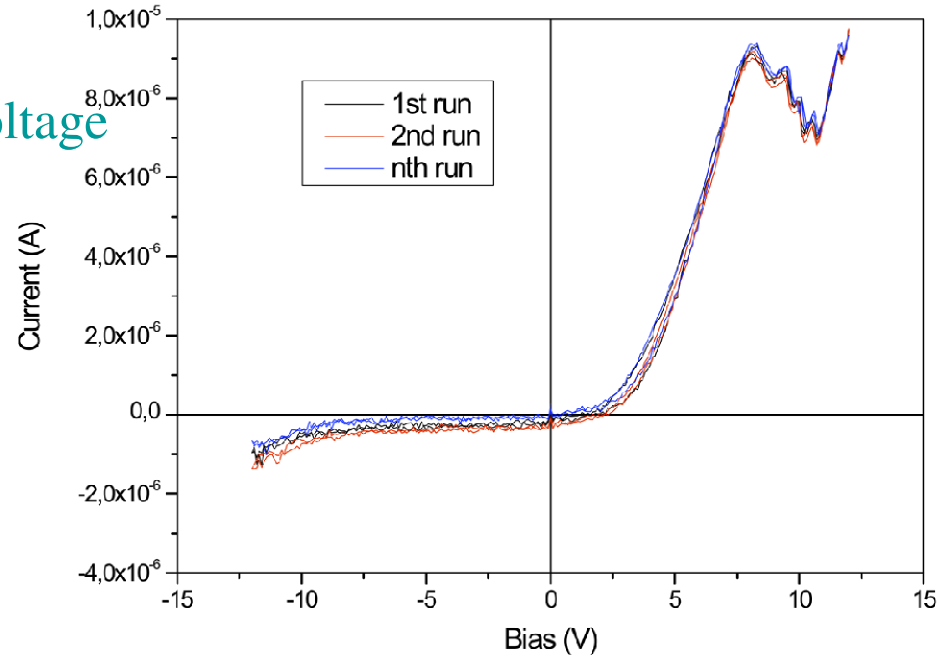
S. Golka et al., Appl Phys Lett 88, 172106 (2006)

Resonant tunneling in a GaN/AlN superlattice









Reproducible resonant tunneling in a GaN/AlN superlattice

Attributed to the consecutive alignment of e_1 and e_2 levels of adjacent QWs

S. Sakr et al. APEX 5, 052203 (2012)

Conclusions and prospects

- Nitride semiconductors present numerous advantageous for near IR and THz spectral ranges

- Huge progress in crystal growth has made possible III-nitride ISB devices such as electro-optical modulators and cascade photodetectors

- Next route is to achieve ISB laser emission ... Only spontaneous emission has been observed so far

- III-nitride are expected to outperform quantum cascade lasers in the THz frequency range because of the large LO-phonon energy

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