TOSHIBA
Leading Innovation

Intersubband Transition in GaN/AlN Multiple Quantum Wells for Optical Switches

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Outline

1. Background

   > Very fast relaxation in GaN ISBT

   > Effect of built-in field

2. Verification of fast absorption recovery and estimation of intensity of saturable absorption

3. Fabrication and characterization of optical switches

   >Optical gate within 1 ps

   >Switching with extinction ratio of 10 dB

4. Issues to be resolved

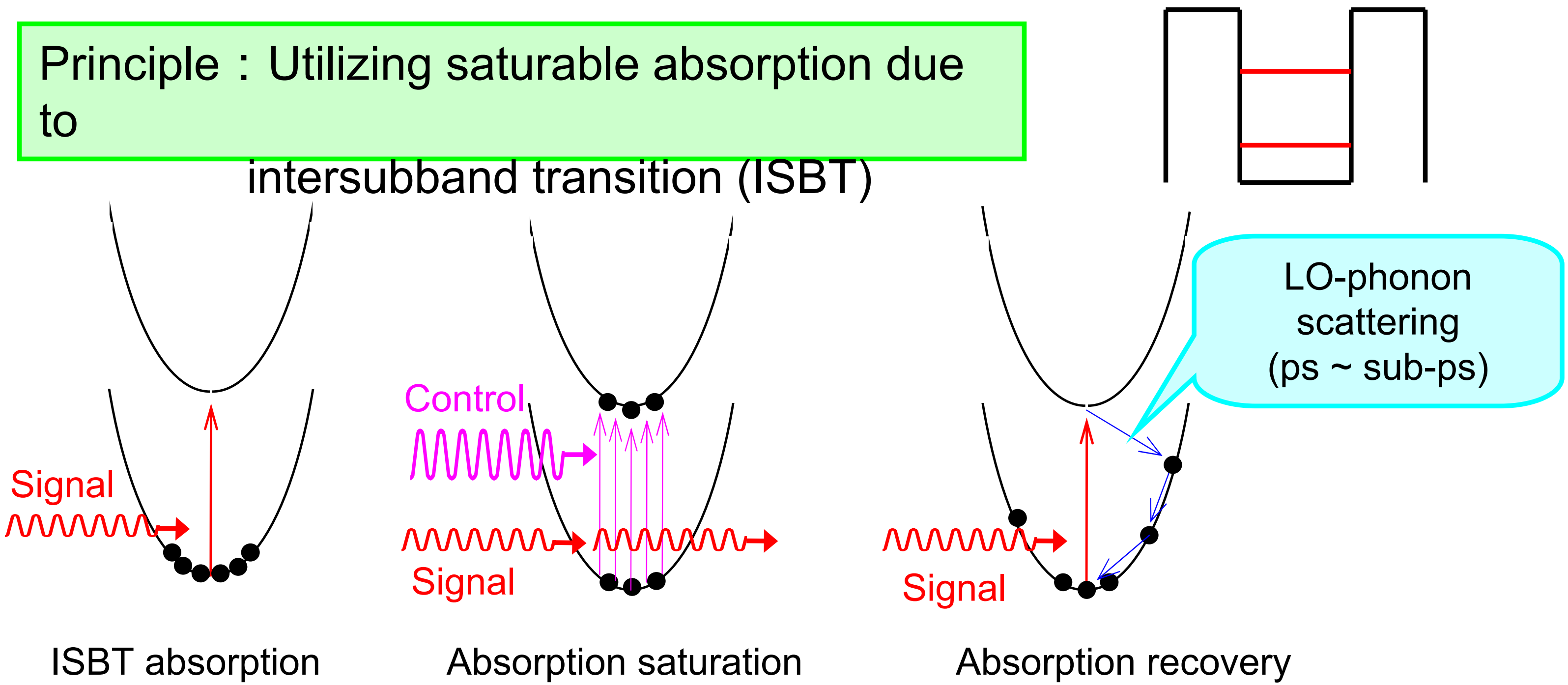
   >Slow decay

   >High switching energy

5. Schemes for further improvement

Optical switching by utilizing ISBT

Principle：Utilizing saturable absorption due to intersubband transition (ISBT)



＊ Polarization dependency: Absorption occurs only for TM-polarization

ISBT relaxation time

- 2→1 ISB scattering (after Ridley)

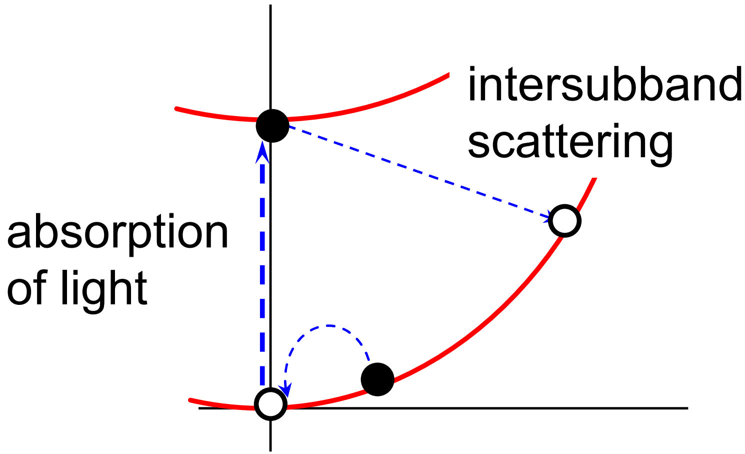
$$W_{21} = \frac{1}{2} W_0 \left(\frac{\hbar\omega_{LO}}{E_1}\right)^{1/2} \left[\frac{1}{4-(\hbar\omega_{LO}/E_1)} + \frac{1}{12-(\hbar\omega_{LO}/E_1)}\right]$$

E_1: energy of 1st subbnad

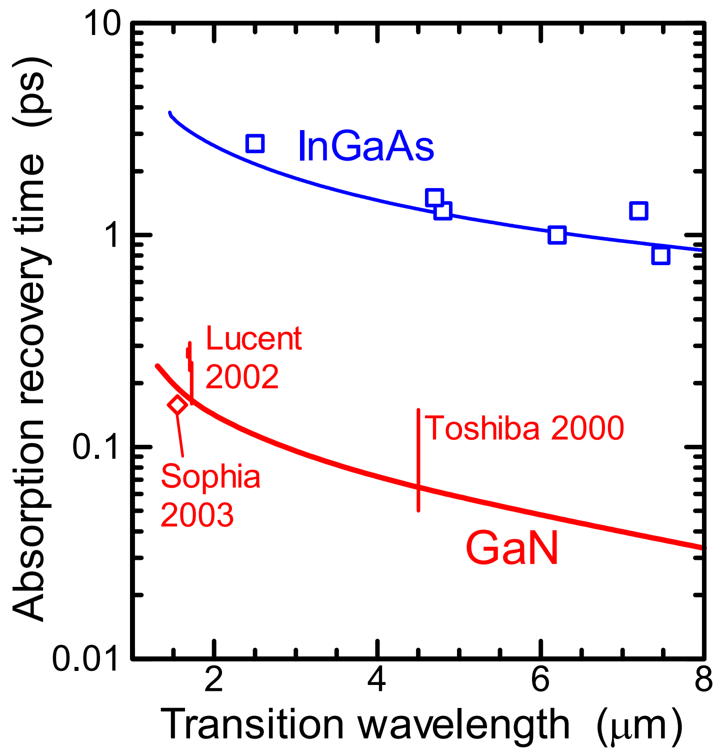
material parameters		GaN	InGaAs	CdS
effective mass (m_0)	m^*	**0.2**	**0.042**	**0.19**
static dielectric constant	ε_s	**9.5**	**14.1**	**10.3**
optical dielectric constant	ε_∞	**5.4**	**11.6**	**5.2**
LO phonon energy (meV)	$\hbar\omega_{LO}$	**88**	**36**	**38**
$W_0 = \frac{e^2}{4\pi\hbar}\left(\frac{2m^*\omega_{LO}}{\hbar}\right)^{1/2}\left[\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_s}\right]$	$(p^{-1}s^{-1})$	**121**	**6.7**	**90**

GaN has the largest ISB scattering rate.

Wavelength dependence of relaxation time

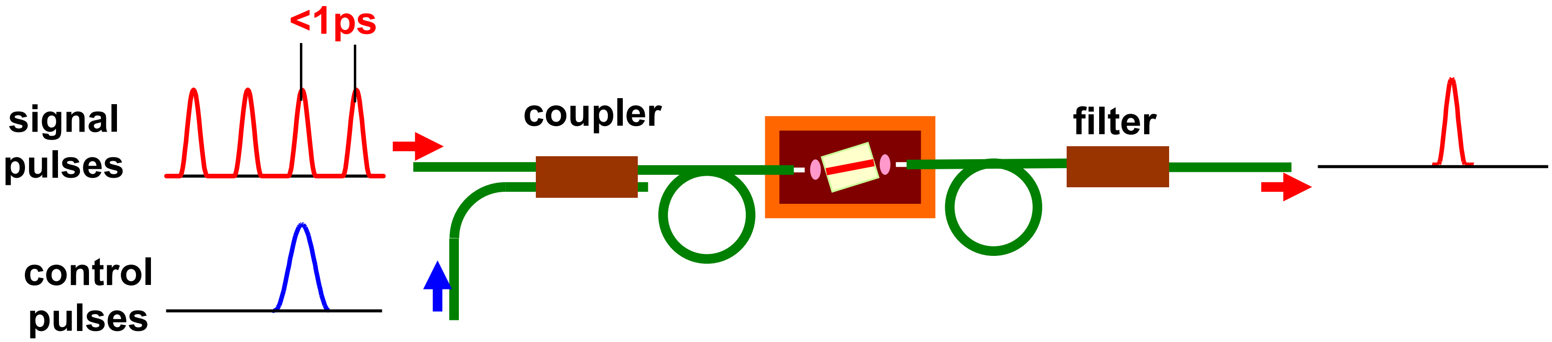


τ_{recov} ~ 200 fs @ 1.55 μm

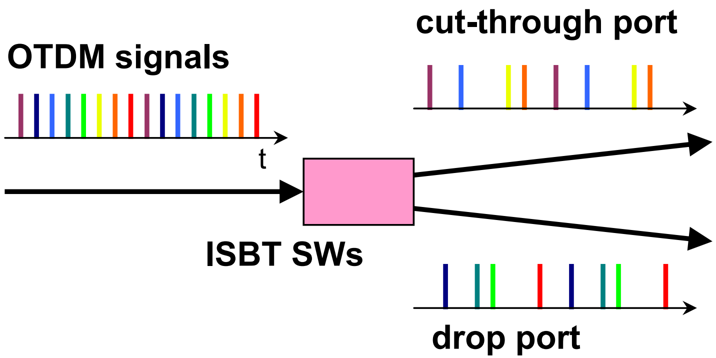


Our proposal:
Utilizing ISBT in GaN QWs for ultrafast optical devices

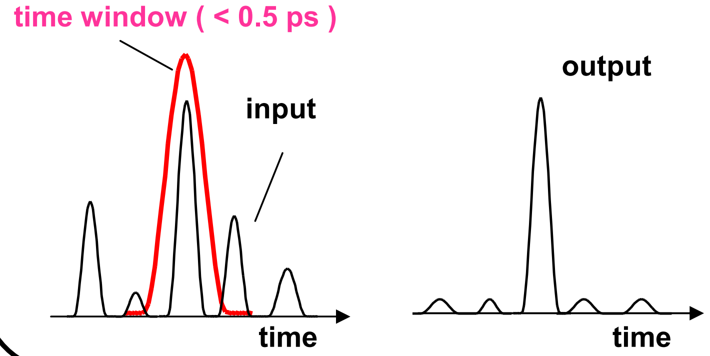
Potential applications



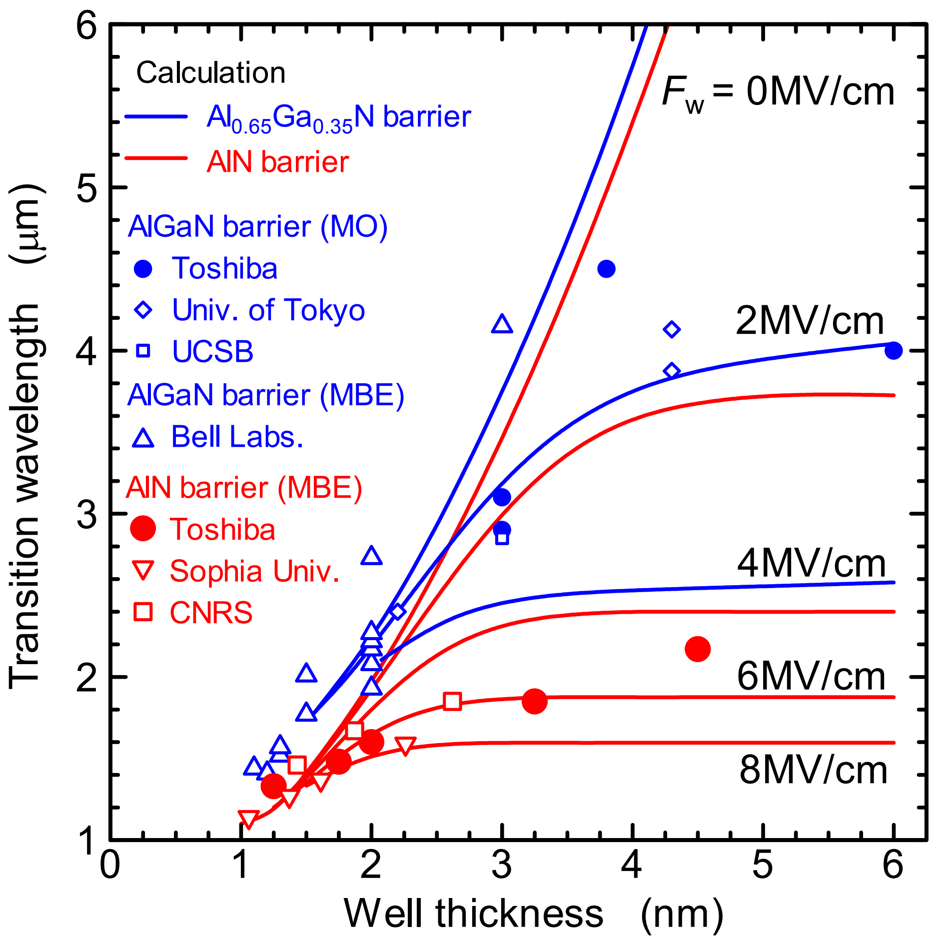
Pulse selector for OTDM-ADM



Ultrafast optical gate in OCDM



Transition wavelength & well thickness



History

Year	Group	λ (μm)	Growth
1997	UCSB	2.9 μm	MOCVD
1998	Toshiba	2.9 μm	MOCVD
2000	Lucent	1.4 μm	MBE
2002	Sophia U.	1.08 μm	MBE
2002	Toshiba	1.33 μm	MBE
2003	U. Tokyo	2.4 μm	MOCVD

Field strength in GaN wells

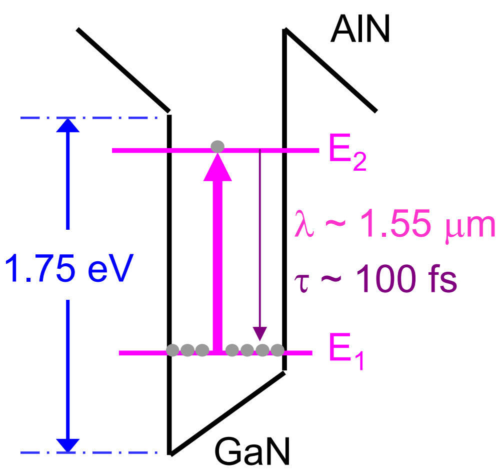
~ 2 MV/cm in GaN/$Al_{0.65}Ga_{0.35}N$

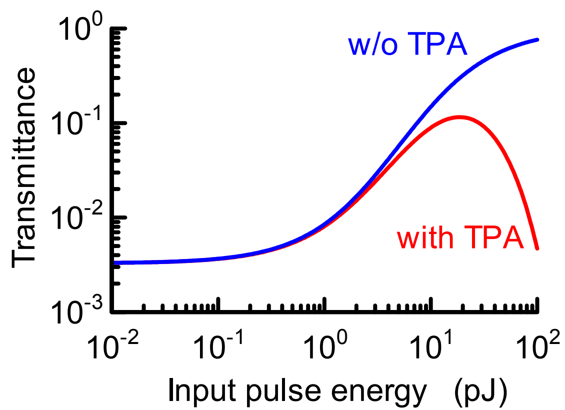
> 5 MV/cm in GaN/AlN

- Piezoelectric effect
- Spontaneous polarization

Features of ISBT in GaN QWs

- Large ΔE_c (> 1.75 eV)
  → optical communication wavelength (1.55 μm)
- Short intersubband relaxation time (~ 200 fs)
  → Ultrafast response (~ 1 Tb/s)
- Short dephasing time (< 30 fs)
  → Broad bandwidth (> 150 nm)
- Wide gap (> 3.6 eV)
  → Suppression of TPA
  (*Cf.* TPA interferes with SA in InGaAs)
- Robust and less toxic material





Early studies on GaN ISBT (~2002)

- Feasibility study of optical switch utilizing ISBT in GaN
  - 1997 N. Suzuki et al. (Toshiba)
- Realization of GaN-ISBT at MIR
  - 1997 R. Kehl Sink et al. (UCSB)
  - 1998 N. Iizuka et al. (Toshiba)
- Realization of GaN-ISBT at NIR
  - 2000 C. Gmachl et al. (Bell Labs)
  - 2002 N. Iizuka et al. (Toshiba)
  - 2002 K. Kishino et al. (Sophia U.) @ 1.08 μm: shortest wavelength
- Verification of fast absorption recovery
  - 2000 N. Iizuka et al. (Toshiba) @ 4.5 μm
  - 2001 C. Gmachl et al. (Bell Labs.) @ 1.55 μm

Recent studies on GaN ISBT (2002~)

- Intensive studies on the nonlinearity
  - 2002 ~ 2003 Bell labs
  - 2004 ~ 2005 J. Hamazaki et al. (Sophia U.)
- Realization of GaN-ISBT at NIR by MOCVD
  - 2004 I. Waki et al. (U. Tokyo) @ 2.4 μm
  - 2006 S. Nicolay et al. (EPFL) @ 2.0 μm
  - 2007 (ITQW07) M. Halsall et al. (U. Manchester) @ 1.2 - 1.7 μm
- Light emission
  - 2007 (ITQW07) L. Nevou et al. (U. Paris-Sud) @ 1.3 - 2 μm, SHG @ 1 μm
- Detector
  - 2003 D. Hofstetter et al. (U. Neuchâtel)
  - 2006 (ITQW07) E. A. DeCuir et al. (U. Arkansas)
  - 2007 (ITQW07) A.Vardi et al. (Technion-Israel Inst. Tech.)
- Switching / modulation
  - 2004 N. Iizuka et al. (Toshiba): XAM (Cross absorption modulation)
  - 2006 E. Baumann et al. (U. Neuchâtel): E-O modulator
  - 2007 (ITQW07) N. Kheidrodin et al. (U. Paris-Sud): E-A modulator
  - 2007 Y. Li et al. (Boston U.): Saturable absorption
- Dots
  - 2003 Kh. Mousmanis et al. (U. Paris-Sud)
  - 2006 G. Guillot et al. (CEA-Grenoble)
  - 2007 (ITQW07) L. Nevou et al. (U. Paris-Sud)
  - 2007 (ITQW07) G. Bahir et al. (Technion-Israel Inst. Tech.)

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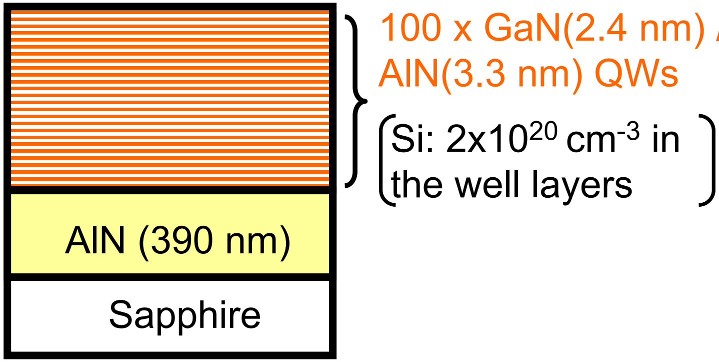
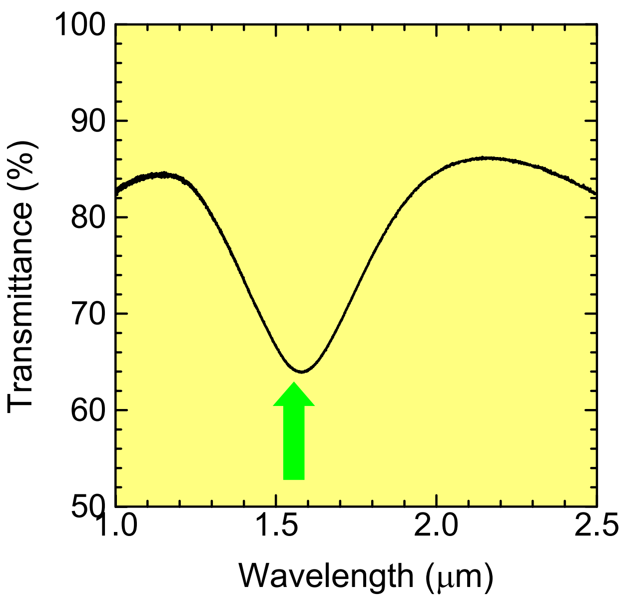
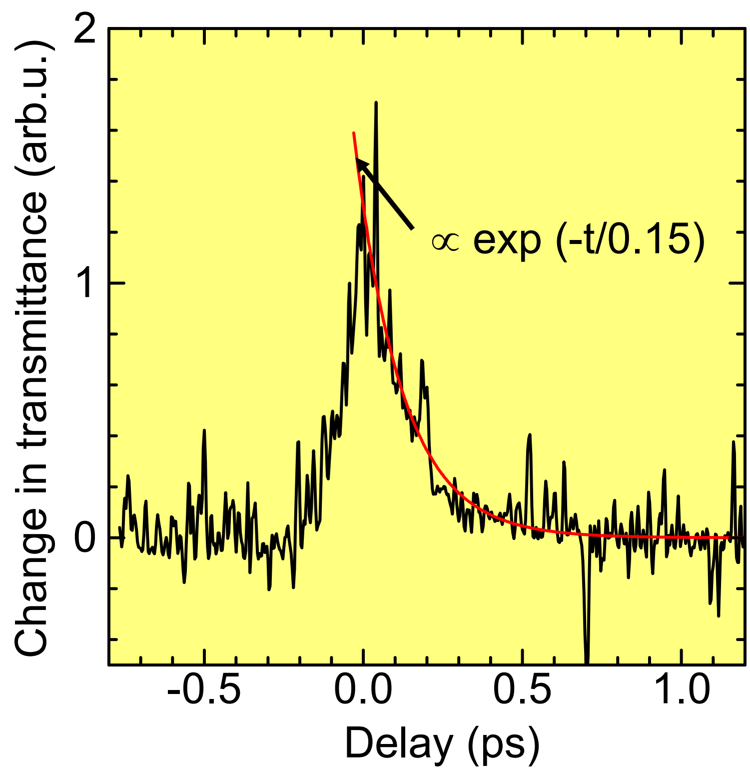
Sub-picosecond absorption recovery





Pump-probe measurements:
1.55 μm, 1 KHz, 130 fs

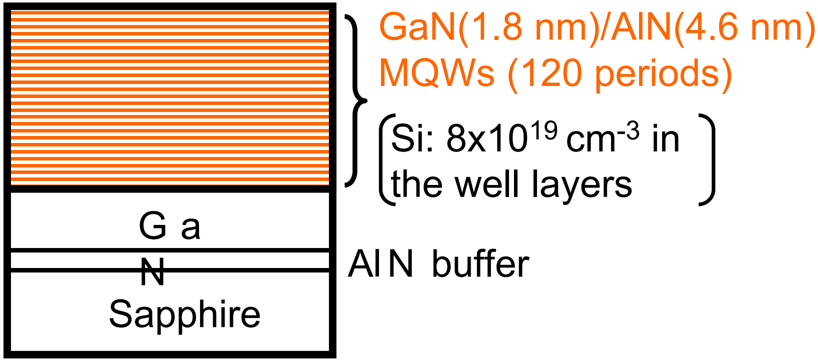


Absorption recovers within 1 ps.

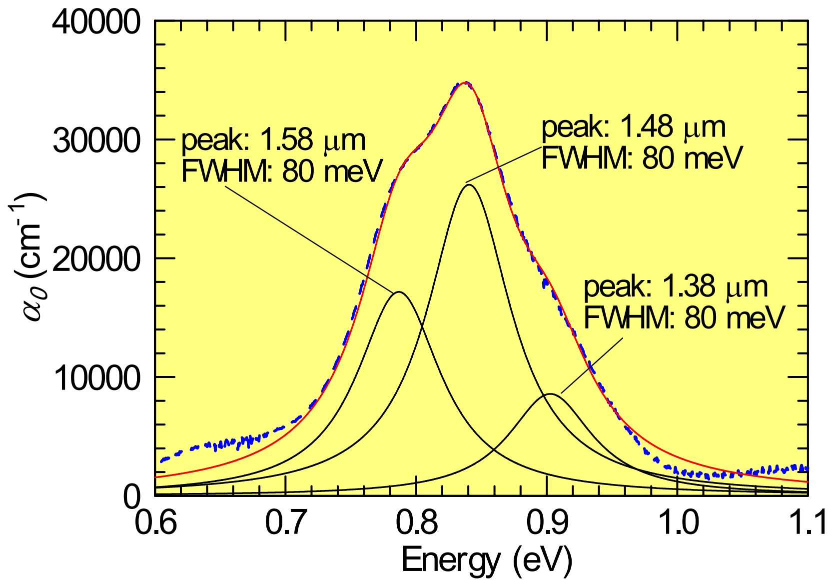
Estimation of saturation intensity

$$\frac{\alpha(I)}{\alpha(0)} = \sum \frac{p_i g_i(\nu)}{1 + I/I_{si}} \Big/ \sum p_i g_i(\nu)$$

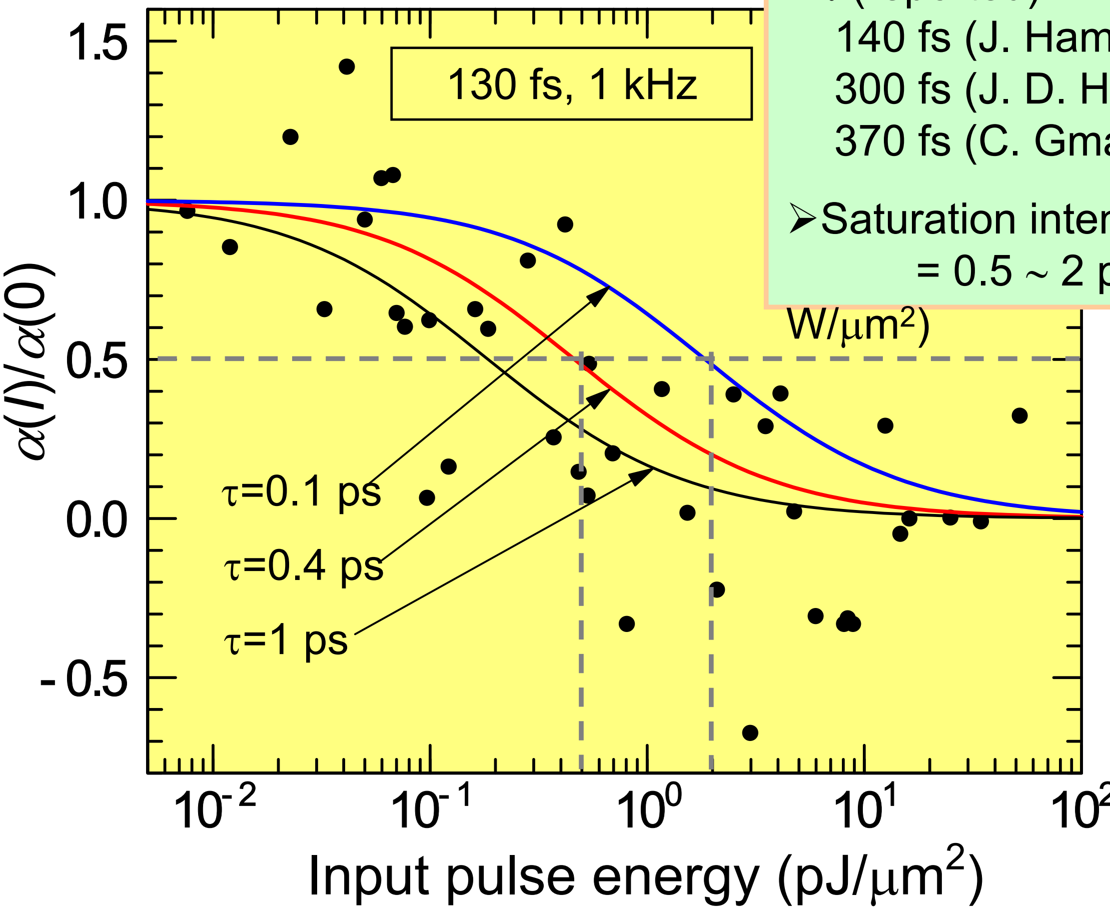
$$I_{si} = \frac{n_i \pi h \nu_0 \Delta\nu}{4\tau} \frac{1}{\int \alpha_0(\nu) d\nu}$$



I: intensity
I_{si}: saturation intensity
p_i: ratio of the carrier density
g_i: normalized Lorentzian
ν: optical frequency
τ: absorption recovery time (fitting parameter)



Comparison between calculation and experiment



- τ (reported)
  140 fs (J. Hamazaki et al.)
  300 fs (J. D. Heber et al.)
  370 fs (C. Gmachl et al.)
- Saturation intensity (pulse width: 130 fs)
  = 0.5 ~ 2 pJ/μm^2 (3.6 ~ 14.4 W/μm^2)

Iizuka et al., APL, vol. 81 (2002)

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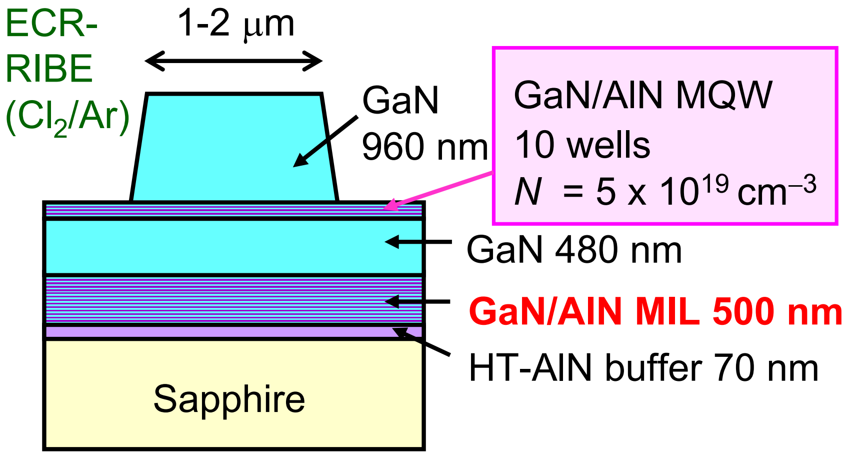
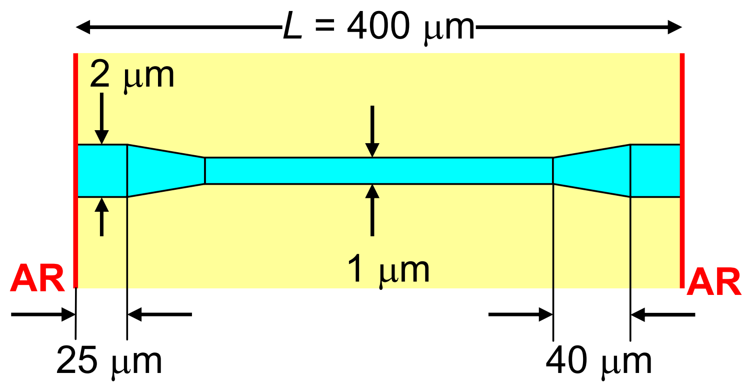
Structure of gate switch

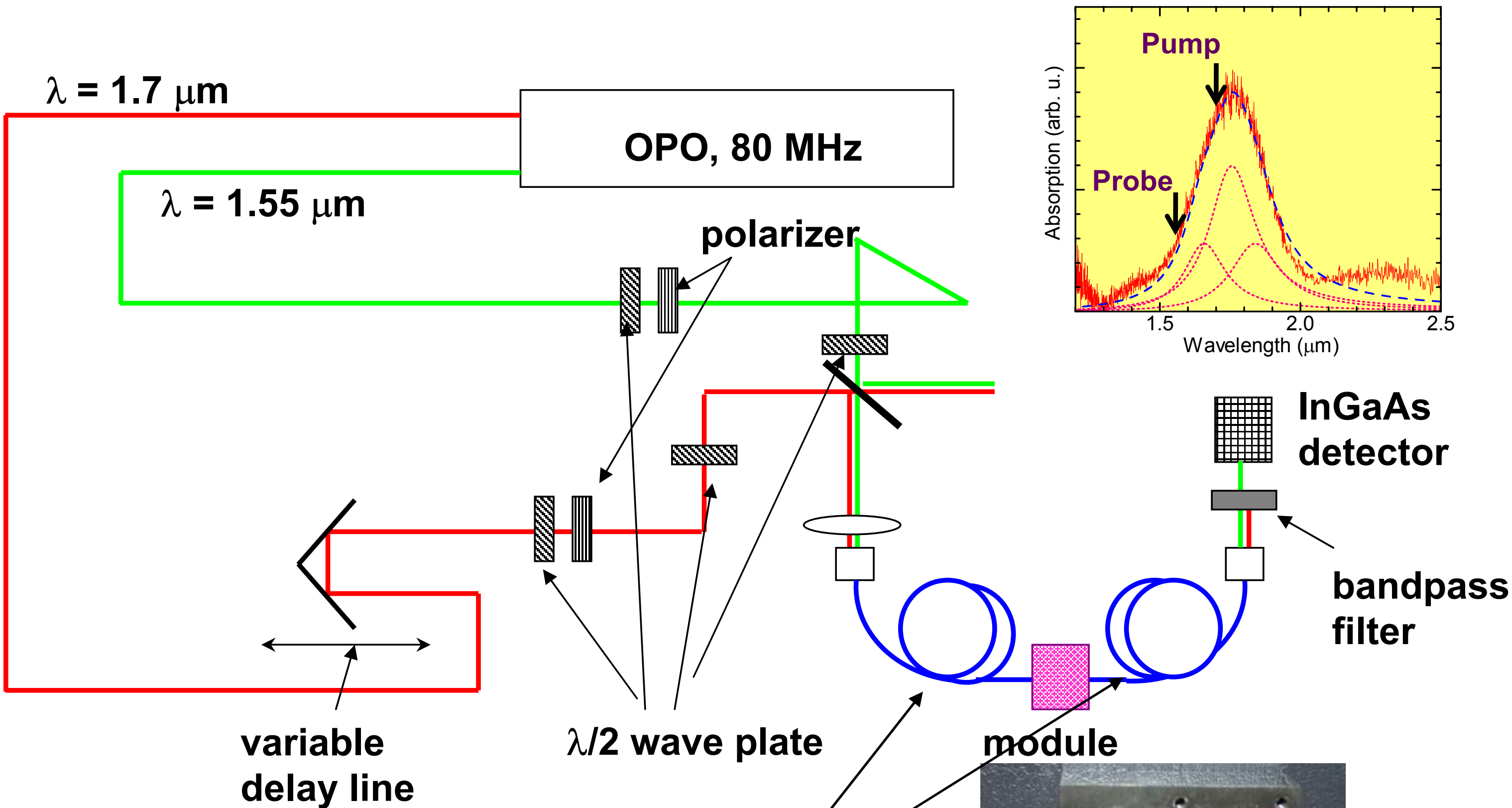
Grown with RF-MBE

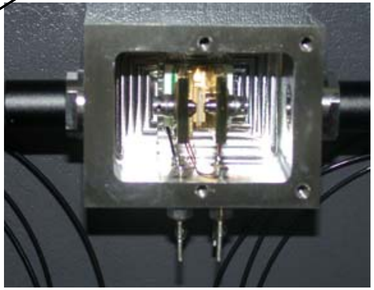




PMDSF : 1 m

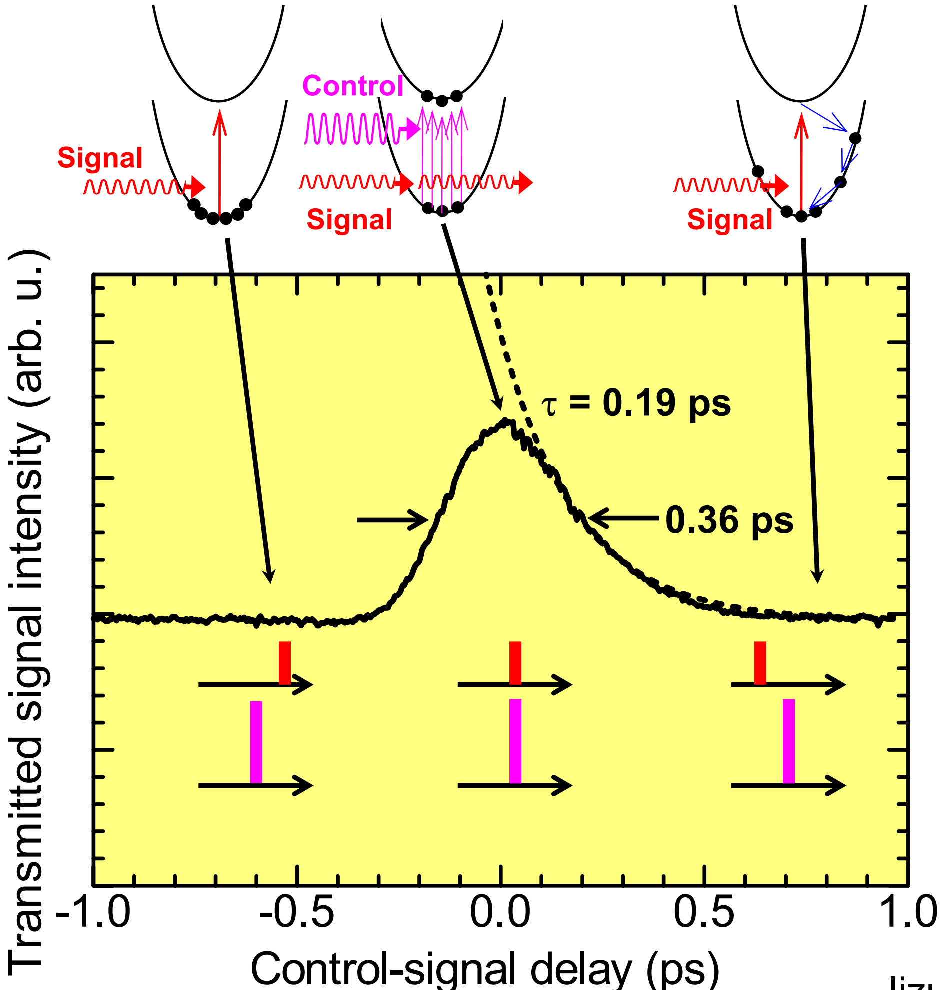
Setup for measurements





Polarization-maintaining dispersion-shifted fibers (PMDSF) to suppress pulse broadening

Gate switch operation



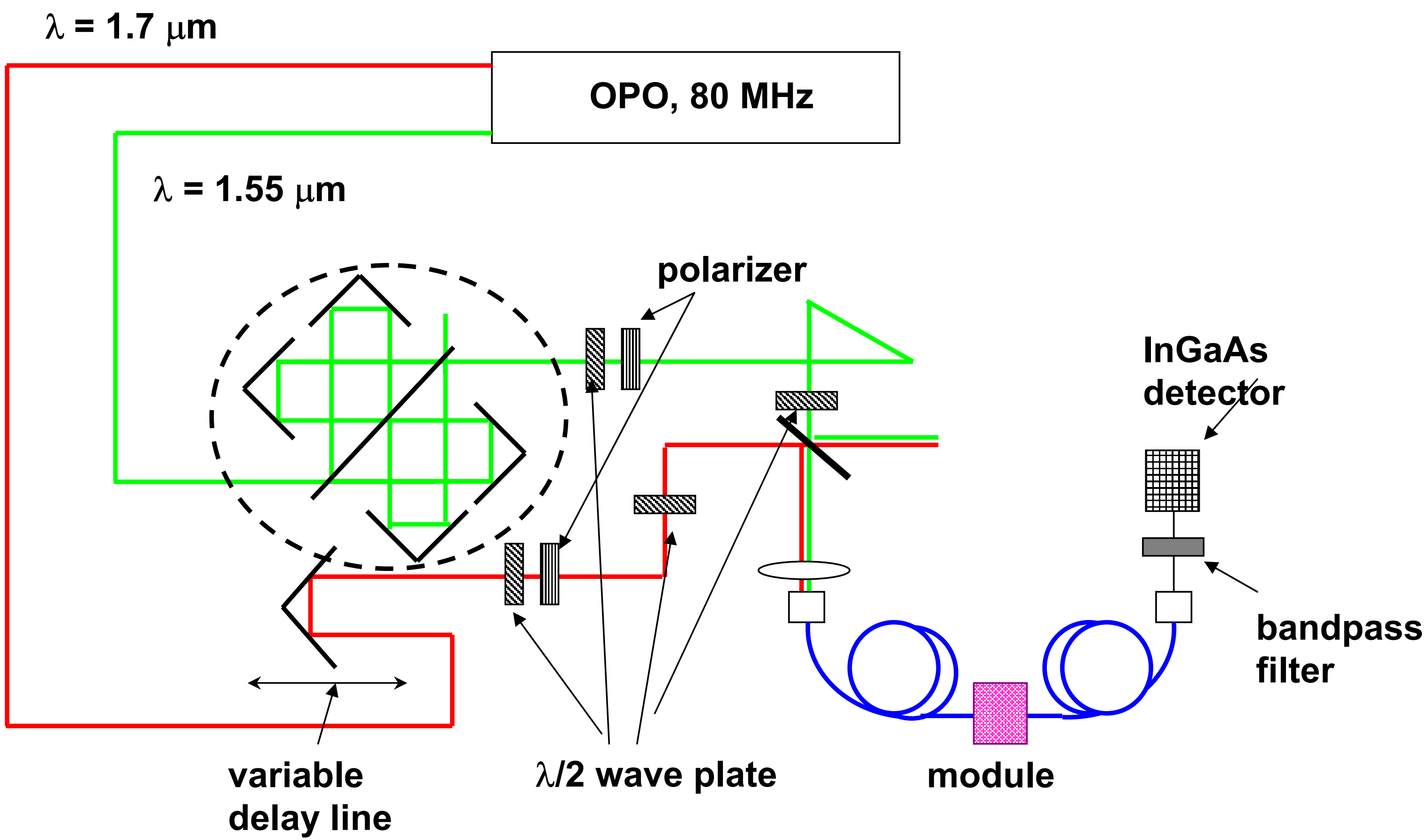
Control (1.7 μm):
120 pJ, 230 fs
Signal (1.55 μm):
10 pJ, 130 fs

⇒2.2 dB modulation

Ultrafast modulation
Gate FWHM:
360 fs
Absorption recovery:
190 fs

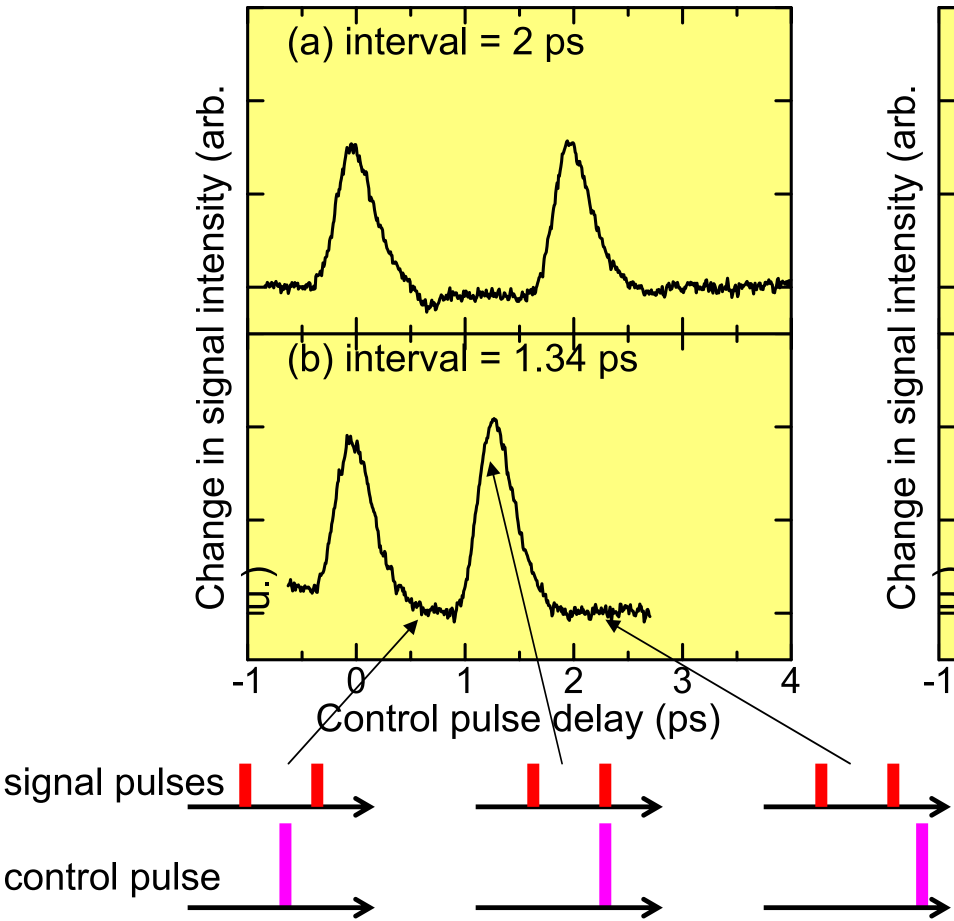
Iizuka et al., Electron. Lett., vol. 40 (2004)

Generation of four serial pulses



Response for serial pulses

Pump: 1.7 μm, 100 pJ, 230 fs   Signal: 1.55 μm, 4 pJ, 130 fs



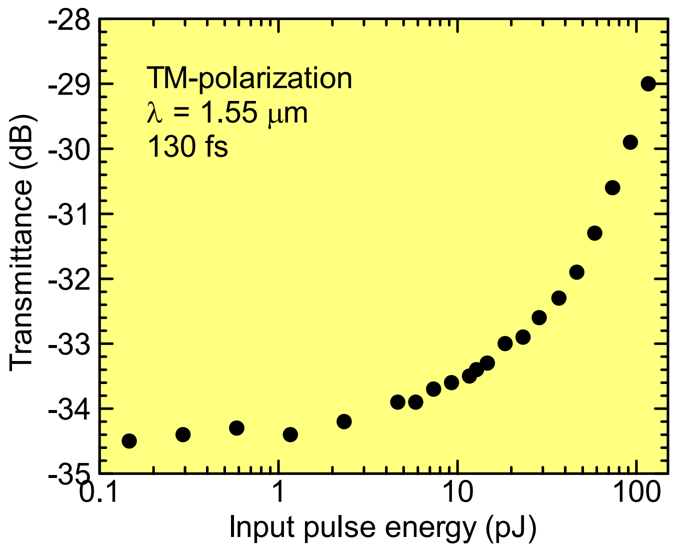
Iizuka et al., IEEE JQE, vol. 42 (2006)

Evidence of DEMUX

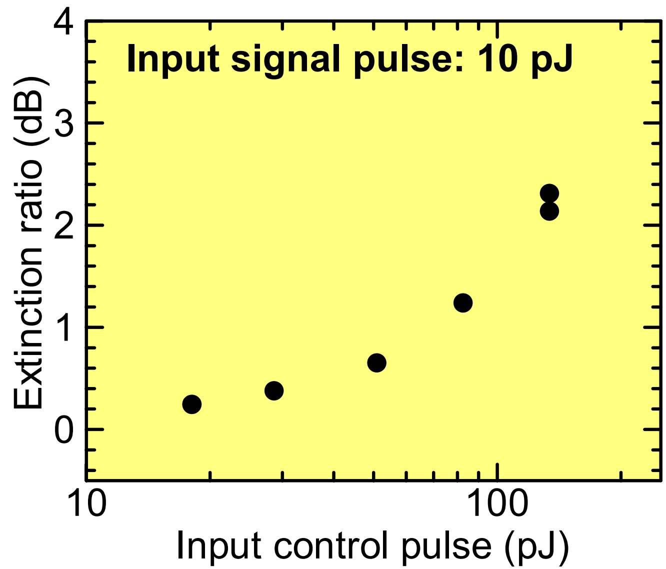
⇒Encouraging with respect to realizing all-optical devices that operate at a bit rate of 1 Tb/s or higher

Absorption saturation and extinction ratio

Saturation characteristics



Switching extinction ratio



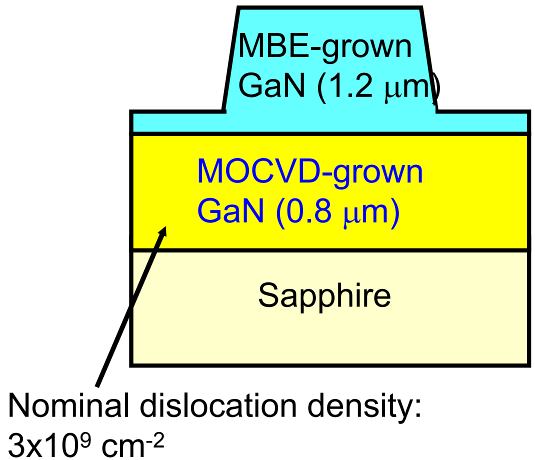
Absorption saturation by 5.5 dB with input of 120 pJ

Switching extinction ratio was 2.2 dB with input of 120 pJ.

➔Too small for practical use

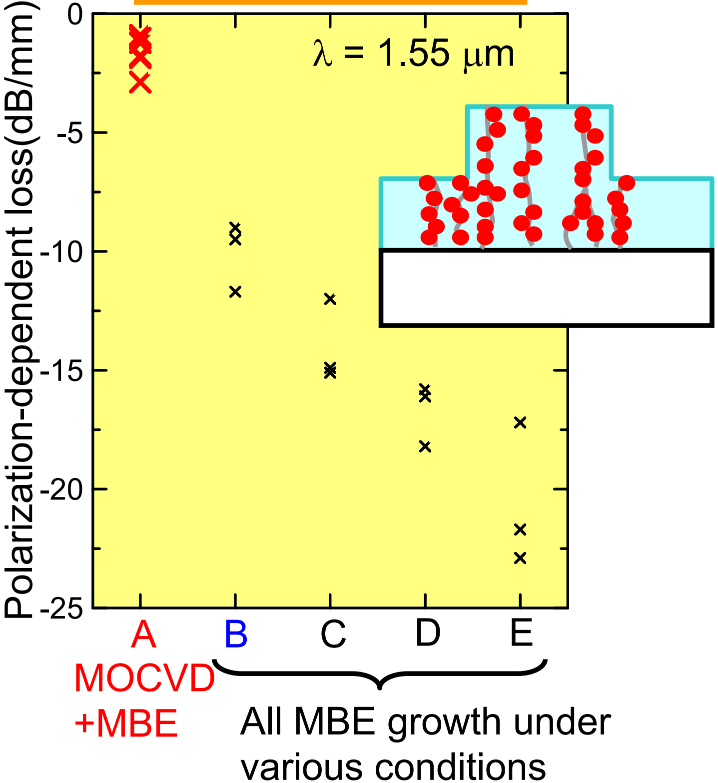
Reduction of excess propagation loss

MOCVD+MBE



Excess PDL was drastically reduced with MOCVD-grown GaN
(2004 MRS Fall Meeting, E8.9)

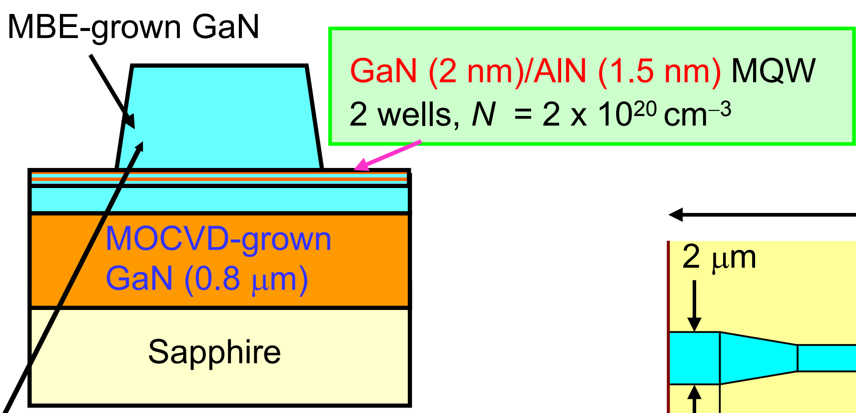
PDL in GaN WG



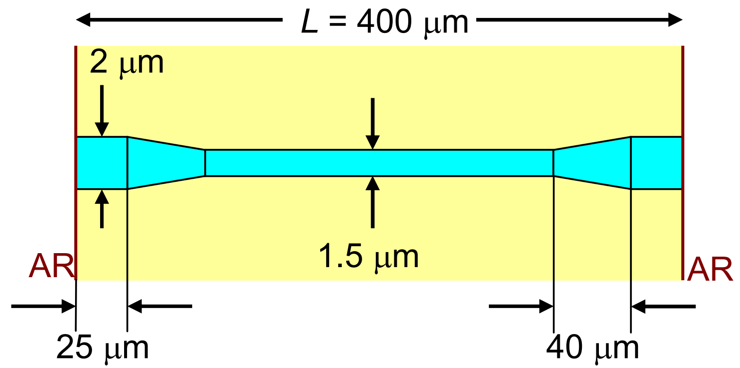
For NIR-ISBT with better crystalline quality, MBE-regrowth of MQWs was attempted on MOCVD-grown GaN.

Iizuka et al., JAP, vol. 99 (2006)

Improved device structure



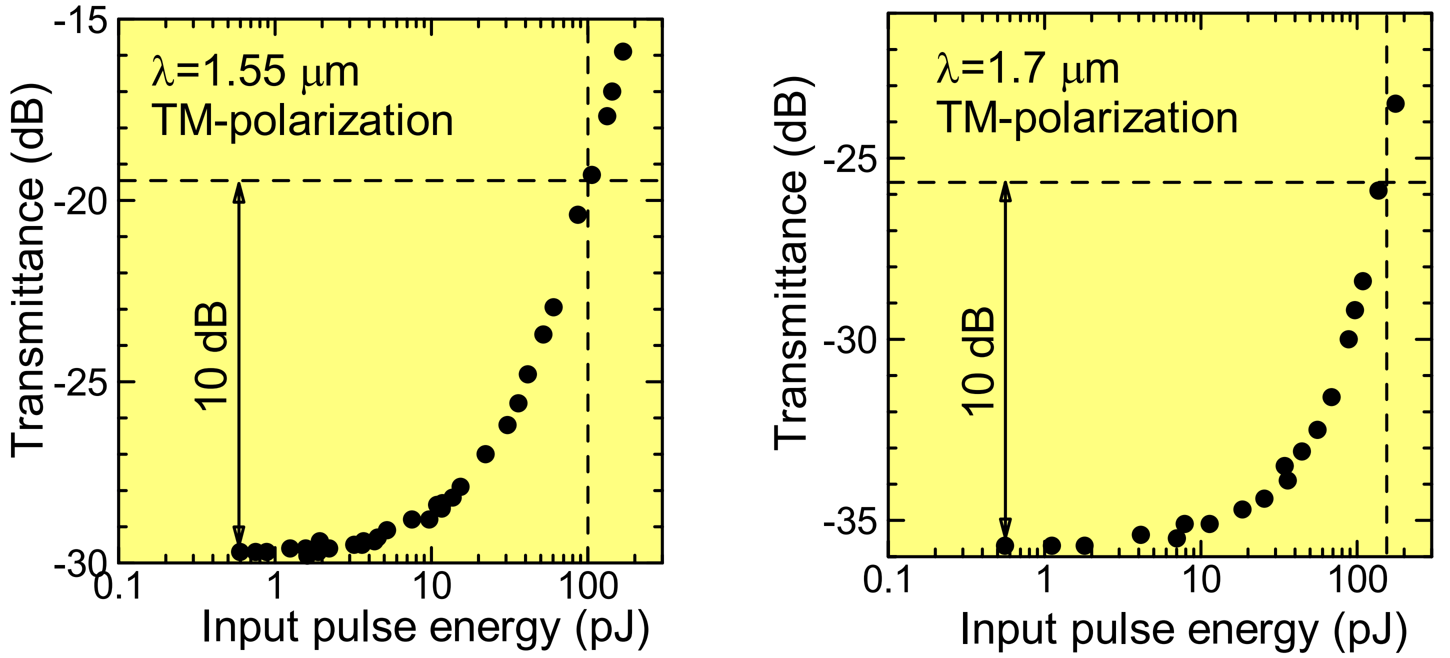
Dislocation density: 1.7x10^{9} cm^{-2}
(previous sample: ~$10^{10}$$cm^{-2}$)



PMDSF : 1 m→0.5 m

⇒Suppression of pulse broadening

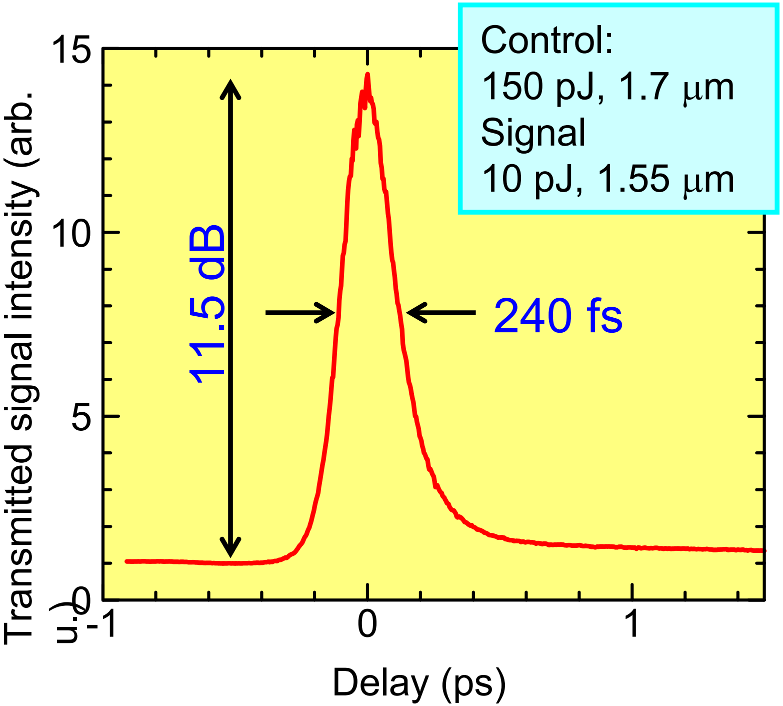
Absorption saturations

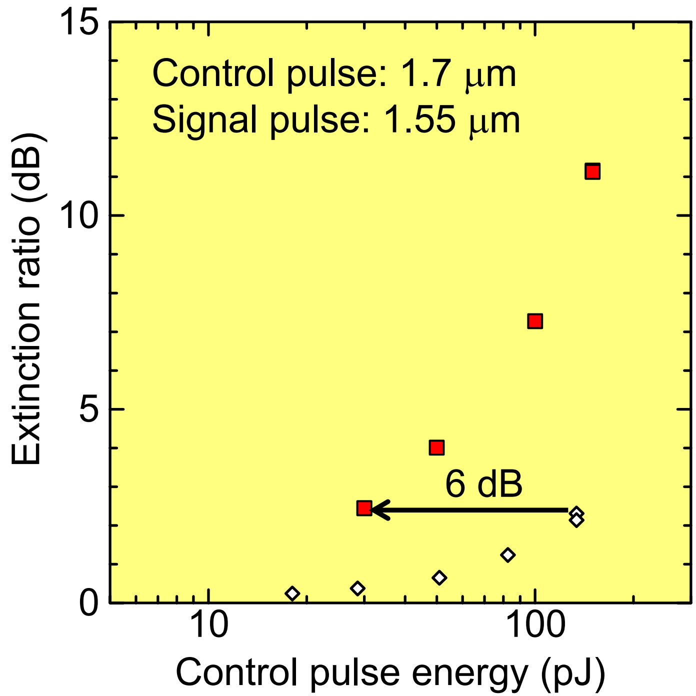


10-dB saturation was achieved for wavelengths of 1.55 μm (100 pJ) and 1.7 μm (150 pJ)

Iizuka et al., Optics Express, vol. 13 (2005)

Improvement of gate switch operation





Switching energy decreased by 6 dB.

As a result, extinction ratio improved.

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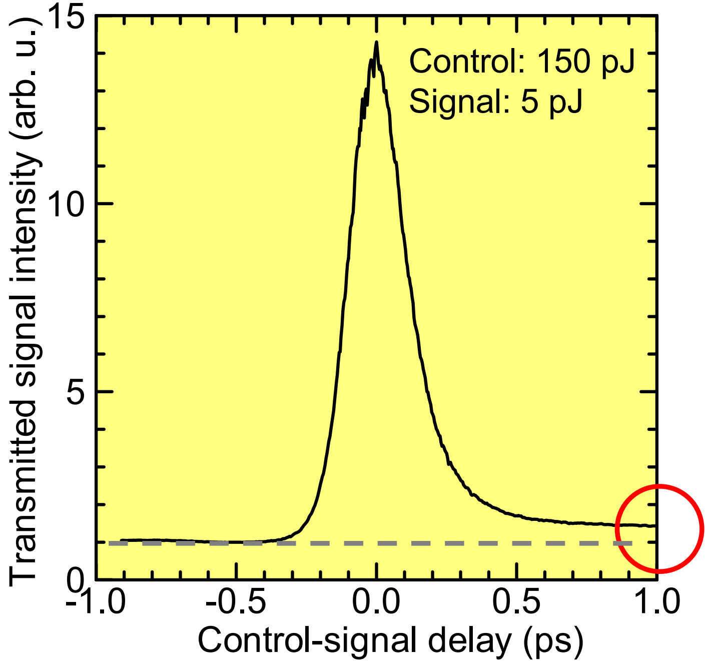
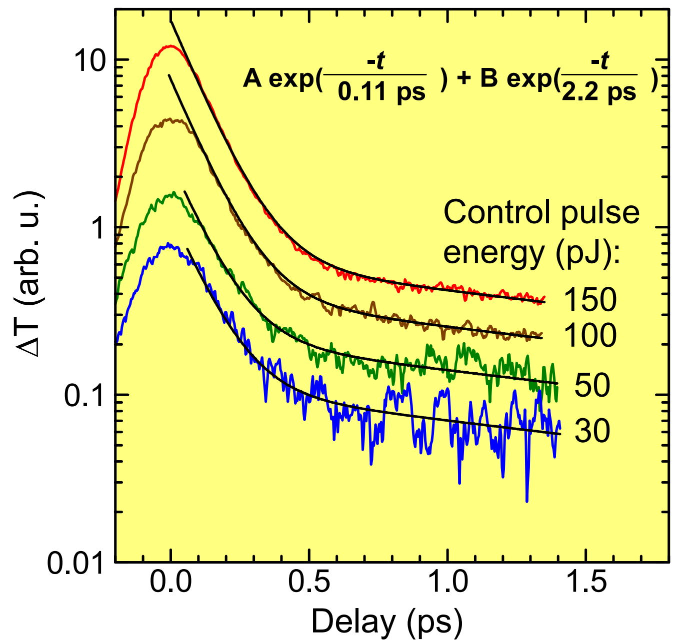
Issues to be resolved - (1) slow decay

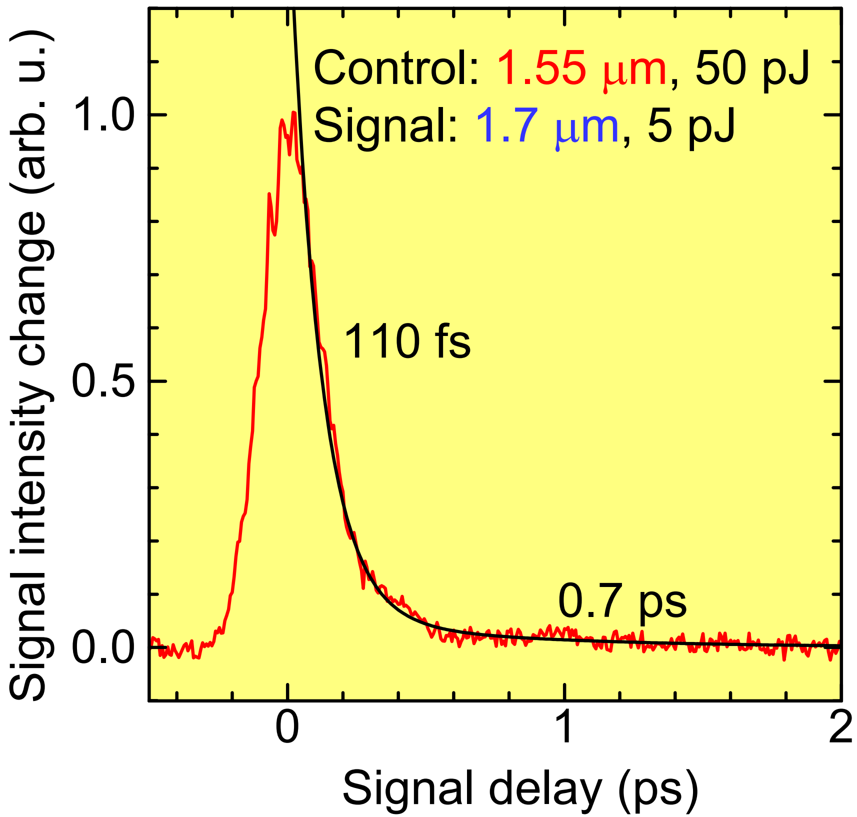




➢The signal did not fully recover within 1 ps.

- It is due to the slow decay (2.2 ps). What is the cause?

Exchange of wavelengths for control and signal

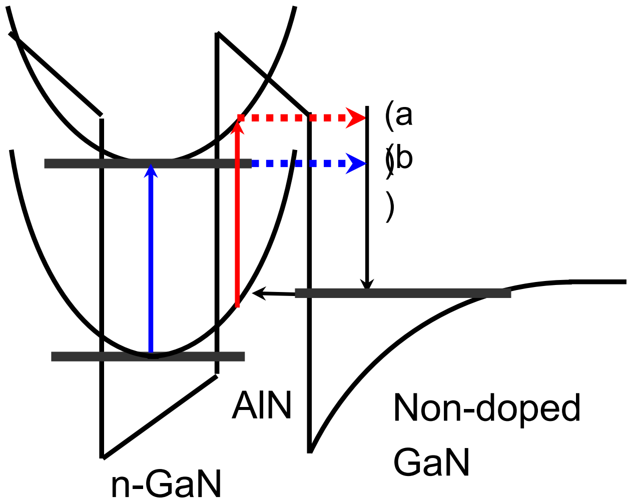


Exchange of wavelength resulted in shortening the time constant of the slow component from 2.2 ps to 0.7 ps.

Iizuka et al., IEEE JQE, vol. 42 (2006)

Our proposed model

◆Proposed model:
The barrier thickness was as thin as 1.5 nm and the number of wells was only two. Then, carriers in the wells may diffuse (tunnel) out to the undelying GaN layer.



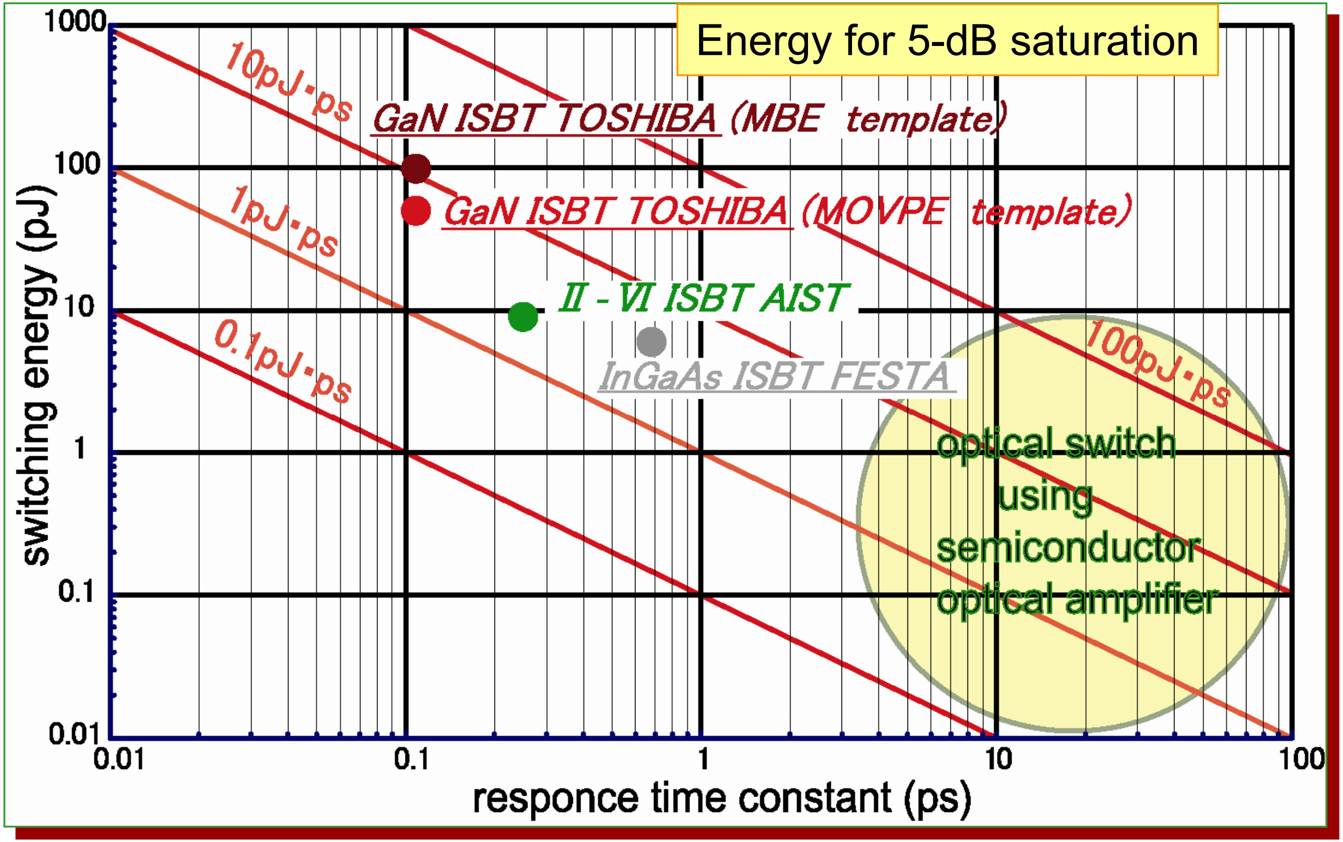
Longer-wavelength probe

⇨Smaller ΔE because of band nonparabolicity

⇨Shorter decay

If parameters of QW structure, e. g. number of wells, barrier thickness and doping, are optimized, the slow decay component can be suppressed.

Issues - (2) switching energy



N. Iizuka et al., J Quantum Electron. **42**, 765(2006)
T. Shimoyama et al., OFC2003 proceedings
R. Akimoto et al., phys. stat. solidi **243**, 805(2006)

Switching energy of GaN ISBT is higher than those of other materials

Issues - (2) switching energy

150 pJ/pulse ⇨ 150 W for 1 Tb/s:Too high for practical use.

Major cause and solutions

1. Device structure was not fully optimized
   - ➢ISBT peak at longer wavelength
   - ➢Simulation suggests the peak of beam profile did not match MQWs

2. Coupling loss (3 dB/facet)
   - ✓improvement of quality of facet
   - ✓greater cross-section

3. Excess polarization-dependent loss (5dB)
   - ✓further reduction in dislocation density
   - ✓suppression of carrier diffusion

4. Size of WG (2 x 1.5 μm)
   - ✓Submicron scale WG with spot-size converter

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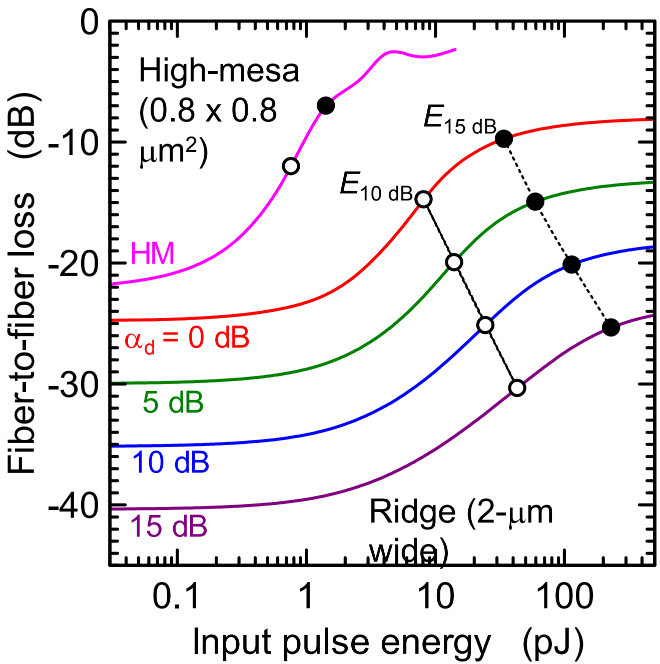
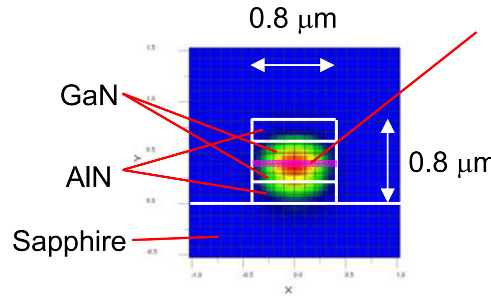
Expected improvement - simulation -



RWG (α_d = 15 dB):	E_{10dB} = 43 pJ
RWG (α_d = 0 dB):	E_{10dB} = 8 pJ
HM (0.8 x 0.8 µm²):	E_{10dB} = 0.8 pJ

High-mesa (HM) WG



MQW (3 wells)
λ_{ISBT} = 1.57 µm
N = 1 x 10^{19} cm^{-3}

η_c = 1 dB/facet
λ_{pump} = 1.6 µm
λ_{probe} = 1.5 µm

According to the simulation,

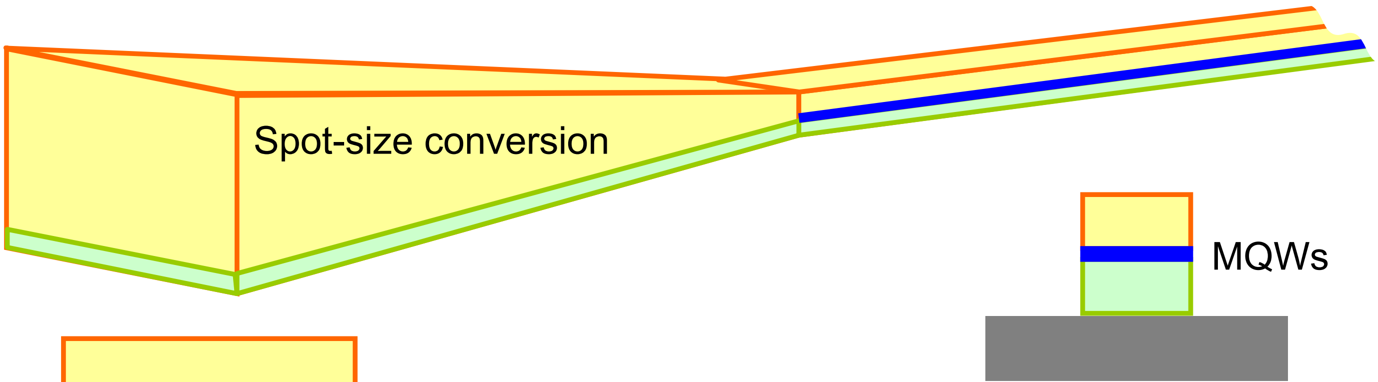
the switching energy can be reduced to ~1 pJ, when

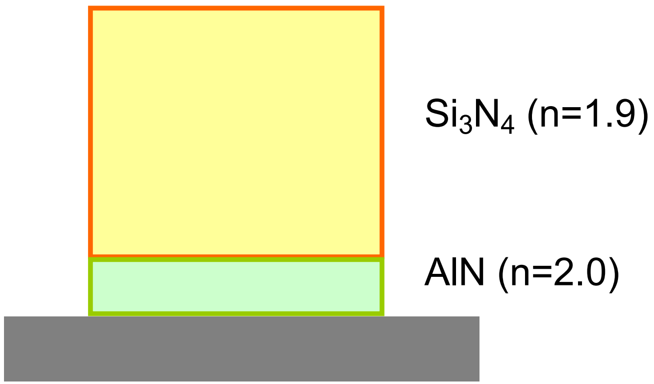
the excess propagation loss is completely suppressed,

the coupling loss decreases to 1 dB/facet, and

the device size is submicron.

Proposed structure (plan)

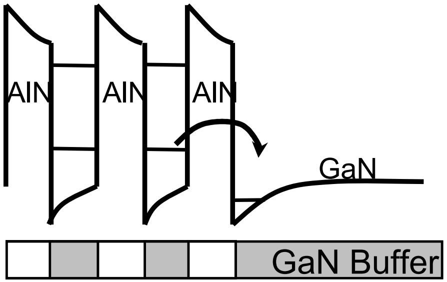


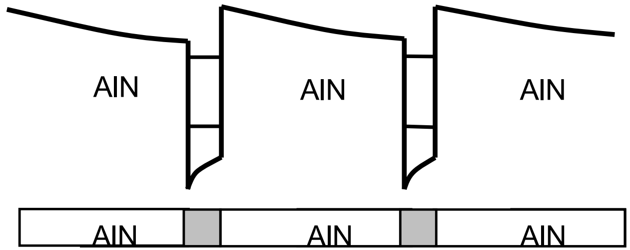


✓Small waveguide
✓Carriers hardly leak out to SiN or AlN
✓SiN : No excess loss

✓Large input facet
✓SiN provides better cleaved facet
✓SiN : No excess loss

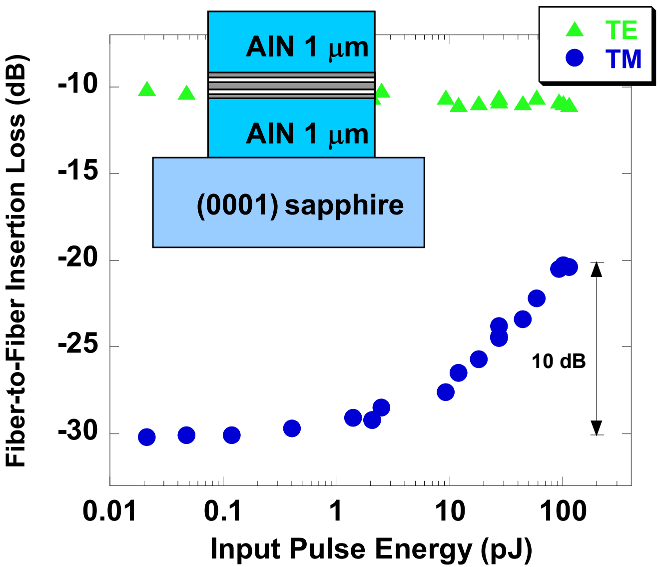
AlN-based waveguide I





- Good carrier confinement

  ⇨ Suppression of excess loss and slow relaxation



MQWs : 5 x n-GaN (3.3 nm)/AlN (3.3 nm)
n = 1×10^{19} cm^{-3}

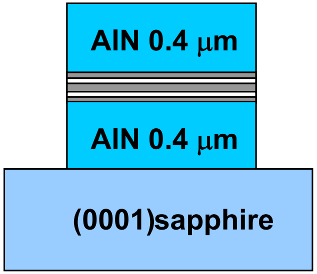
- **First 1.55 μm AlN-Waveguide Switch**
- **ISBT Saturation 10dB @ 90 pJ**
  3dB @ 8 pJ
- **Saturation Characteristic better than GaN-Waveguide Switch (3dB @ 20 pJ)**

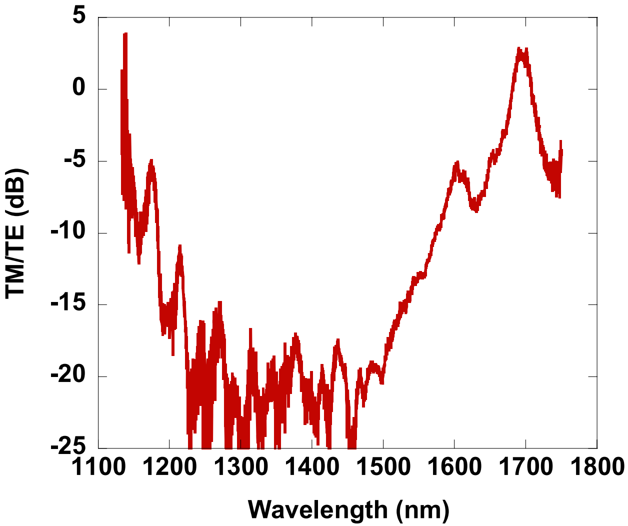
Owing to…

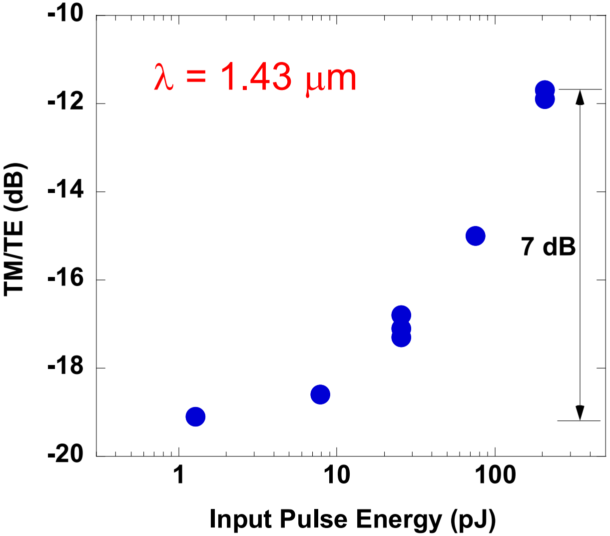
- **Improved optical confinement**
- **Decreased carrier concentration (10^{19}/cm^3)**

AlN-based waveguide II

MQWs : 2 x n-GaN (2 nm)/AlN (10.5 nm)
$n = 1 \times 10^{20}$ cm^{-3}



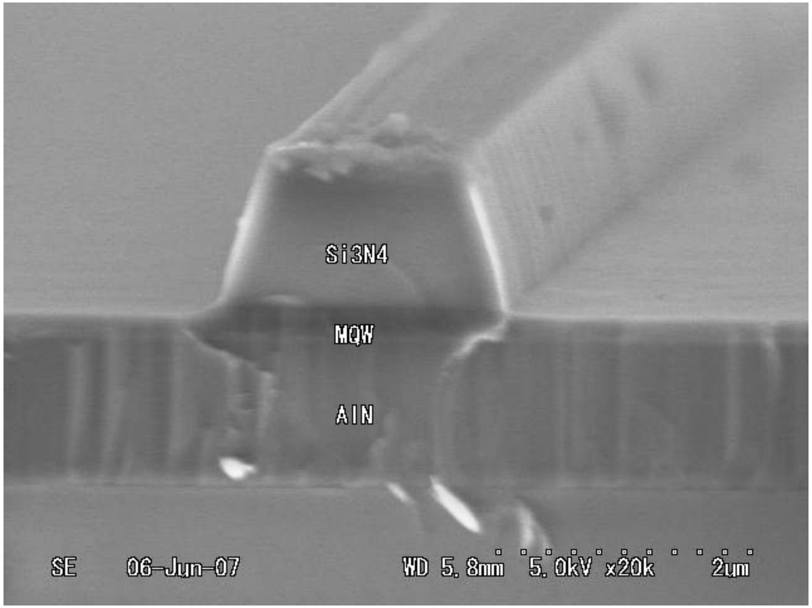


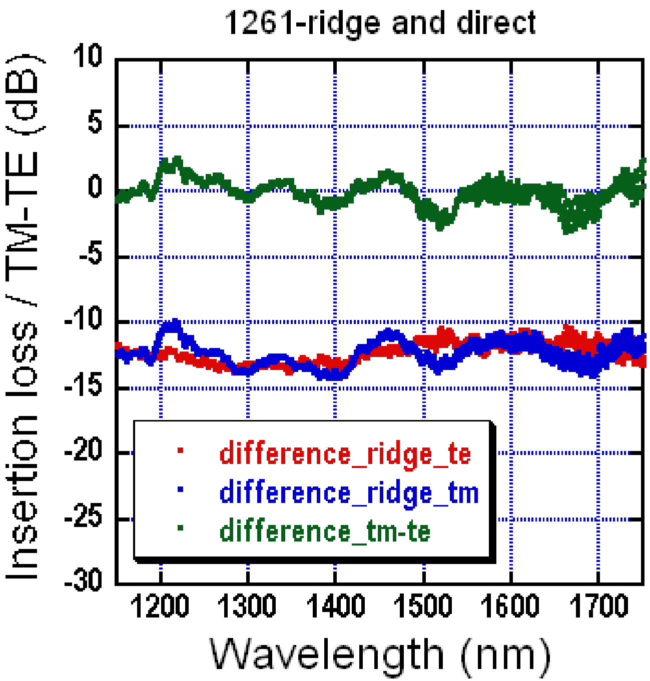


- **First 1.3 μm ISBT device**
- **ISBT saturation 7 dB @ 200 pJ (input wavelength 1.425 μm)**

Kumtornkittikul et al., Jpn. J. Appl. Phys, vol. 46 (2007)

SiN cladding





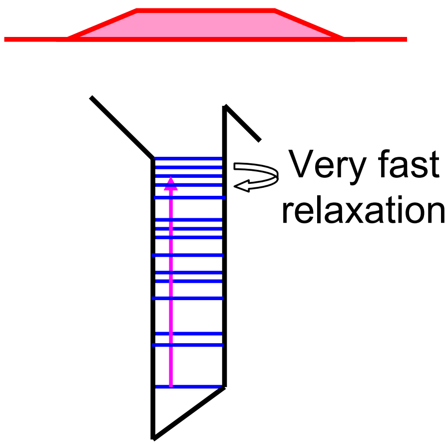
As expected:
Smooth facet was obtained for SiN cladding.
No excess polarization-dependent loss was observed.

Shimizu et al., JSAP Annual meeting (2007)

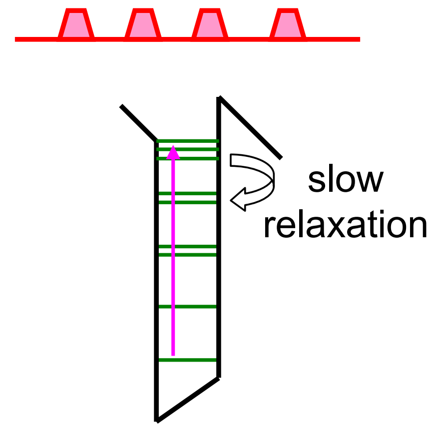
Possibility of application of quantum dots

Purpose: control of relaxation time

Large-diameter dots



Small-diameter dots

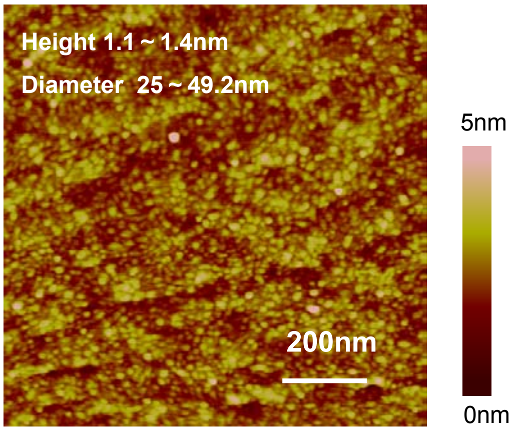


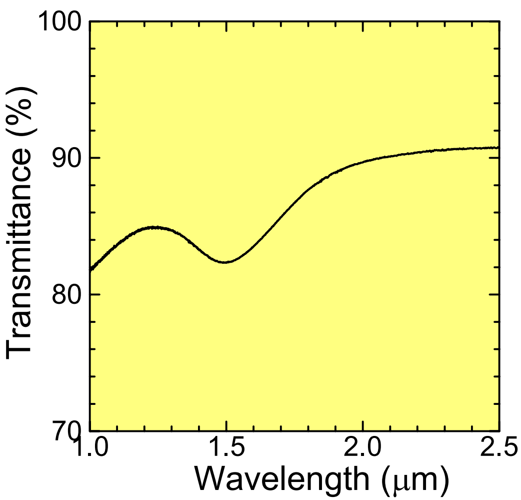
By control of relaxation time, switching energy can be adjusted.

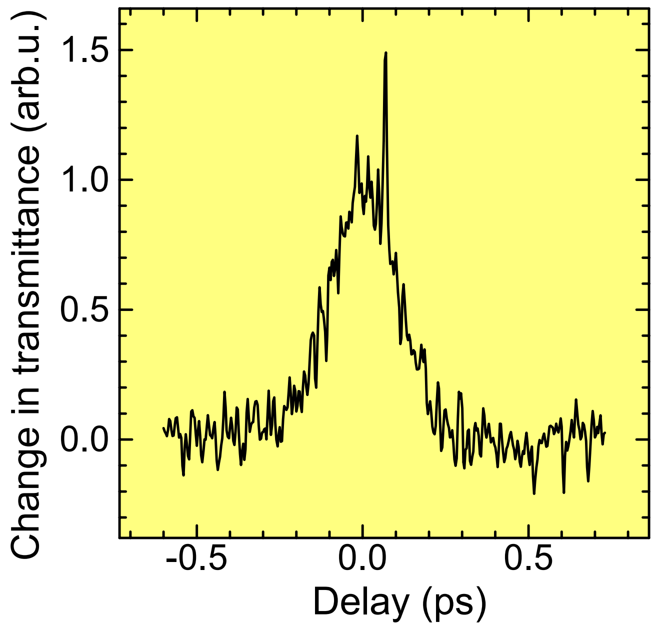
Although growth of small-diameter QDs with good uniformity is extremely difficult, the application of the dots to switching devices is very attractive.

Pump-probe measurement for large dots

60 QD layers (large diameter)







Very fast relaxation in QDs was verified.

Summary -I-

- Applications of ISBTs in GaN QWs/QDs to optical signal processing were discussed.
- Sub-picosecond absorption recovery was verified.
- Saturation intensity was estimated to be 4 - 15 W/μm^2
- All-optical switching was demonstrated for serial pulses with an pulse interval of as short as 0. 67 ps.
- Switching extinction ratio of greater than 10 dB was achieved.
- Gate width of as narrow as 230 fs was realized.

Summary -II-

- It was pointed out that thin barriers brought about a slow absorption recovery and that the switching energy was too high for practical use.
- For the issues to be resolved, utilizing AlN lower cladding and SiN upper cladding was proposed.
- Potential of quantum dots was pointed out and results of preliminary experiment were shown.
- In conclusion, ISBTs in GaN QWs/QDs are promising with respect to realizing optical switches and signal processing devices.