Intersubband spectroscopy of electron tunneling in GaN/AlN coupled quantum wells

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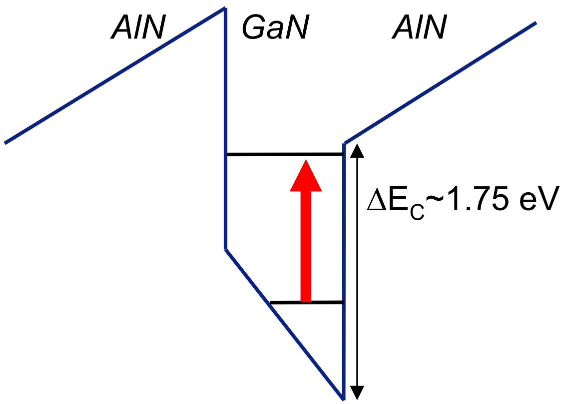
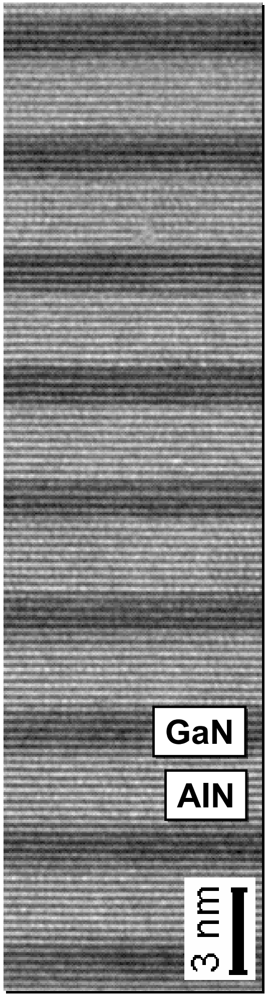
Outline

- Motivations
- Coupled QW modulators : Demonstration of electron tunneling between QWs
- Waveguide depletion modulators
- Conclusions

Motivations





- High CB offset (1.75 GaN/AlN)
  ⇒ ISB transitions at 1.3 – 1.55 μm
- Mature MBE growth
- ISB devices can compete with the existing interband InGaAsP-on-InP technology

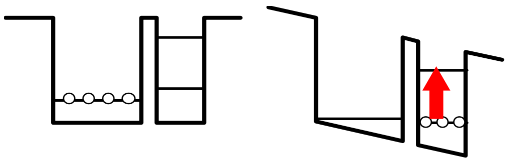
ISB modulators

Potential advantages of ISB electro-optical modulators

- intrinsically very fast
- insensitive to saturation
- possibility to obtain negative chirp parameter
- large spectral bandwidth

First proposal by *Vodjani et al*., APL, 91

GaAs/AlGaAs coupled quantum wells
Operation wavelength ~10 µm



Nitride ISB modulators

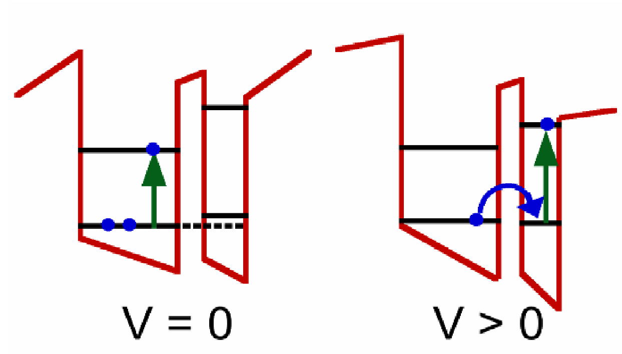
- Theoretical proposal *by P. Holmström, IEEE J. Quantum Electron. QE-42, 810 (2006)*

- Experimental realization of 2DEG-superlattice modulator *by Bauman et al. APL 89, 101121 (2006)*

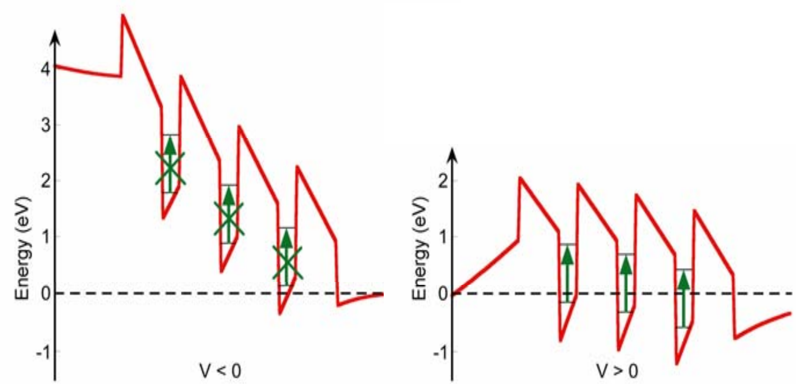
Operation principle of ISB GaN/AlN electro-optical modulators

Two kinds of electro-optical modulators have been investigated:

✓ Electron tunneling in coupled quantum wells

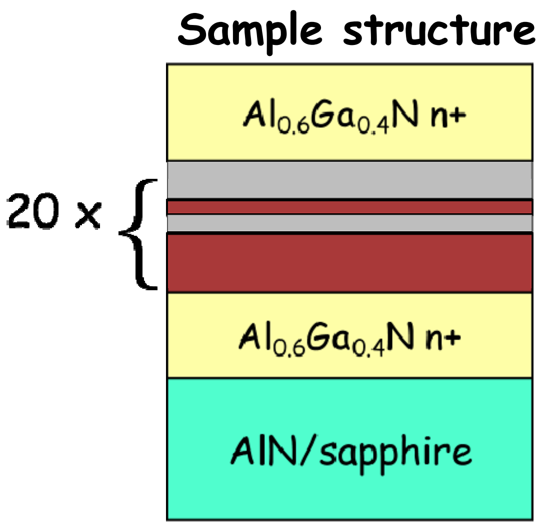


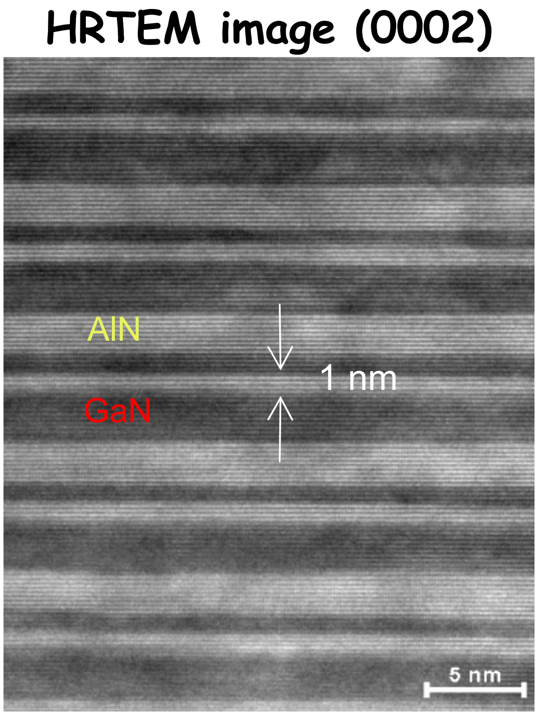
✓ Waveguide depletion modulators



GaN/AlN coupled quantum well modulator

CQW modulator structure



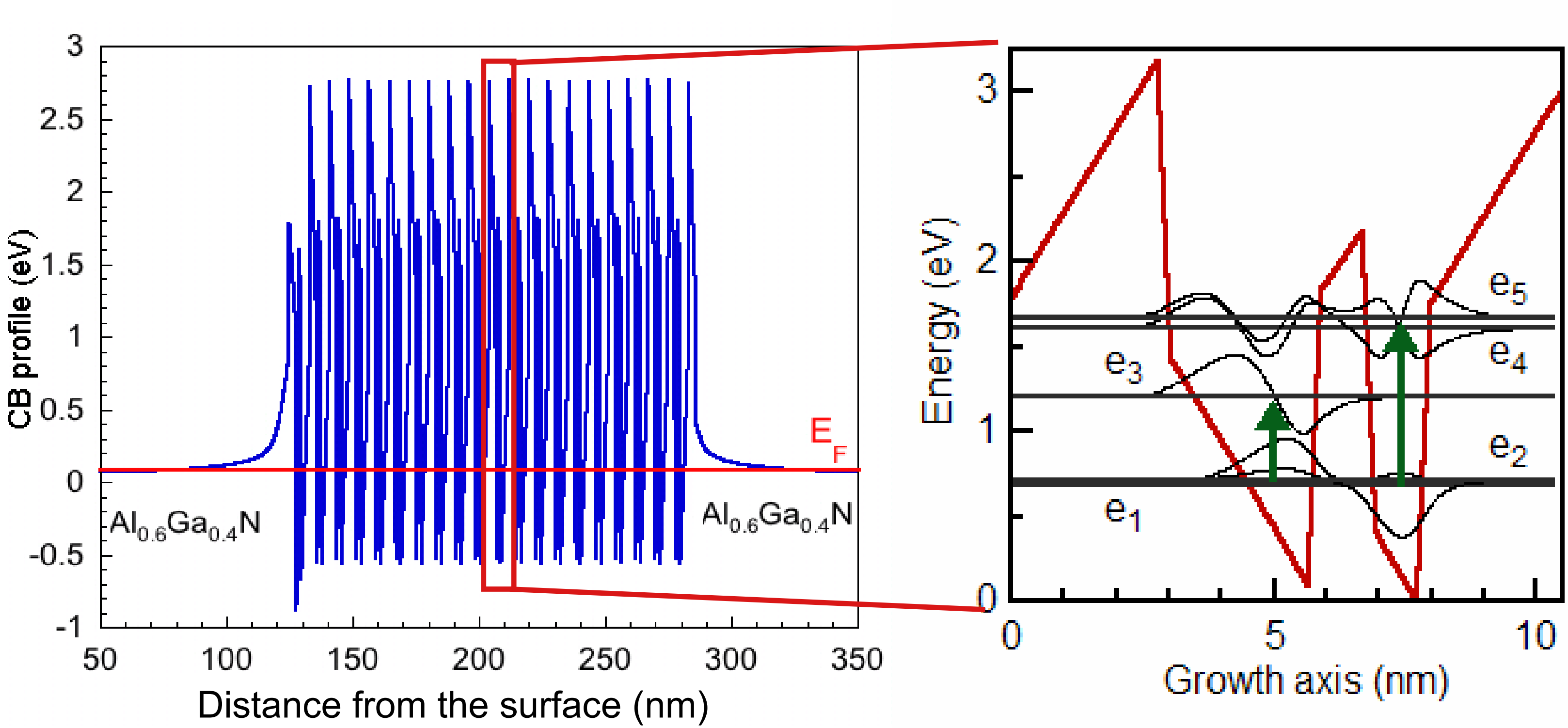


- ✓ 20 periods of GaN/AlN coupled QWs
  Thickness in growth order 3/1/**1**/3 nm
  Si doping of QW 5×10^{19} cm^{-3}

- ✓ Growth by PA-MBE
  Substrate temperature 720°C
  Ga-rich conditions

- ✓ Chemically abrupt interfaces
  Good structure periodicity
  Thickness fluctuations of 1 ML

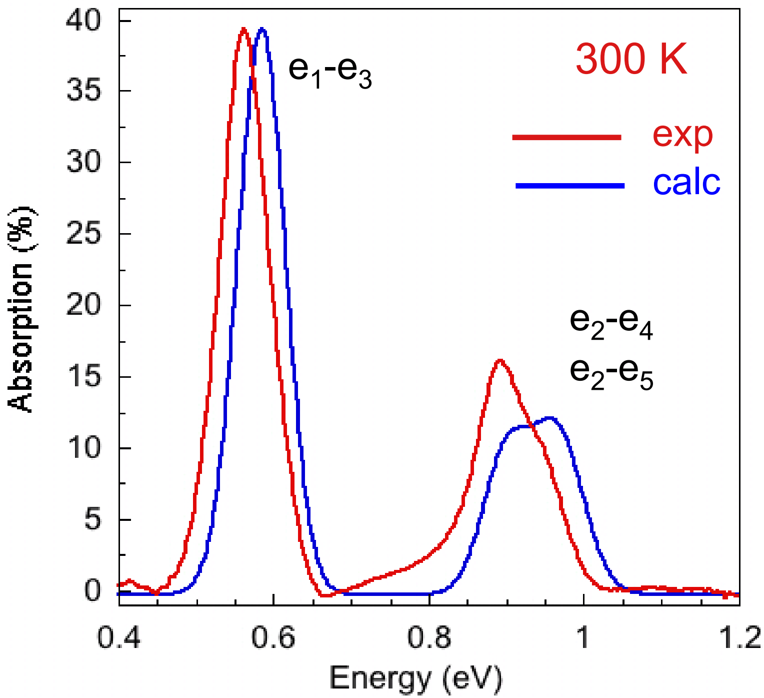
Simulation of the electronic structure

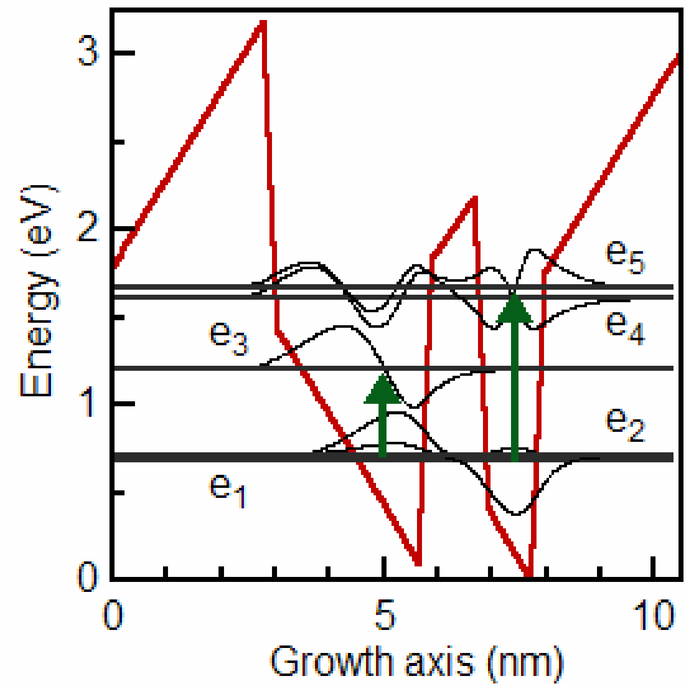


Conduction band profile of the active region

Energy levels and corresponding envelope functions for one period of coupled QWs
Calculated e_1-e_2 = 28 meV

ISB absorption of coupled QWs



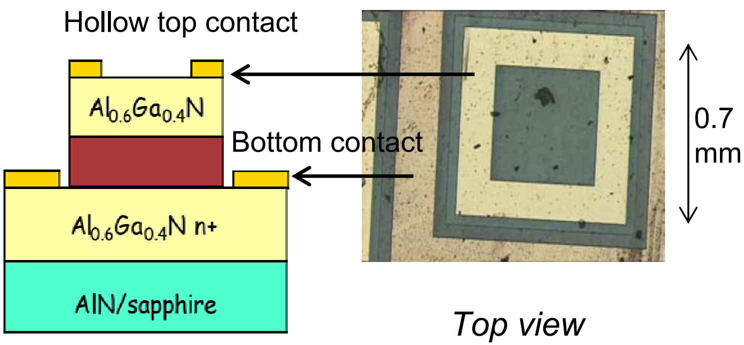


2 p-polarized absorption peaks at 0.56 eV (FWHM=0.85 eV) and 0.9 eV (FWHM = 0.105 eV)

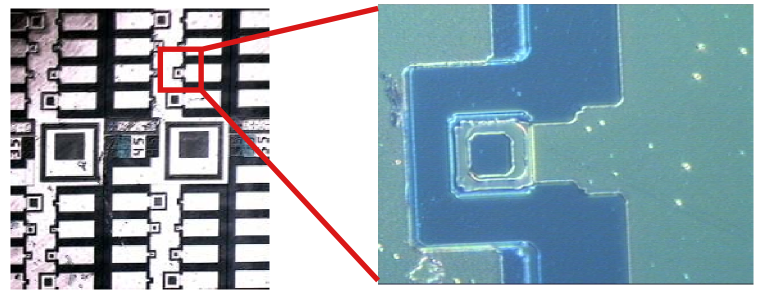
The arrows mark the observed transitions
Estimated subband carrier concentrations are n_{S1}=3.4x10^{12} cm^{-2}; n_{S2}=1.7x10^{12} cm^{-2}

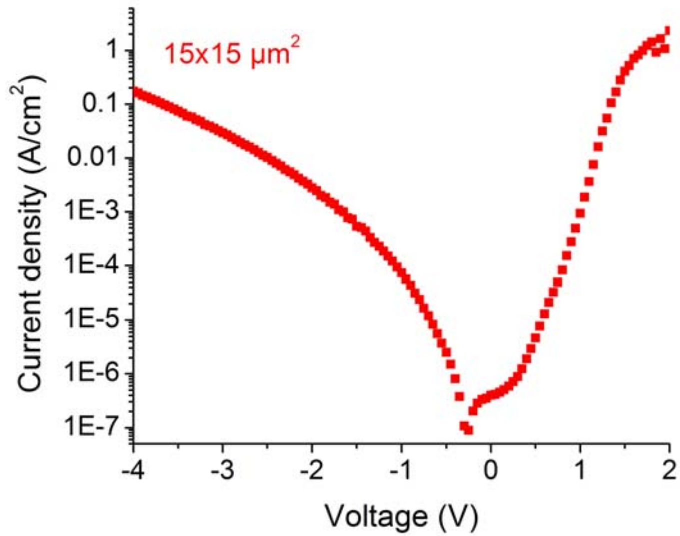
*L. Nevou et al., APL **90**, 121106 (2007)*

Device fabrication



Top view





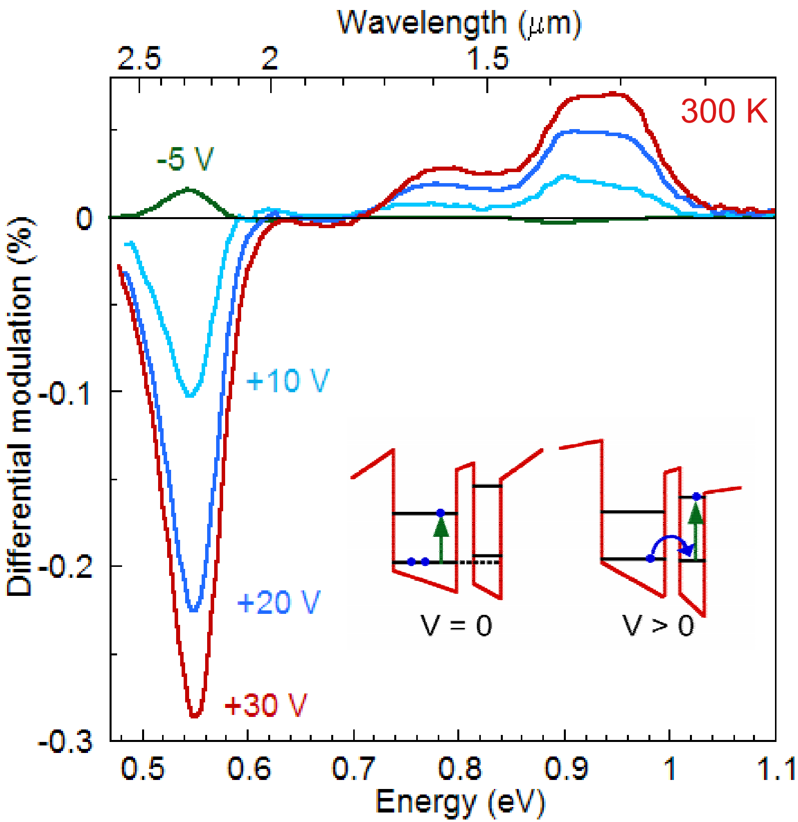
Mesas of different sizes defined by ICP etching :

- ✓ big mesas (700x700 and 500x500 µm^2)
- ✓ micro-devices with side contact pads: 90x90, 50x50, 30x30 and 15x15 µm^2

Open contacts allow optical testing at Brewster's angle of incidence

I-V curve shows diode-like behavior with relatively small leakage current

Differential transmission measurements



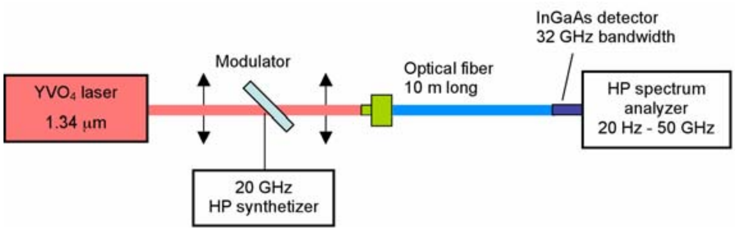
*L. Nevou et al., APL **90**, 121106 (2007)*

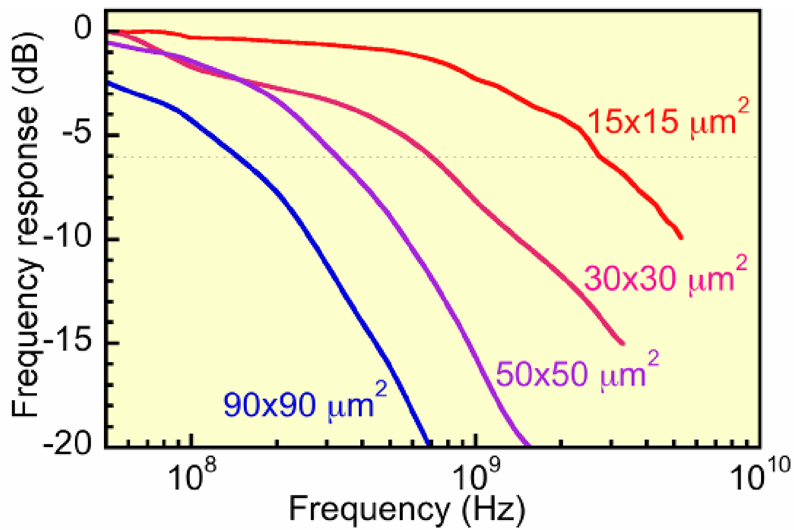
- ✓ Modulation peaks at 2.25, 1.65 - 1.25 µm
- ✓ Measurements performed with FTIR spectrometer operating in step-scan mode
- ✓ The relative phase of peaks is calibrated using 1.34µm laser (high-energy peak) and a Ge filter (low-energy peak)
- ✓Reduction of e_1-e_3 absorption increase of e_2-e_4 and e_2-e_5 absorptions
- ✓ Good agreement with simulations

- ✓ Opposite behavior of 2 peaks
- ✓ Change of sign when reversing bias

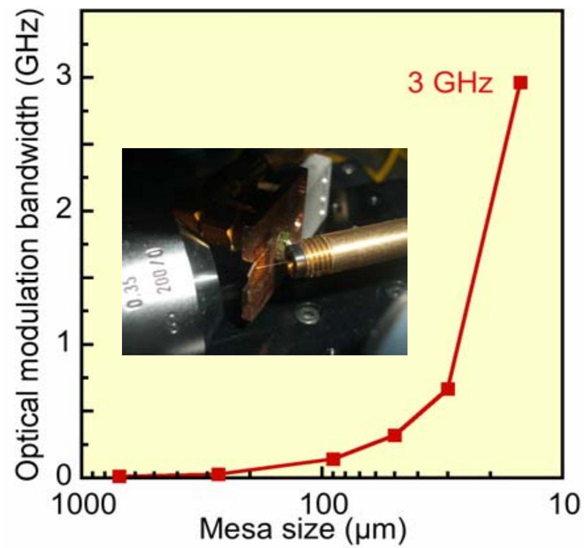
⇒ Demonstration of electron tunneling between QWs at 300K

Modulator frequency response





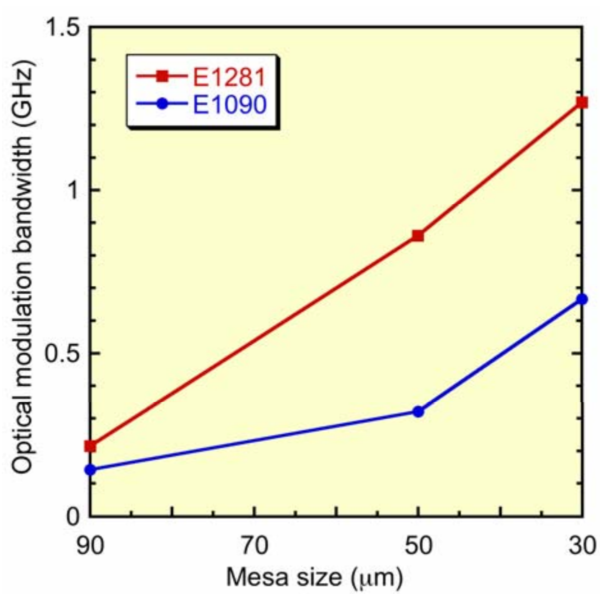
Cut-off frequency increases with decreasing mesa size

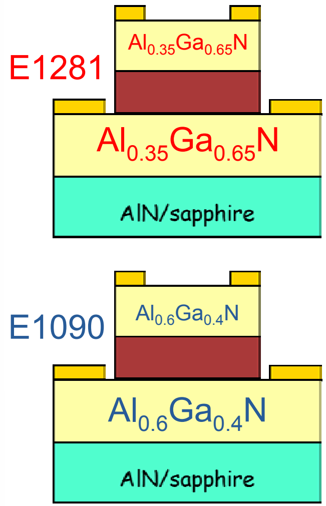


Optical modulation bandwidth 3 GHz for 15x15 μm² mesas

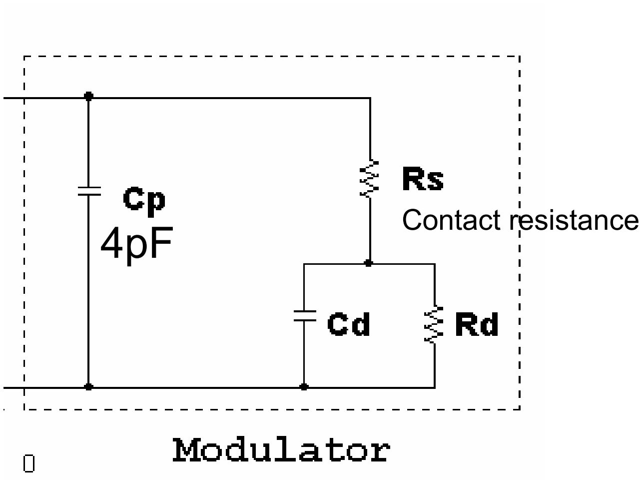
Bandwidth is limited by access resistance of AlGaN contacts and parasitic capacitance

Increasing the cut-off frequency

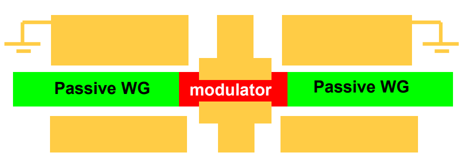




Device equivalent circuit

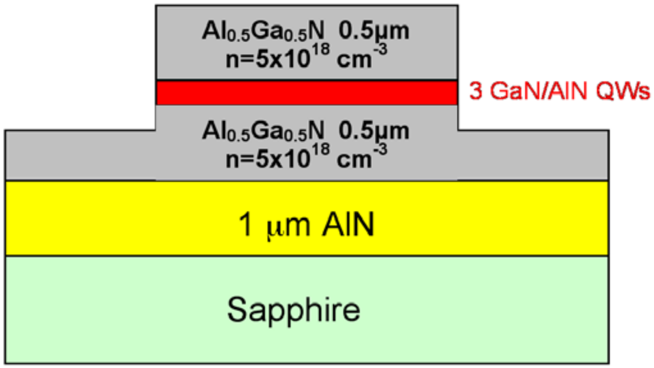


- ✓ Optical bandwidth and modulation depth increased by a factor of 2 by reducing Al content of contact layers from 60% to 35% (R_{access} = 230 Ohm to 110 Ohm)
- ✓ Modulation optical bandwidth beyond 20 GHz can be achieved by RF contact designs.



GaN/AlN waveguide depletion modulator

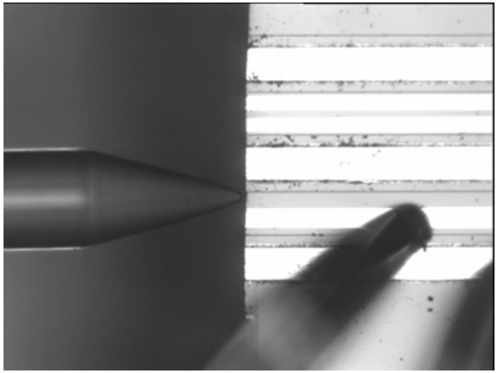
Waveguide modulator based on QW depletion



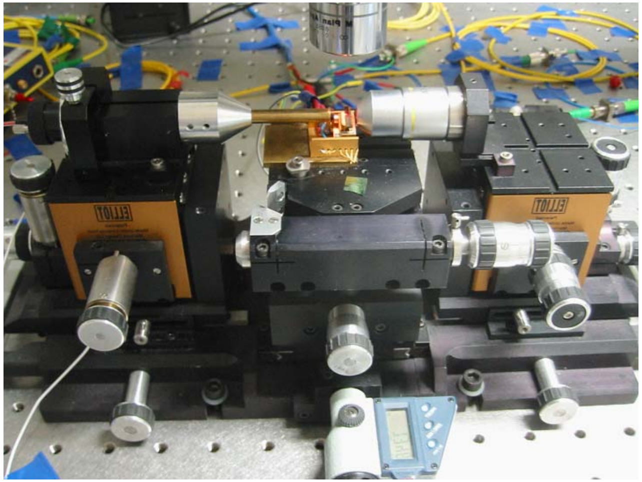
Sample structure

- ✓ 3 GaN/AlN QWs (**1.3** nm / 3 nm)
- ✓ Si doped at 2x10^{19} cm^{-3}
- ✓ 0.5 µm thick $Al_{0.5}Ga_{0.5}N$ claddings
- ✓ Waveguides fabricated by ICP etching
- ✓ WG length 1.6 mm, width 50 µm
- ✓ Cleaved facets

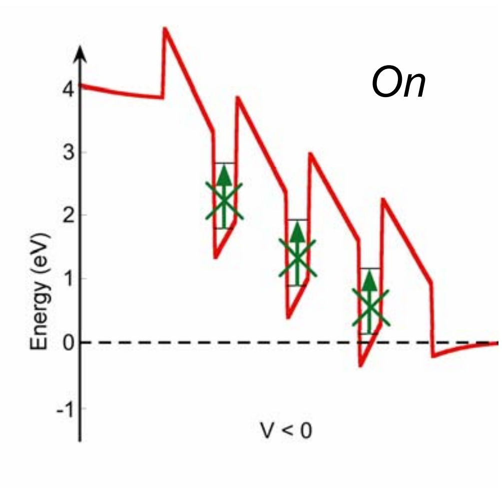
Optical microscope image : top view of 5 ridge waveguide modulators.

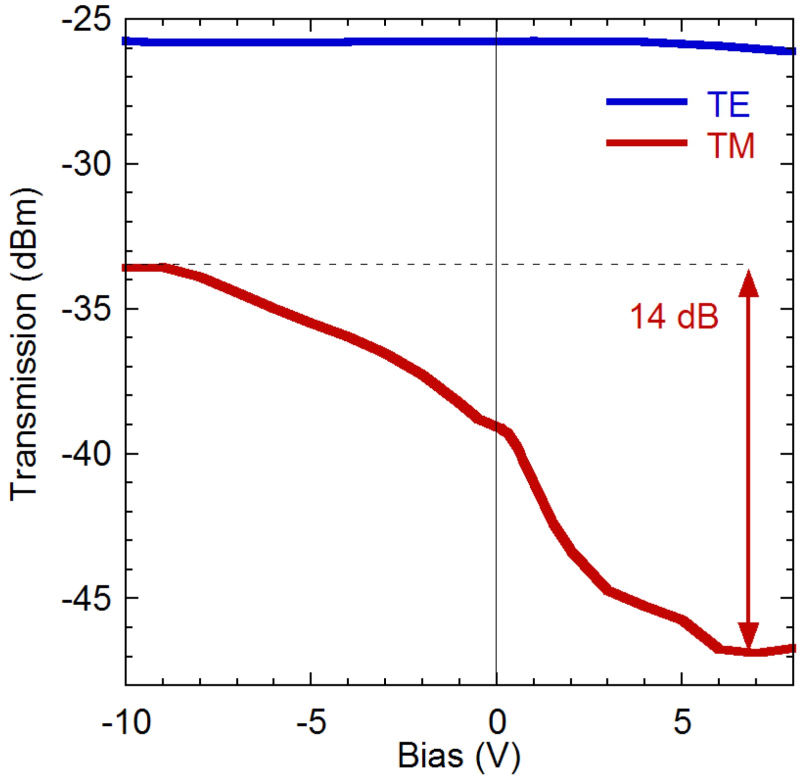


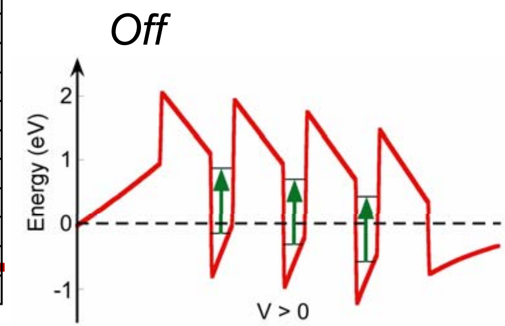
Experimental set-up

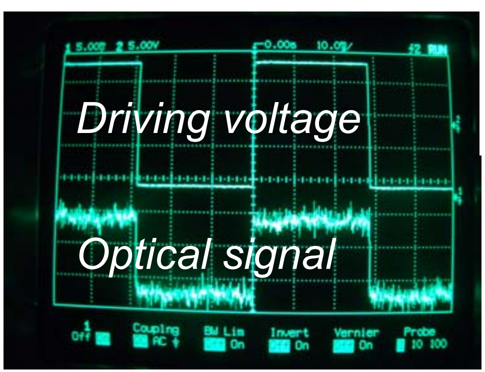


Modulation measurements









- ✓ Modulation depth at λ=1.5 µm as high as 14 dB
- ✓ Wide spectral bandwidth from 1.35 µm to 1.6 µm

Conclusions et Perspectives

- Demonstration of electron tunneling between GaN/AlN quantum wells
- Observation of ISB electro-optical modulation at 300 K at telecommunication wavelengths
- 3 GHz bandwidth (mesa) and 14 dB modulation depth (WG) achieved
- Prospects for high-speed waveguide micro-modulators

E-O MODULATORS	Interband modulators InGaAsP MQWs on InP	This work
Modulation bandwidth	45 GHz	3 GHz (mesa)
Extinction ratio	12-20 dB	14 dB (waveguide)
Propagation losses	0.02-3 dB/mm	1.4 dB/mm
Switching voltage	3-10 V	5 - 15 V
Spectral bandwidth	50 nm	150-350 nm
Device length	125 µm (waveguide)	15 µm - 1 mm

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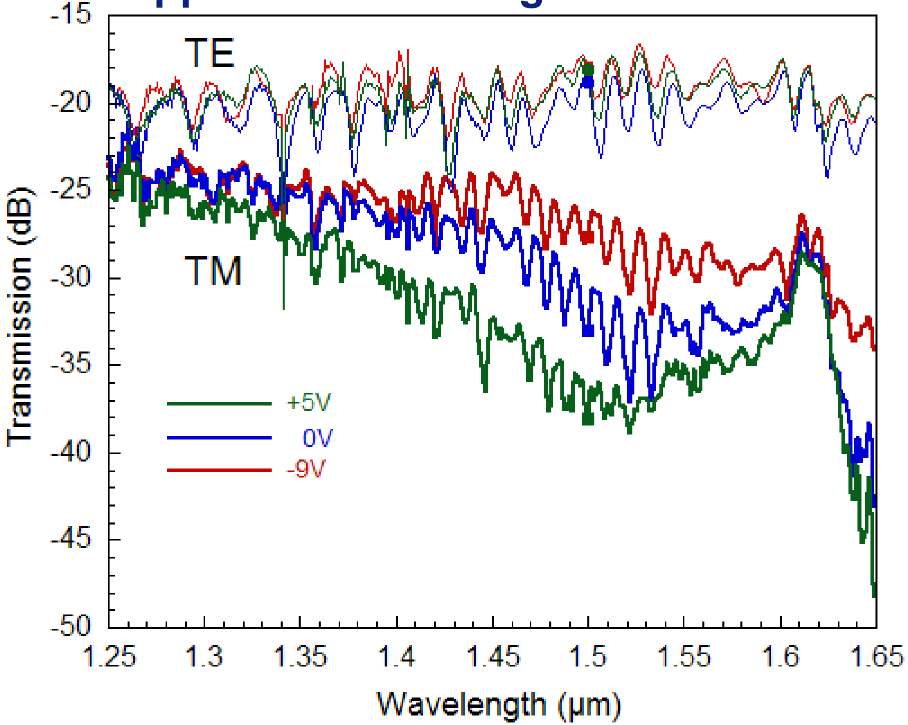
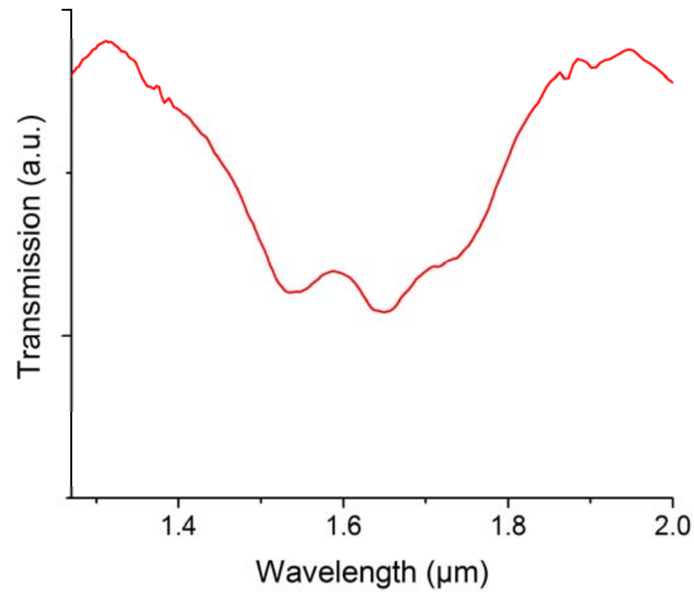
Waveguide modulator based on QW depletion

WG transmission spectrum under applied static voltage



- ✓ ISB absorption changes with applied bias
- ✓ Large spectral bandwidth
- ✓ Constant transmission for s-polarized light

FTIR transmission spectrum



✓ Structured p-polarized ISB absorption at 0.8 eV (FWHM = 120 meV)