NANYANG
TECHNOLOGICAL
UNIVERSITY

Normal incidence silicon doped p-type GaAs/AlGaAs quantum well infrared photodetector on (111)A substrate

T. Mei[1], H. Li[1],G. Karunasiri[2], W. J. Fan[1], D. H. Zhang[1], S. F. Yoon[1], and K. H. Yuan[1]

1)School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore, 639798

2)Department of Physics, Naval Postgraduate School
Monterey, California 93943

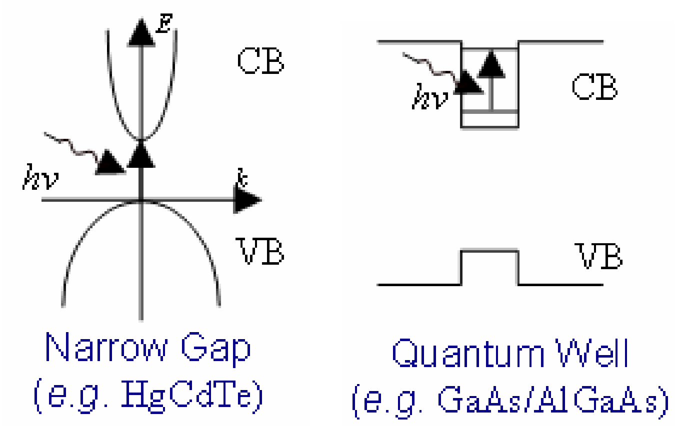
Outline

- Introduction
- Growth and material characterization
- Dark I-V, Infrared absorption, and photocurrent measurement
- Summary

Introduction

- **Intersubband transition vs interband transition ⇨ infrared detection**

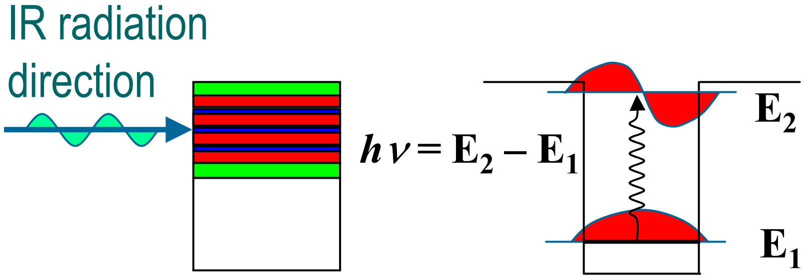
  Quantum well infrared photodetector (QWIP) using intersubband transition for infrared detection
  (1) Choices of material of good stability
  (2) Process technology with maturity
  (3) Large area uniformity for focal plane array



Narrow Gap (e.g. HgCdTe)

Quantum Well (e.g. GaAs/AlGaAs)

- **Updated interests in QWIP research**
  - Multicolor detection; Voltage tunable
    - Multistack QWs[1,etc]
    - Multiple transitions in asymmetric or coupled QWs[2,3,etc]
  - Normal incident QWIP
    - high strained n-type QWIP[4,etc]
    - p-type QWIP[5,6,etc]



Selection rule: electric field along the growth direction

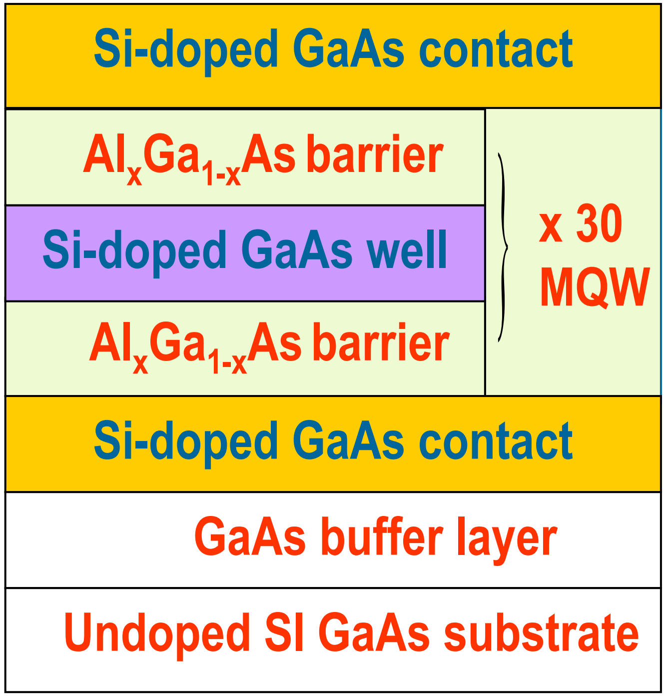
- **p-type QWIP grown on high index plane**
  - New features for comparison to (100) QWIP
  - Expected higher normal incidence response

[1] J. Li et al, Appl. Phys. Lett.,86(2114)2005
[2] T.Mei et al, Appl. Phys. Lett.,71(2017)1997
[3] Amlan Majumdar,K.K. Choi et al, Appl. Phys. Lett.,80(707)2002

[4] G. Karunasiri et al, Appl. Phys. Lett., 67(2600)1995
[5] F. Szmulowicz et al, Appl. Phys. Lett. 66, (1659)1995
[6] H. C. Liu, et al, J. Appl. Phys., 85, (2972) 1999

Sample growth

Growth structure


Si-doped GaAs contact

$Al_xGa_{1-x}As$ barrier

Si-doped GaAs well

$Al_xGa_{1-x}As$ barrier

x 30 MQW

Si-doped GaAs contact

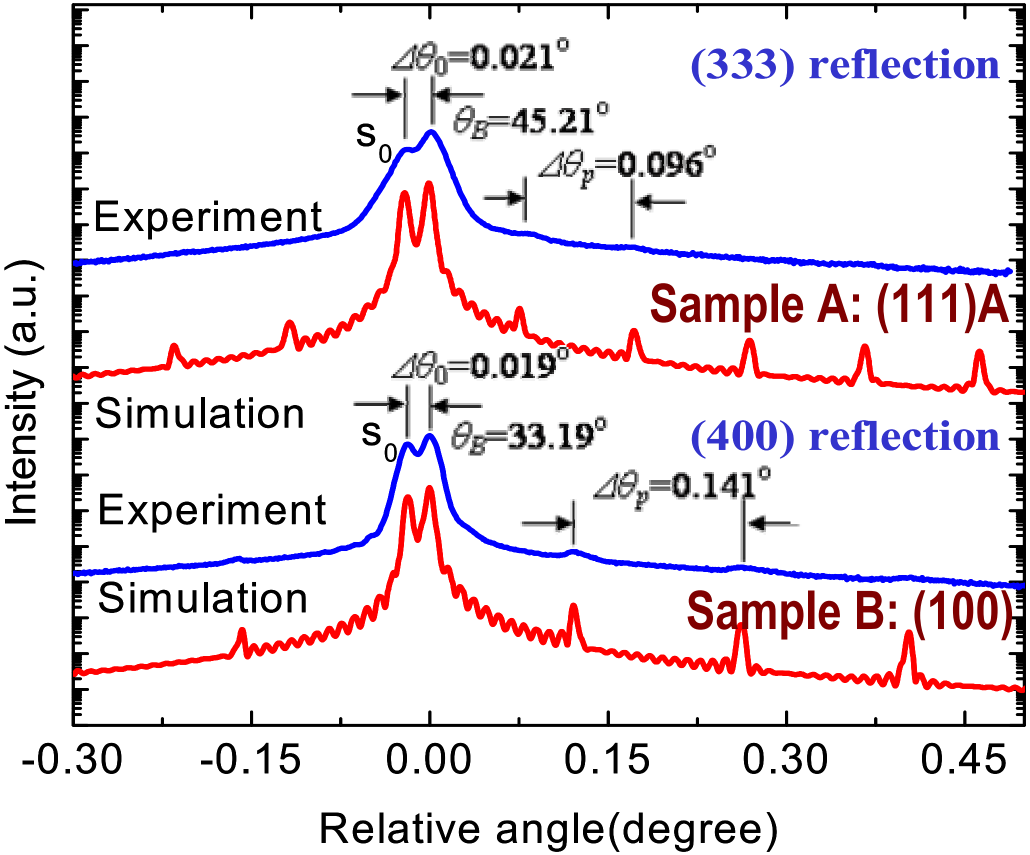
GaAs buffer layer

Undoped SI GaAs substrate

Growth condition

- Oxide desorption at 650 °C with As_4 flux irradiation
- Concurrent growth on (111)A and (100) substrates
- Substrate temperature $T_g = 650$ °C
- As_4/III flux ratio = 23:1
- As_4 beam equivalent pressure: 1.0×10^5 Torr, from a valved crack cell
- Si cell temperature: 1020 °C
- Solid source Riber 32 MBE system

HRXRD characterization



- $\Delta\theta_p$ → Periodicity of MQW

$$L = \frac{\lambda|\gamma_H|}{\Delta\theta_P \sin(2\theta_B)}$$

$$\gamma_H = \sin(\theta_B + \varphi)$$

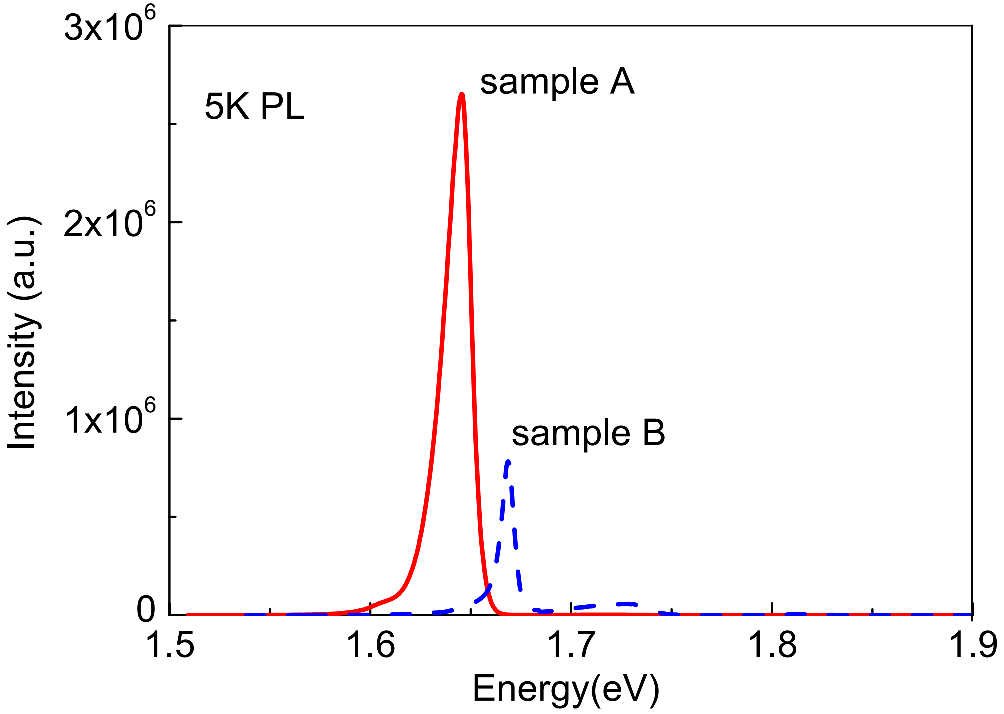
- $\Delta\theta_0$ → Average mismatch

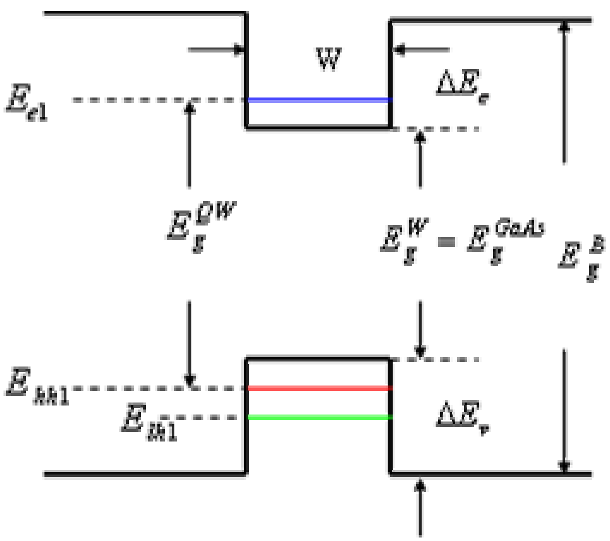
$$(\varepsilon_{QW})_\perp = \frac{(\varepsilon_B)_\perp B + (\varepsilon_W)_\perp W}{B+W}$$

$$= -\Delta\theta_0 coth\theta_B$$

Samples	Period (Å)	Angular spacing of satellite peaks(°)	Bragg diffraction angle (°)		FWMH (arc second)	
			AlGaAs (0^{h}-order satellite peak)	GaAs substrate	AlGaAs (0^{t} order satellite peak)	GaAs substrate
Sample A	601	0.021°	45.18	45.21	61.2	50.4
Sample B	377	0.019°	33.17	33.19	36.0	32.4

PL analysis





Samples	A: (111)A MQW	B: (100) MQW
x (%)	18	22
L_b (Å)	563	346
L_w (Å)	38	31
PL FWHM (meV)	13	6
E_p (eV)	1.64	1.66

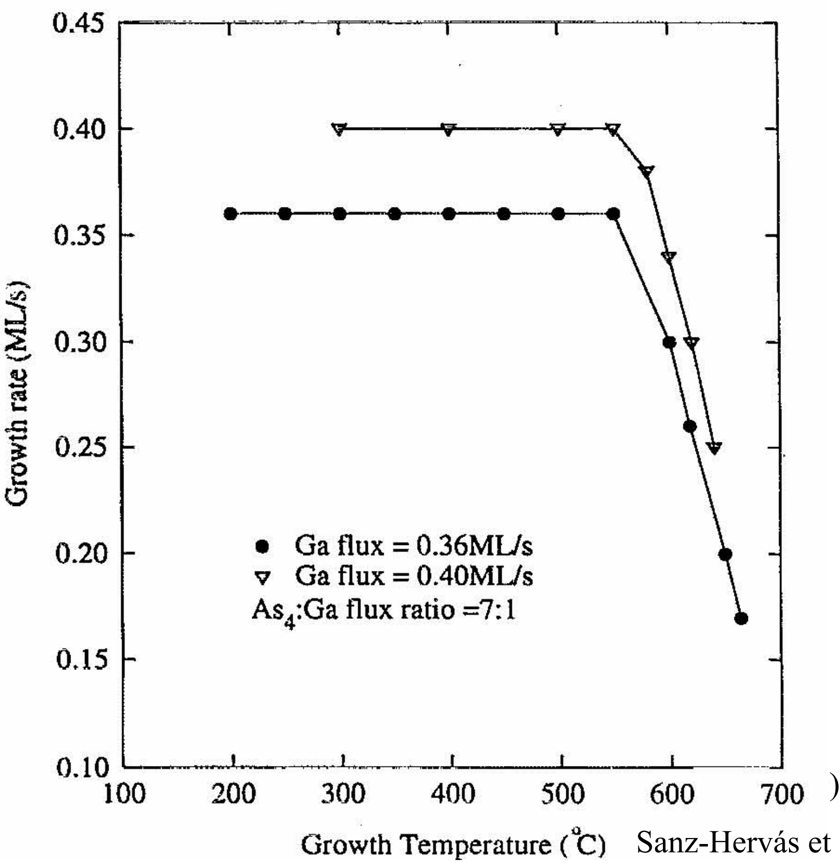
Higher optical transition results from the large anisotropy of heavy-hole band in the host GaAs along the [111] direction[a]:

$$m_{hh}^{*}[111] / m_{hh}^{*}[100] = 2.65$$

[a] Toshiro Hayakawa et al, Phys. Rev. Lett. 60(349)1988

MBE Growth on GaAs (111)A

- Smooth layers can be obtained under high As$_4$/Ga flux ratio and/or low temperature
  - Related to the sticking coefficient of As4 on GaAs (111)A surface
  - The origin of defects is excess Ga
  - A stable reconstructed surface is a Ga-vacancy surface (2x2).
- Faster growth rates of AlGaAs and GaAs epilayers
  - Three dangling bonds for each Ga-adatom
  - Rapid decrease in growth rate is attributed to the limited dissociative chemisorption of As$_4$[b]
- Reduction of Al fraction in AlGaAs epilayer
  - Due to the poor efficiency of Al atom adsorption to Ga atom site under a Ga-predominant (111) A surface, e.g. Sanz-Hervás et al[c]



Sanz-Hervás et al[c]

---

[a] K. Sato, Michael R. Fahy and Bruce A. Joyce, Jpn. J. Appl. Phys., 33, L905(1994).

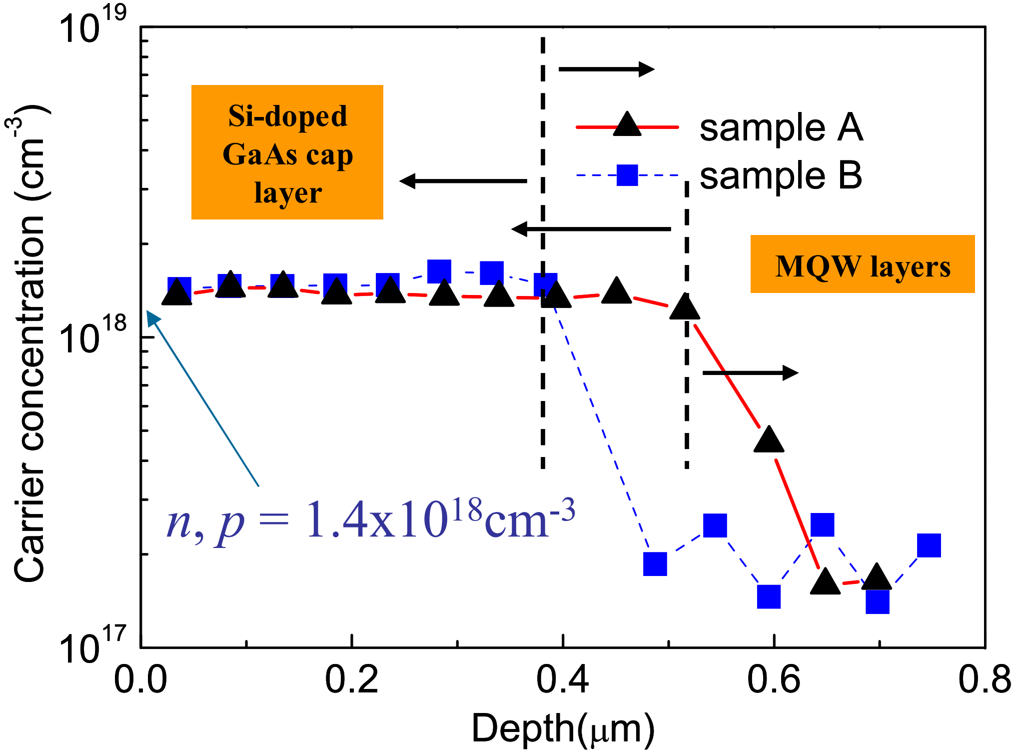
[b] M. R. Fahy et al, Appt. Phys. Lett. 64,190(1994);

[c] A. Sanz-Hervás et al, J. Cryst. Growth **195**, 558 (1998).

Silicon doping on GaAs (111)A

Electrochemical capacitance-voltage (C-V) profiles

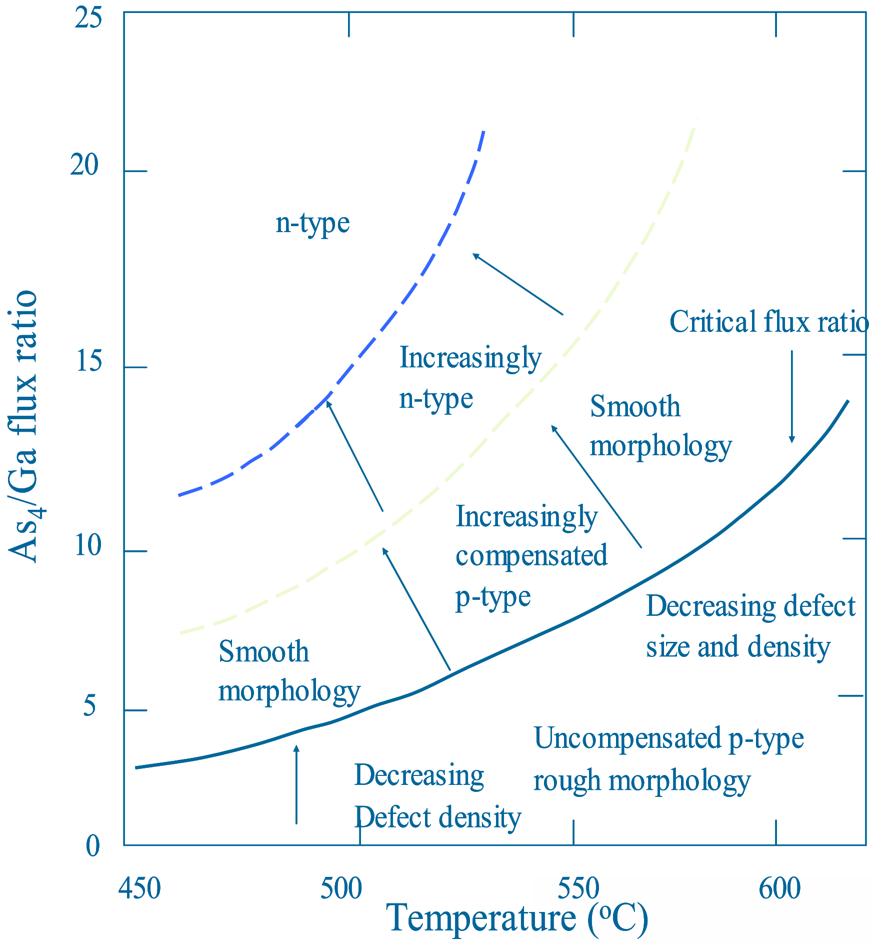
- ✓ Si preferentially occupies Ga site on (100): Both As and Ga has 2 dangling bonds
- ✓ Si preferentially occupies As site on (111)A: Ga atom has 3 dangling bonds and As has only 1.
- ✓ Si-doping behavior in GaAs(111)A surface depends on growth condition



Silicon doping on GaAs (111)A

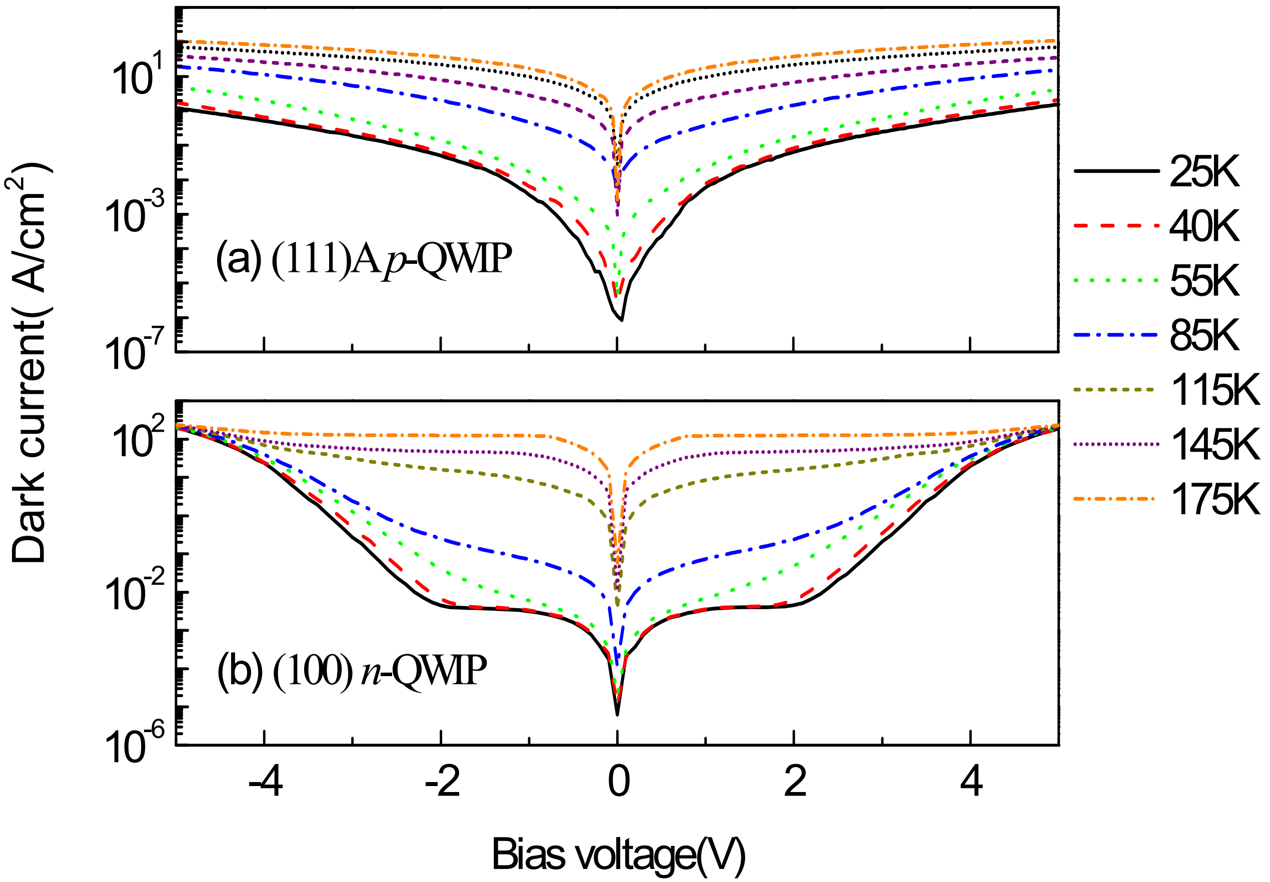
Electrochemical capacitance-voltage (C-V) profiles

- ✓ Si preferentially occupies Ga site on (100): Both As and Ga has 2 dangling bonds
- ✓ Si preferentially occupies As site on (111)A: Ga atom has 3 dangling bonds and As has only 1.
- ✓ Si-doping behavior in GaAs(111)A surface depends on growth condition



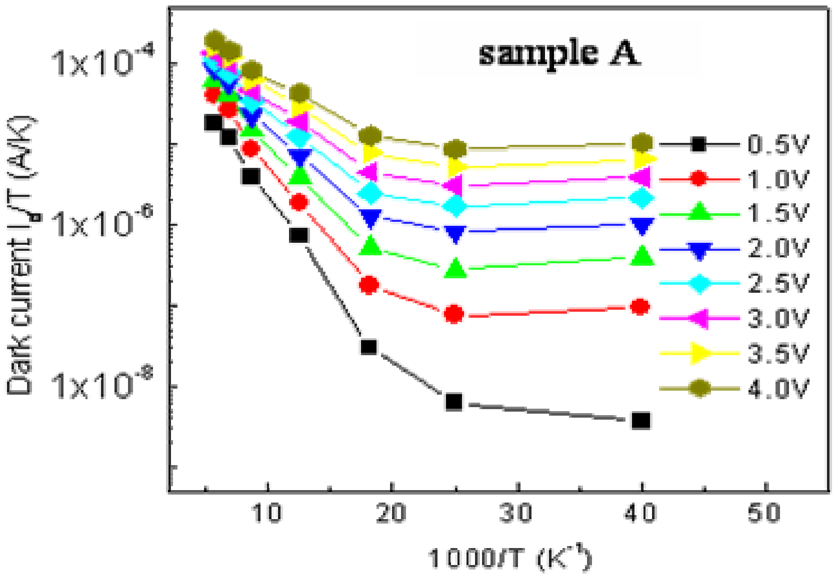
K.Sato et al. J.Crystal growth,165(1996)

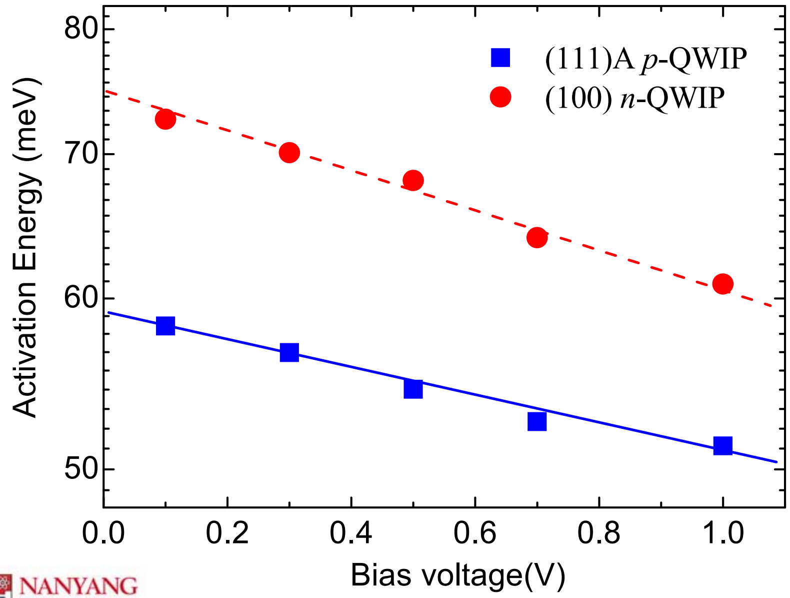
Dark I-V Analysis



- Lower dark current expected in p-type (111)A QW due to the large effective mass of hole
- Under high bias and low T, dominated by tunneling through barrier
- Under low bias and relatively high T, dominated by thermionic emission

Dark I-V Analysis





- E_{ac} is extracted from the slope of the plot I_d/T vs $1000/T$

$$I(T)/T \propto \exp\left(-E_{ac}/k_BT\right)$$

- E_{ac} decreases exponentially due to the energy bending of QWs as the bias increases. The energy bands are no longer symmetric any more and start to bend gradually[a]

$$E_{ac} = E_{ac0}\exp(-V/C)$$

- The extrapolated flatband E_{ac0}

  (111)A p-QWIP: 59 meV
  (100) n-QWIP: 74 meV

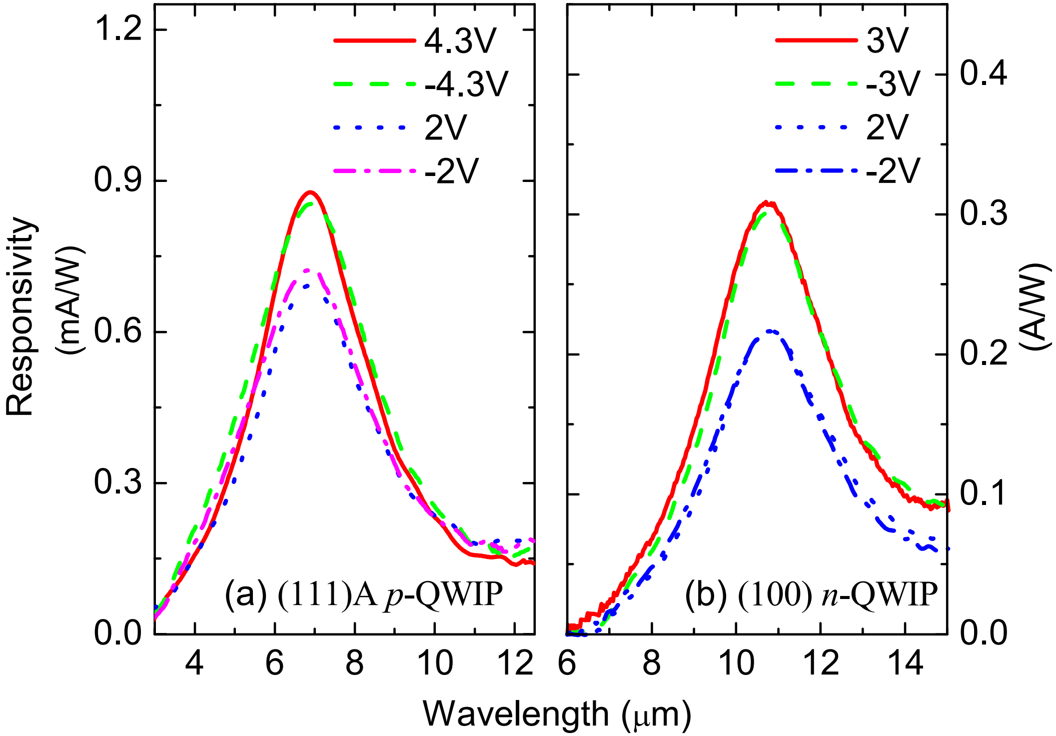
  are used to verify the calculated energy band structures

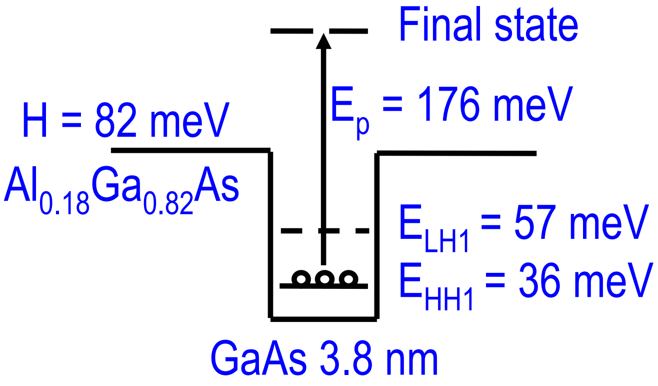
p-QWIP $E_{ac} = V_b + E_{ex} - E_{HH1} - E_F$

n-QWIP $E_{ac} = V_b - E_{e1} - E_F$

[a] D. H. Zhang and W. Shi, Appl. Phys. Lett. 73, 1095 (1998).

Photocurrent spectra and band diagram





Final state

H = 82 meV

E_p = 176 meV

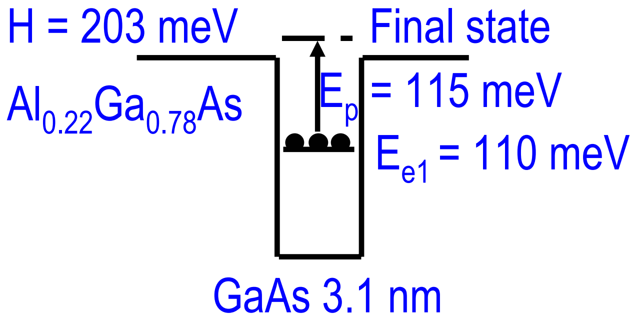
$Al_{0.18}Ga_{0.82}As$

E_{LH1} = 57 meV

E_{HH1} = 36 meV

GaAs 3.8 nm

(a) (111)A *p*-QWIP



H = 203 meV

Final state

E_p = 115 meV

$Al_{0.22}Ga_{0.78}As$

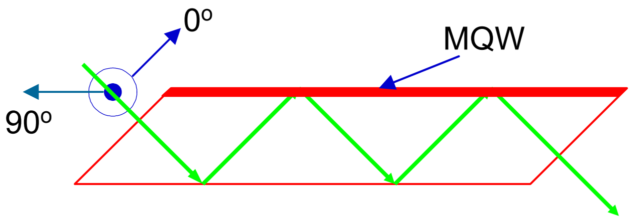
E_{e1} = 110 meV

GaAs 3.1 nm

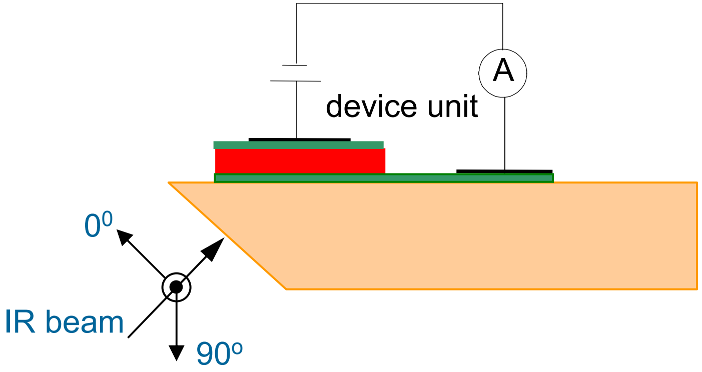
(b) (100) *n*-QWIP

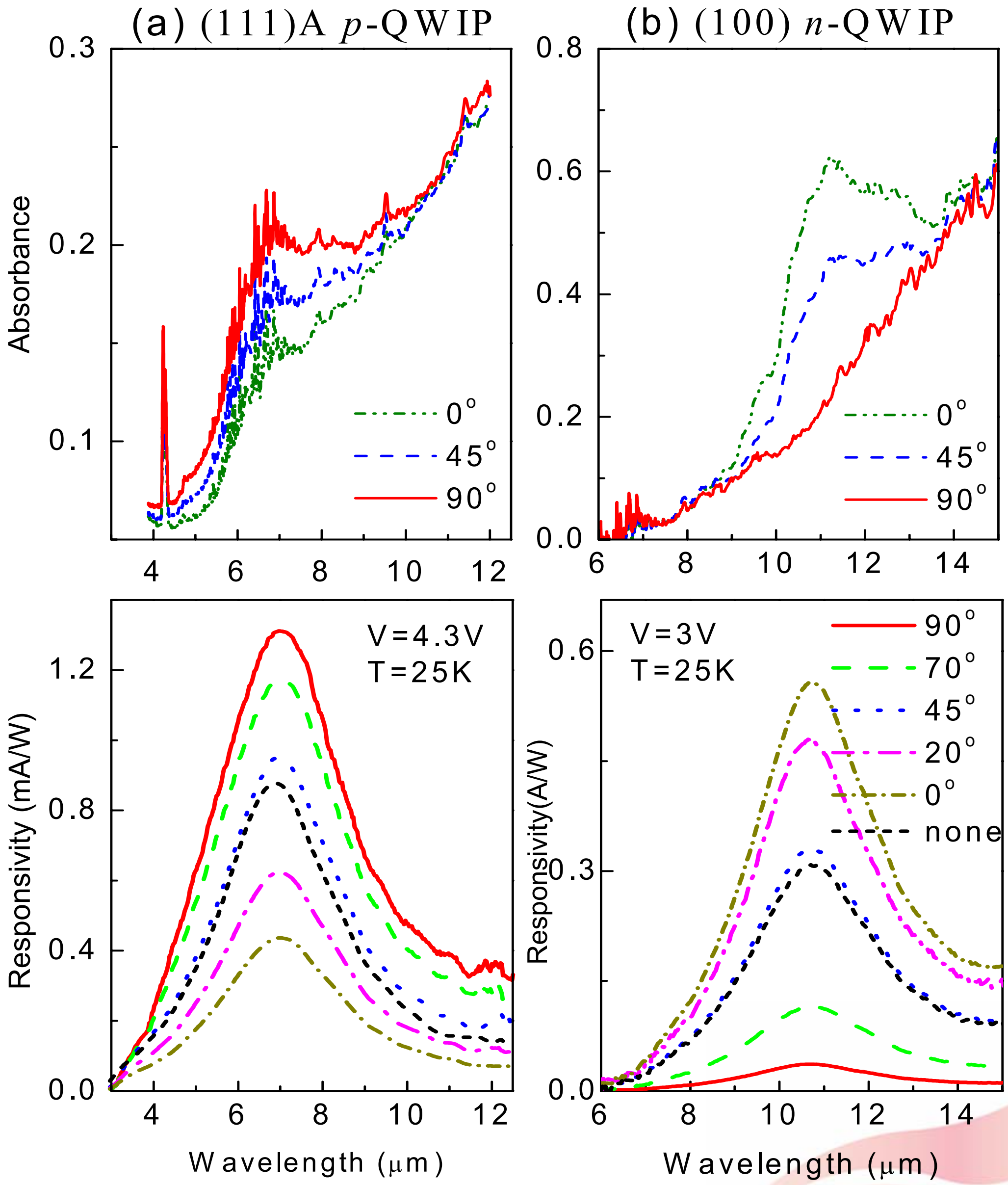
- Similar photoresponse for the bias at the same level but opposite polarities
- n-type (100) QWIP: λ_p = 10.8 μm; $\Delta\lambda/\lambda_p$ ~ 24%; bound-to-continuum
- p-type (111)A QWIP: λ_p = 7 μm; $\Delta\lambda/\lambda_p$ ~ 50%; final states in deep continuum
- Low responsivity of p-QWIP due to the low p-type doping. i.e. commonly 1×10^{19} cm^{-3}

Polarized absorption and photocurrent spectra



Multipass guide





90° – s-polarization; TE mode; normal-incident radiation

0° – p-polarization; TE + TM mode (TE & TM in equal shares)

Normal incidence response

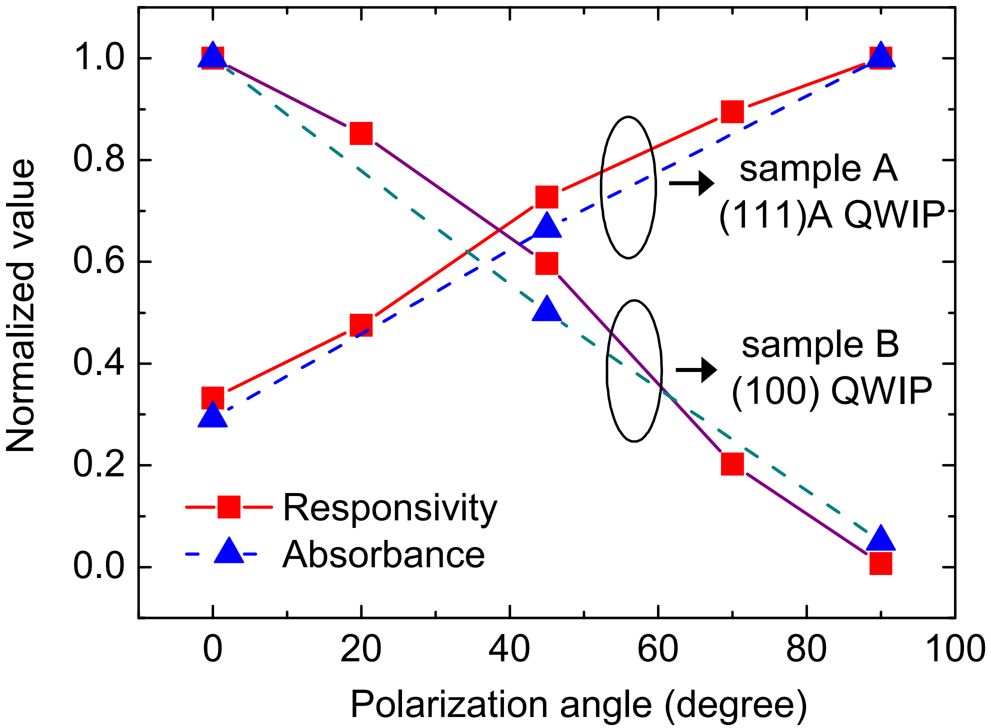
- Dominant normal incidence response being observed
- Highly band-mixing nature of the excited states in deep continuum
- Larger band-mixing effect for nonzero $k_{||}$
- Large difference of HH and LH effective masses along [111] direction

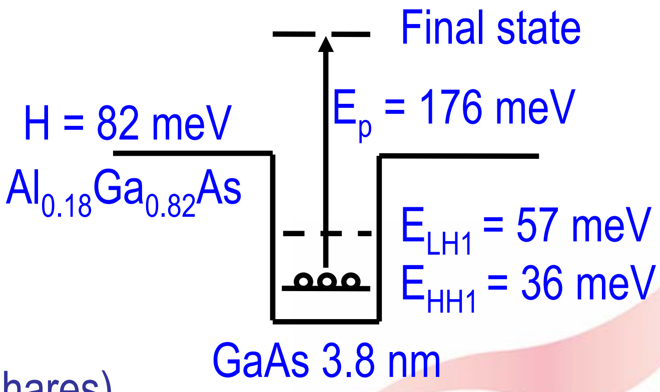
$$m_{hh}[111]/m_0 = 0.952$$

$$m_{lh}[111]/m_0 = 0.079$$

$$m_{hh}[100]/m_0 = 0.35$$

$$m_{lh}[100]/m_0 = 0.117$$




Final state

E_p = 176 meV

H = 82 meV

$Al_{0.18}Ga_{0.82}As$

E_{LH1} = 57 meV

E_{HH1} = 36 meV

GaAs 3.8 nm

90° – s-polarization; TE mode; normal-incident radiation

0° – p-polarization; TE + TM mode (TE & TM in equal shares)

Summary

- Si-doped GaAs/AlGaAs QWIP structure grown on GaAs (111)A substrate by MBE is investigated
  - Faster epitaxial growth rates =>much more dangling bonds of III adatom
  - Reduction of Al composition in AlGaAs layer => weak Al atom adsorption to Ga atom site under Ga-predominant (111)A surface
  - Enhanced PL emission intensity=>larger anisotropy of heavy-hole band along the [111] direction
  - Silicon is incorporated as p-type dopant. The conduction type on (111)A surface is growth-condition-dependent
- The p-type GaAs/AlGaAs (111)A QWIP device has been successfully fabricated and characterized
  - Peak responsivity ~ mA/W, low due to low doping concentration; $\lambda_p = 7\ \mu m$
  - Dominant normal incidence response - Larger band-mixing effect
    - Excited states in deep continuum
    - Large difference of HH and LH effective masses along [111] direction

Thank you!