Characteristics of high responsivity 8.5 μm InGaAs/InP QWIPs grown by metalorganic vapour phase epitaxy

A. Mazumdar[2], S. Ghosh[1], A. P. Shah[1], M. R. Gokhale[1], S. Sen[3], D. C. Tsui[2] and B. M. Arora[1]*

[1] Tata Institute of Fundamental Research, Mumbai –400 005, INDIA.
[2] Dept. of Electrical Engineering, Princeton University, Princeton, U.S.A.
[3] Institute of Radio Physics and Electronics, Kolkata – 700 009, INDIA

*e-mail : brij@tifr.res.in

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Outline

- Introduction
- Device structure and characterisation
- Results
- Discussion
- Summary

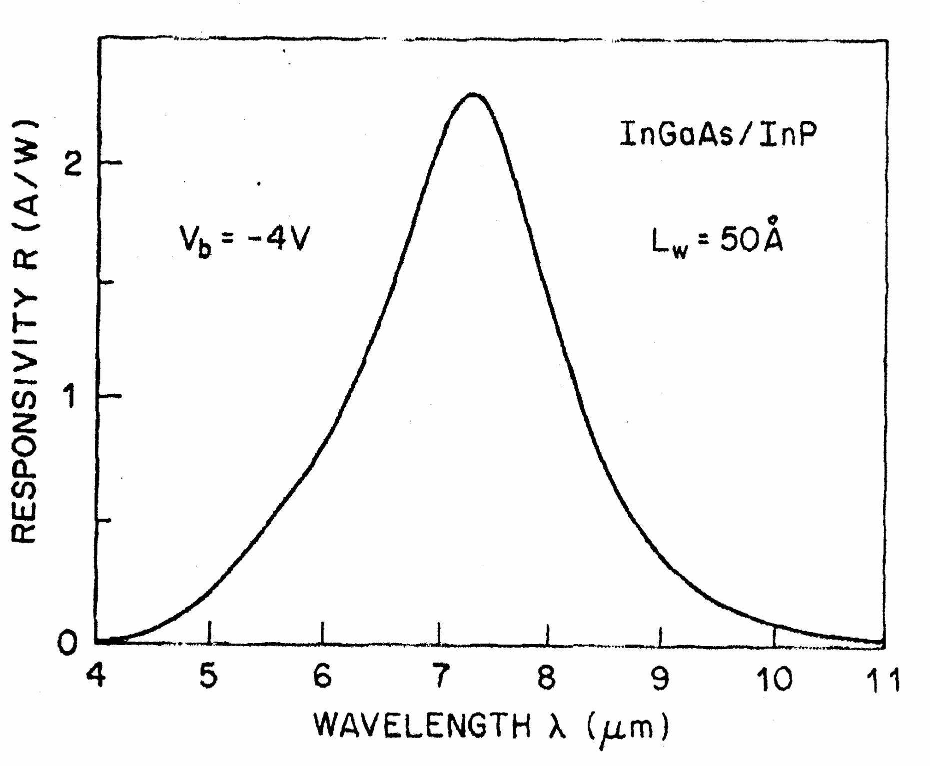
QWIP Material Systems
(8 –14 µm)

- Lattice-matched systems
  - AlGaAs/GaAs/AlGaAs on GaAs substrates
  - InP/$In_{0.53}Ga_{0.47}As$/InP ; $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/\ In_{0.52}Al_{0.48}As$;
  - InP/$In_{1-x}Ga_xAs_yP_{1-y}$/InP (x = 0.47 y) on InP substrates

- Motivation for this work
  - Larger responsivity of InGaAs/InP QWIPs compared to the mature QWIP system of GaAs/AlGaAs[1]
  - Most structures of InGaAs/InP grown by MBE (1-2)
  - Few reports(3-5) by MOVPE

[1] Gunapala et.al., APL,**58**(18),2024,1991
[2] Jelen et.al., IEEE J. Q.E.,**34**,1124,1998
[3] Andersson et.al., SPIE **1762**,216,1992
[4] Pham et.al., IEEE E. D. L.,**14**,74,1993
[5] Erdtmann et.al., SPIE **3948**,220,2000

$In_{0.53}Ga_{0.47}As/InP$ QWIPs

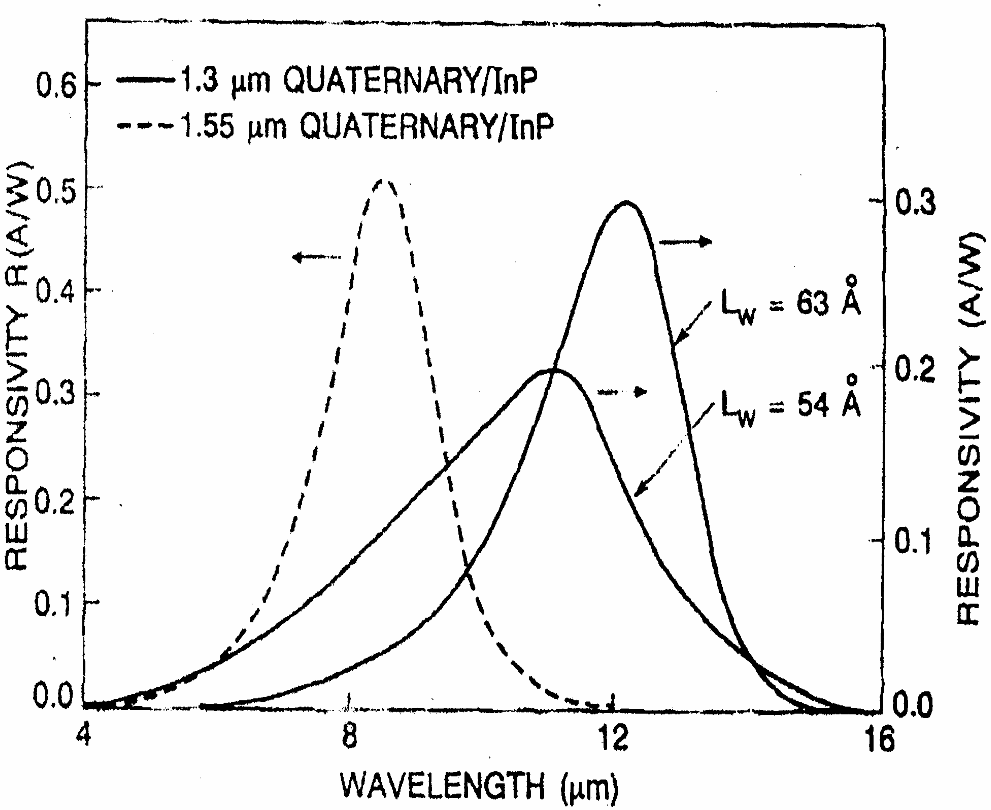


- QWs: $In_{0.53}Ga_{0.47}As$
- Barriers: InP
- Lattice-matched to InP
- InP barriers for higher gain
  - Less alloy scattering in binary material than ternary AlGaAs
  - Higher saturation velocity of InP
- $In_{0.53}Ga_{0.47}As/InP$ QWIPs have
  - 5 x larger responsivity and
  - 10 x larger gain

  than similar GaAs/AlGaAs QWIPs
- ΔE_C = 242 meV is fixed
- $\lambda_p \sim$ 7-8 μm by varying L_w

Gunapala et al., Appl. Phys. Lett. **58**, 2024 (1991)

$In_xGa_{1-x}As_yP_{1-y}$/InP QWIPs



- QWs: InGaAsP
- Barriers: InP
- Lattice matched to InP for x = 0.47 y
- InGaAsP QWs for tuning peak detection wavelength
- InP barriers for higher gain
- InGaAsP/InP QWIPs have
  - 2.5 x larger responsivity than similar GaAs/AlGaAs QWIPs
  - 2 x smaller responsivity than $In_{0.53}Ga_{0.47}As$/InP QWIPs due to more alloy scattering in quaternary QWs

Gunapala et al., Appl. Phys. Lett. **60**, 636 (1992)

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QWIP Structure Parameters

Ref.	Growth method	Well / Barrier	Well doping (cm^{-3})
This work	**MOVPE**	**30 x (68 Å InGaAs/340 Å InP)**	**5×10^{17}**
Gunapala et. al.	MBE	20 x (60 Å InGaAs/500 Å InP)	5×10^{17}
Andersson et. al.	MOVPE	50 x (47 Å InGaAs/550 Å InP)	5×10^{17}
Pham et. al.	MOVPE	50 x (50 Å InGaAsP/50 Å InP) + 500 Å InP blocking barrier	N/A
Erdtmann et. al.	MOVPE	20 x (60 Å InGaAs/500 Å InP)	1.7×10^{17} 5×10^{17} 1.7×10^{18}

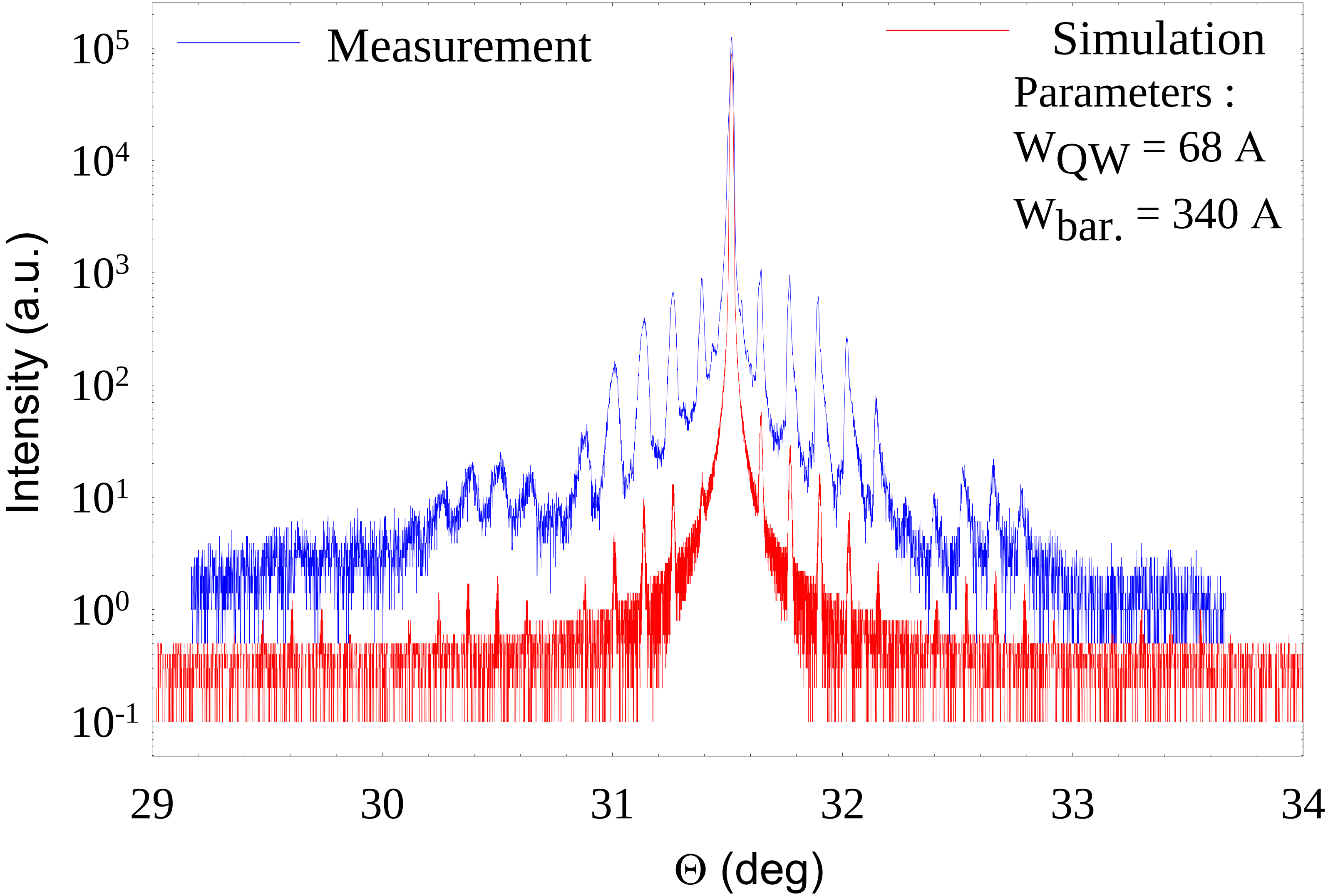
Schematic structure of $In_{0.53}Ga_{0.47}As/InP$ QWIP grown by MOVPE

5000 Å	n ~ 10^{18} cm^{-3}	n-InP	
340 Å	undoped	InP	
68 Å	n ~ 5 x 10^{17} cm^{-3}	n-InGaAs	x 30
340 Å	undoped	InP	
1.0 μm	n ~ 10^{18} cm^{-3}	n-InP	
400 μm	SI-InP substrate		

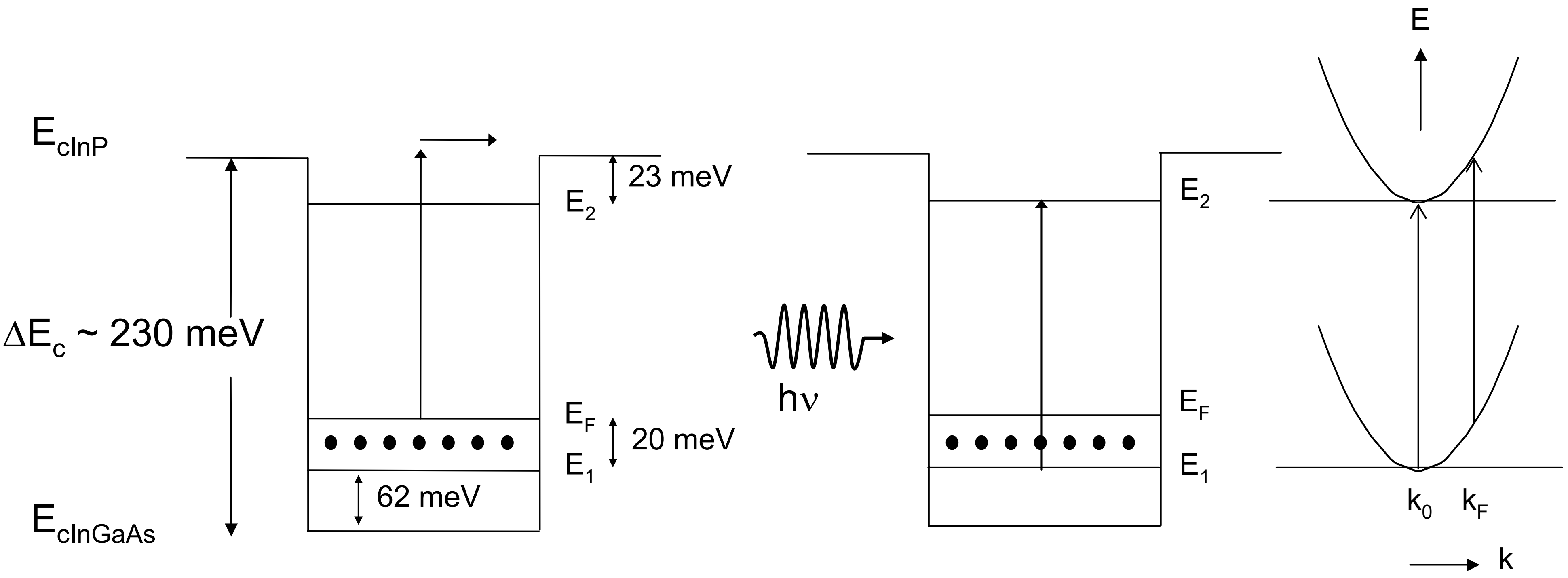
T_G ~ 625°C

Design wavelength ~ 8.5 μm

High resolution x-ray diffraction of InGaAs/InP QWIP

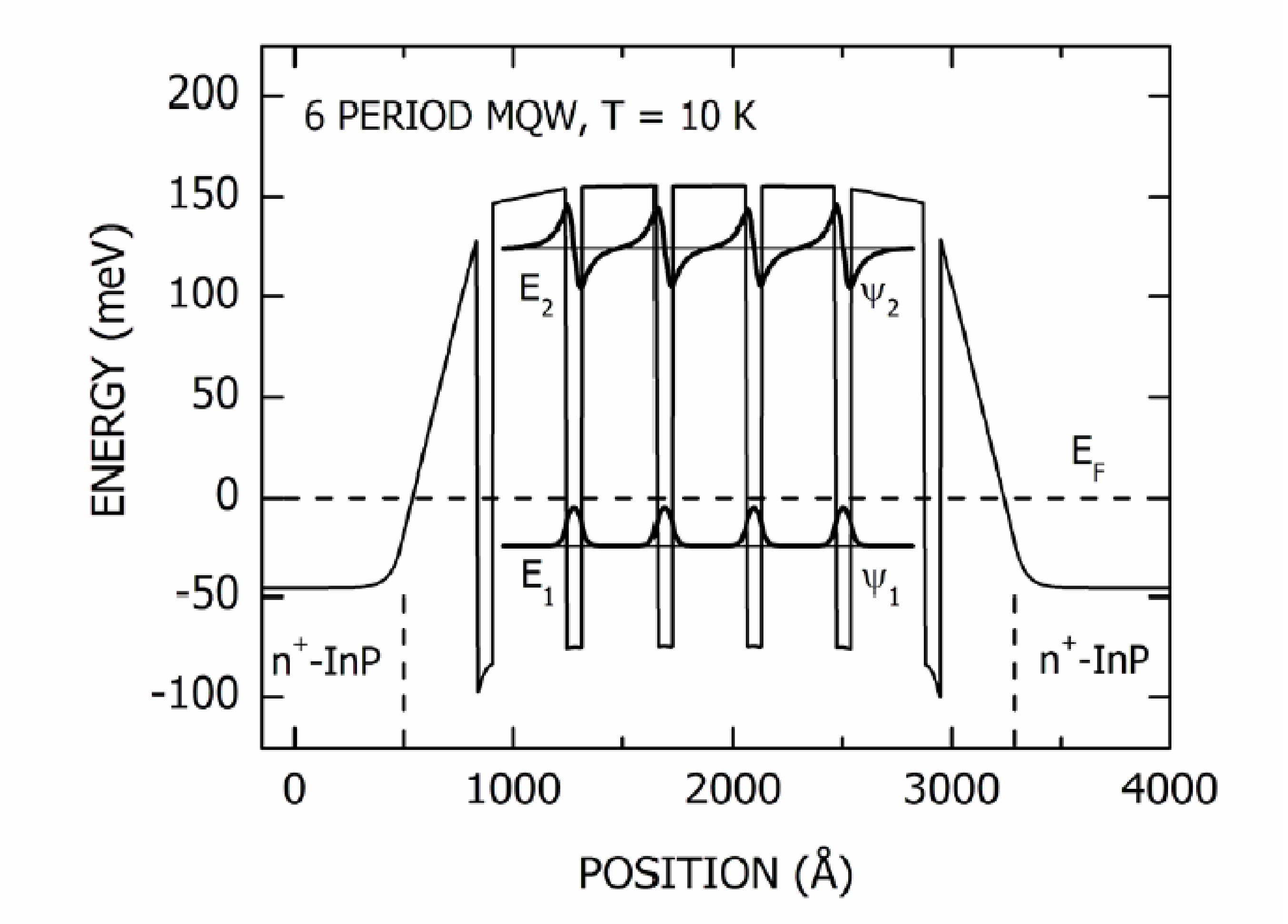


Energy Level diagram of InGaAs/InP QWIP



E_{21} ~ 145 meV

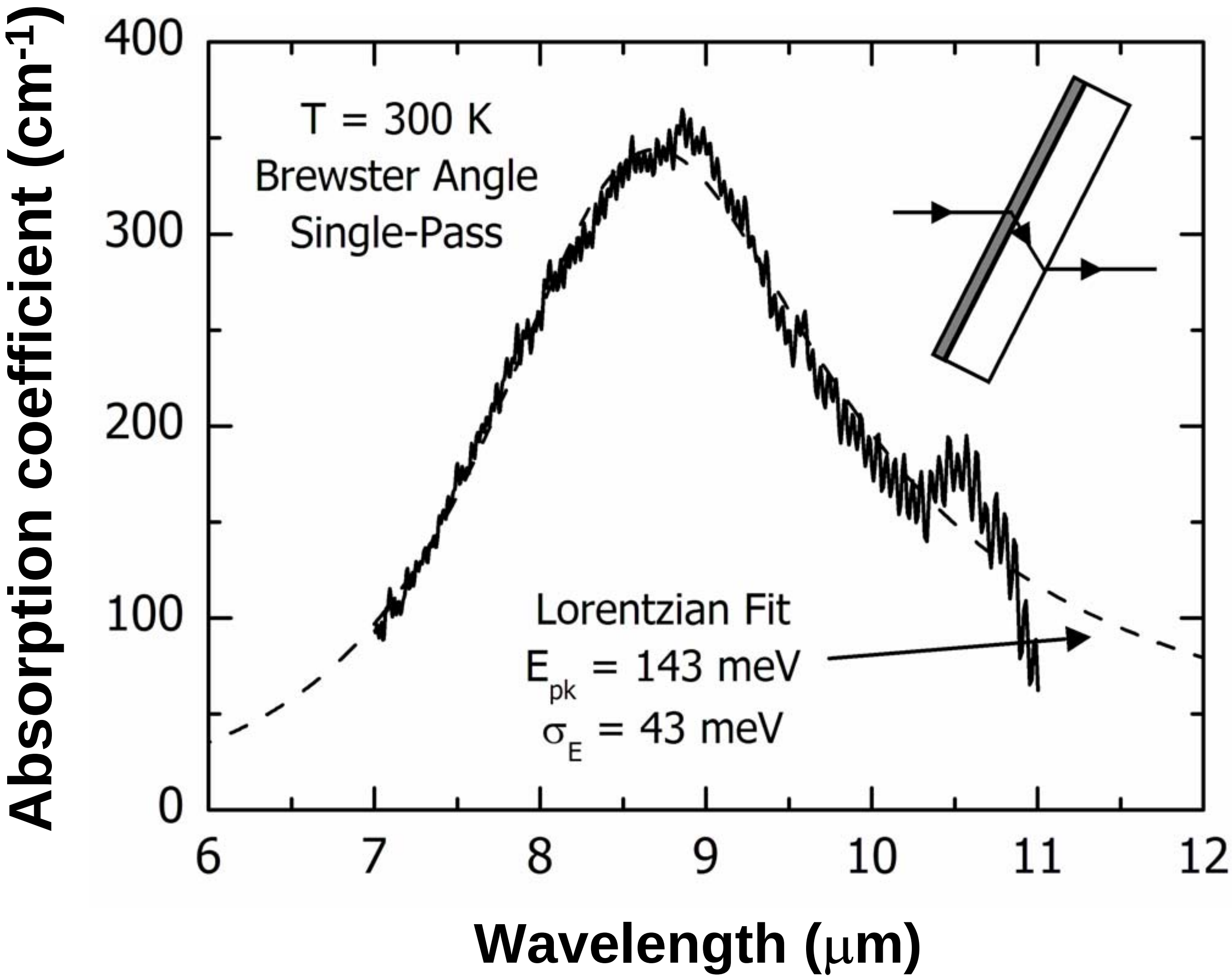
Transfer Matrix Method Calculation



E_{21} ~ 145 meV ; Plasma Energy $\hbar w_p$ = 29.7 meV

$$E_{pk} = \sqrt{E_{21}^2 + \hbar w_p^2} = 148 \text{ meV} \rightarrow \lambda_{pk} = 8.4\ \mu\text{m}$$

Inter-subband absorption measurement with FTIR



λ_{pk} ~ 8.7 μm

σ_E/E_{pk} ~ 30 %

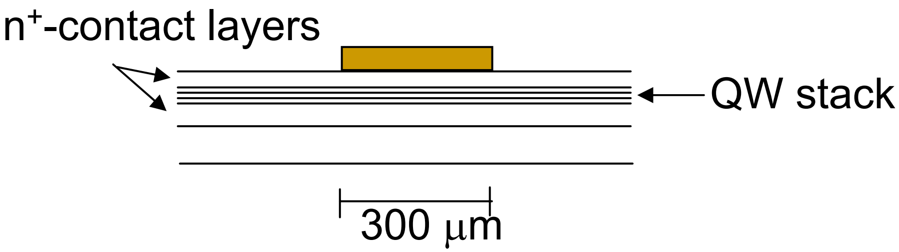
α_{pk} ~365 cm^{-1}

L ~ 1.258 μm

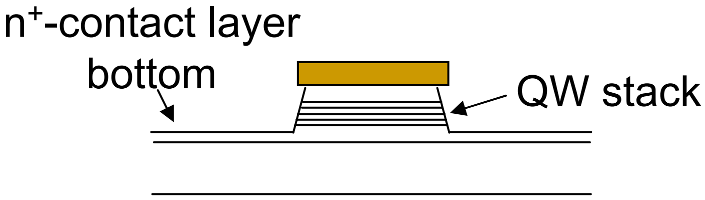
η_{77K} ~ 5.6 %

Device Fabrication Process

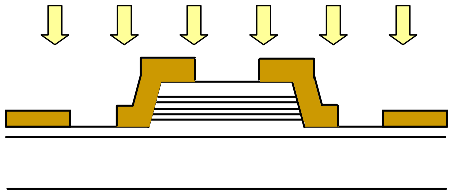
1. Resist mask for mesa etching



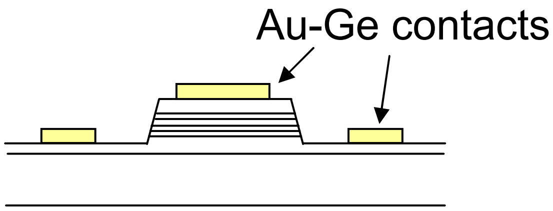
2. Wet chemical mesa etching



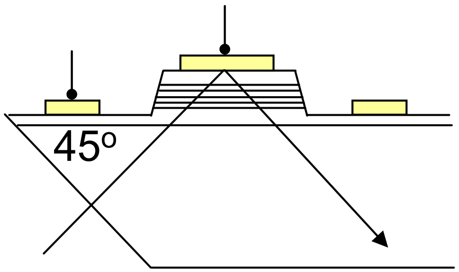
3. Photolithography & metalization



4. Lift-off & annealing



5. Final device after polishing at 45°



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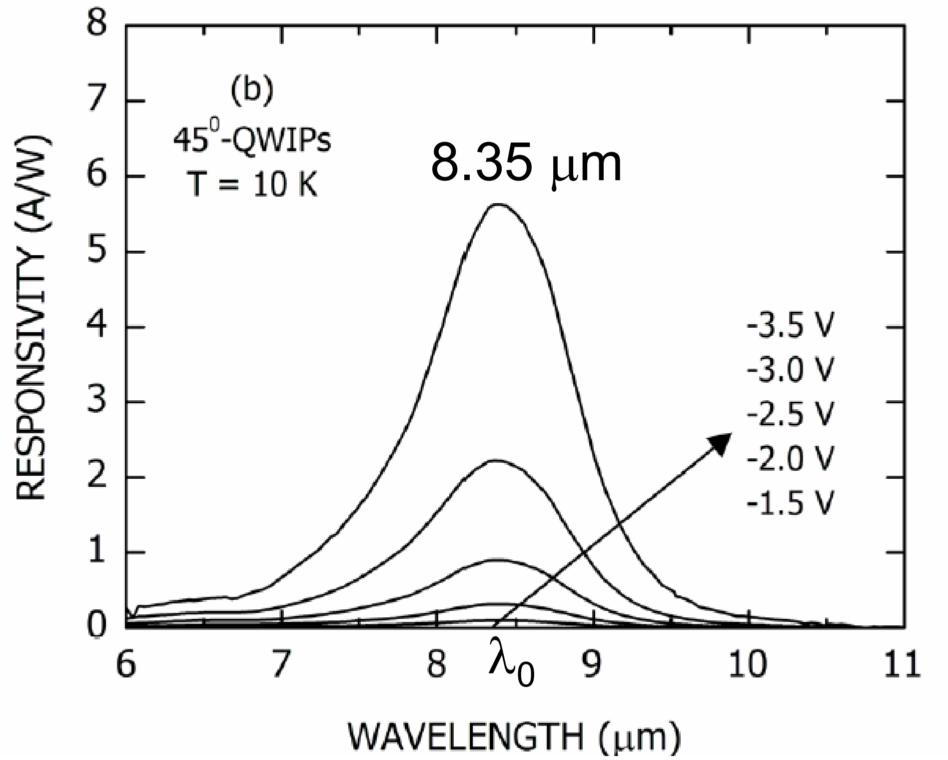
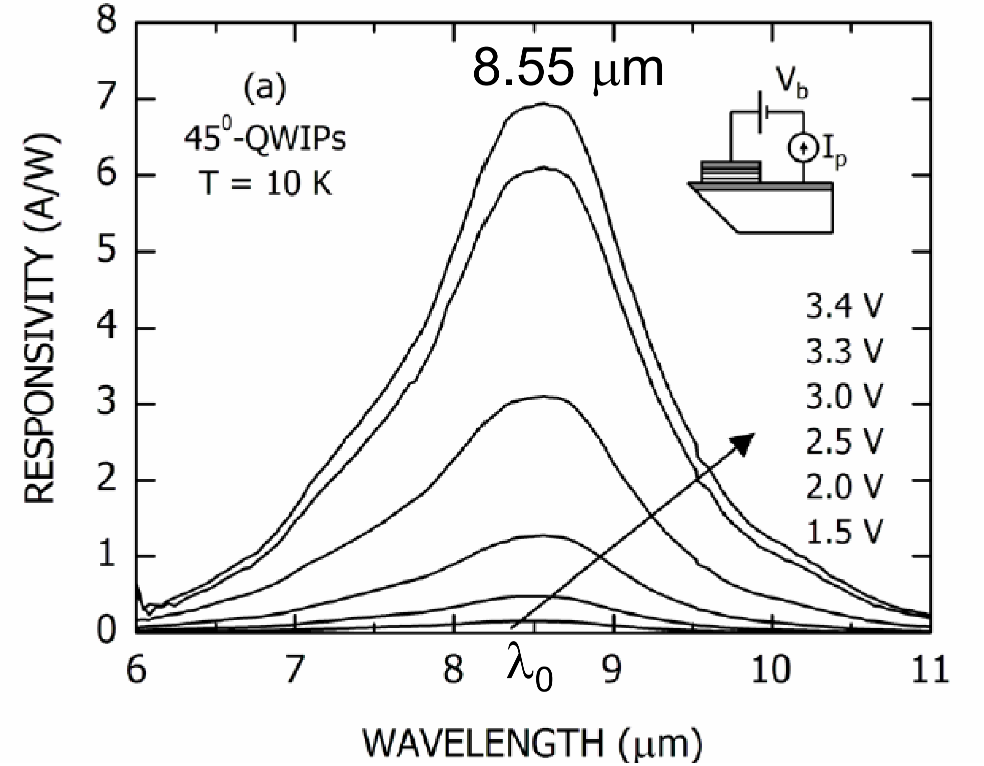
QWIP Response

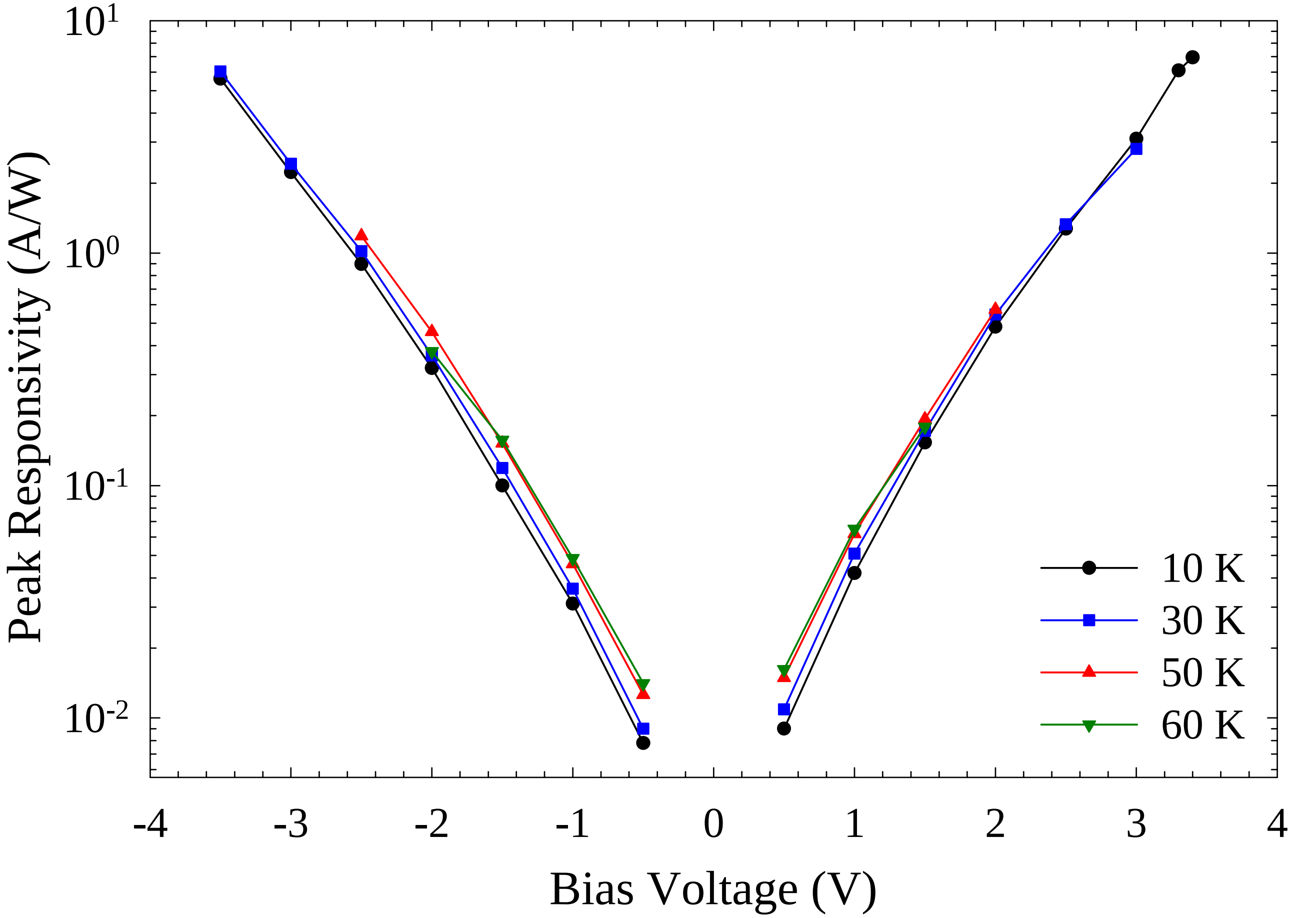




- Tail on short wavelength side
- $\Delta\lambda/\lambda_{pk}$ ~ 18 % +ve bias
  ~ 13 % -ve bias
- λ_0 ~ 8.25 μm

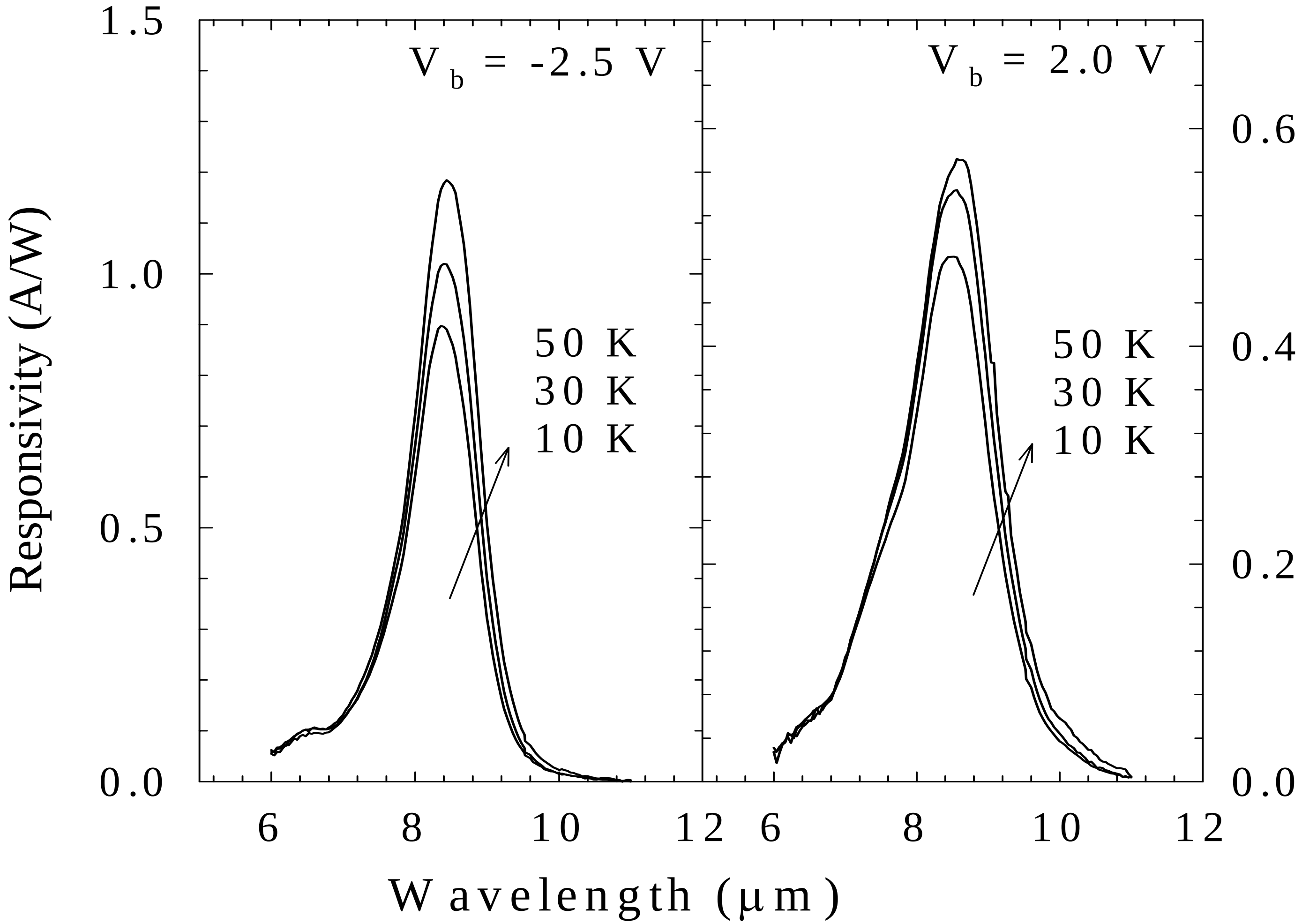
- λ_c ~ 9.3 μm +ve bias
  ~ 8.9 μm -ve bias
- R_{pk} ~ 6.9 A/W +ve bias
  ~ 5.6 A/W -ve bias

Bias dependence of peak responsivity
Temp: 10 - 60 K



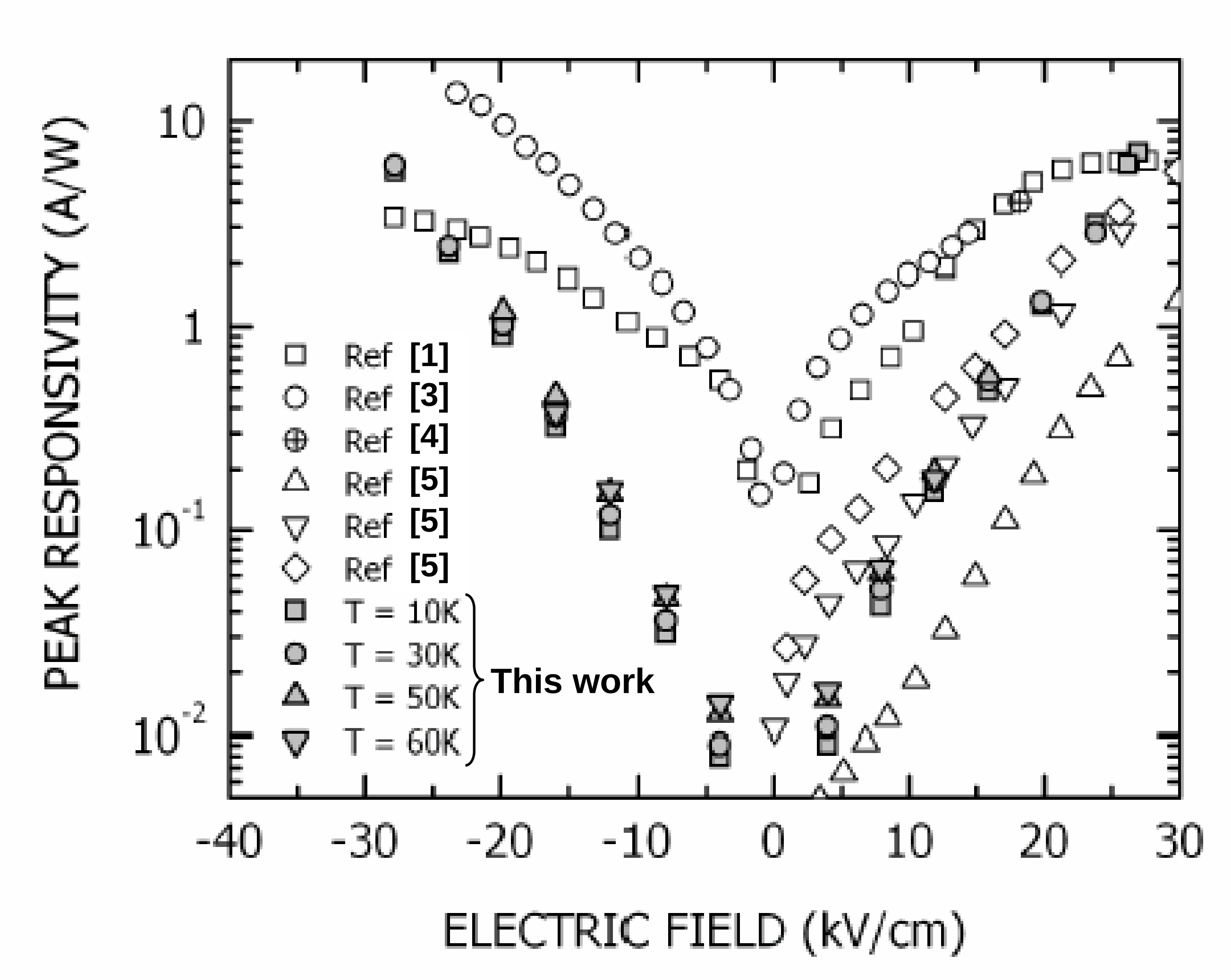
R_{pk} increases nearly exponentially with bias

Temperature dependence of responsivity at fixed bias



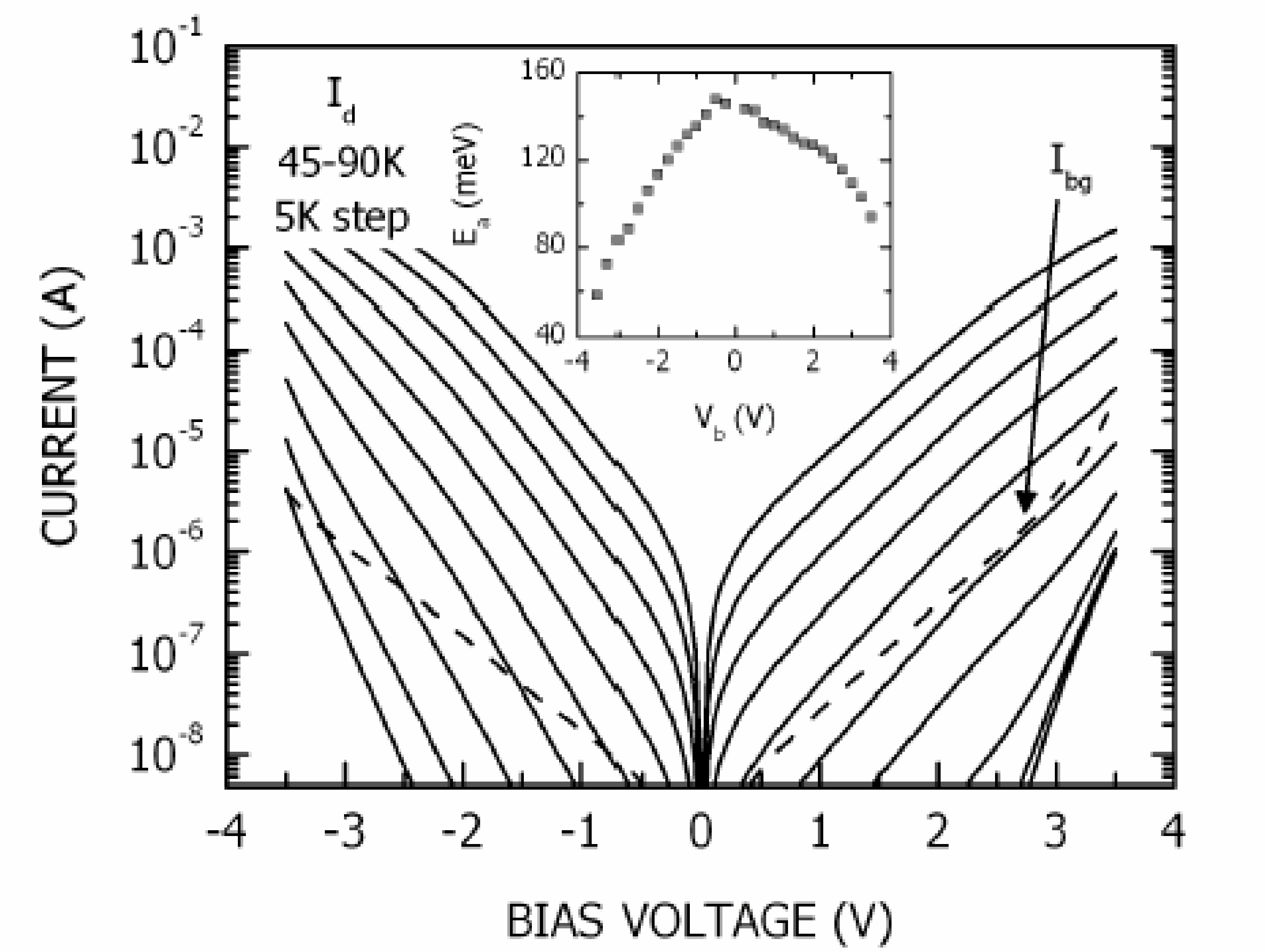
R_{pk} increases with temperature

Comparison of Responsivities with Published Work

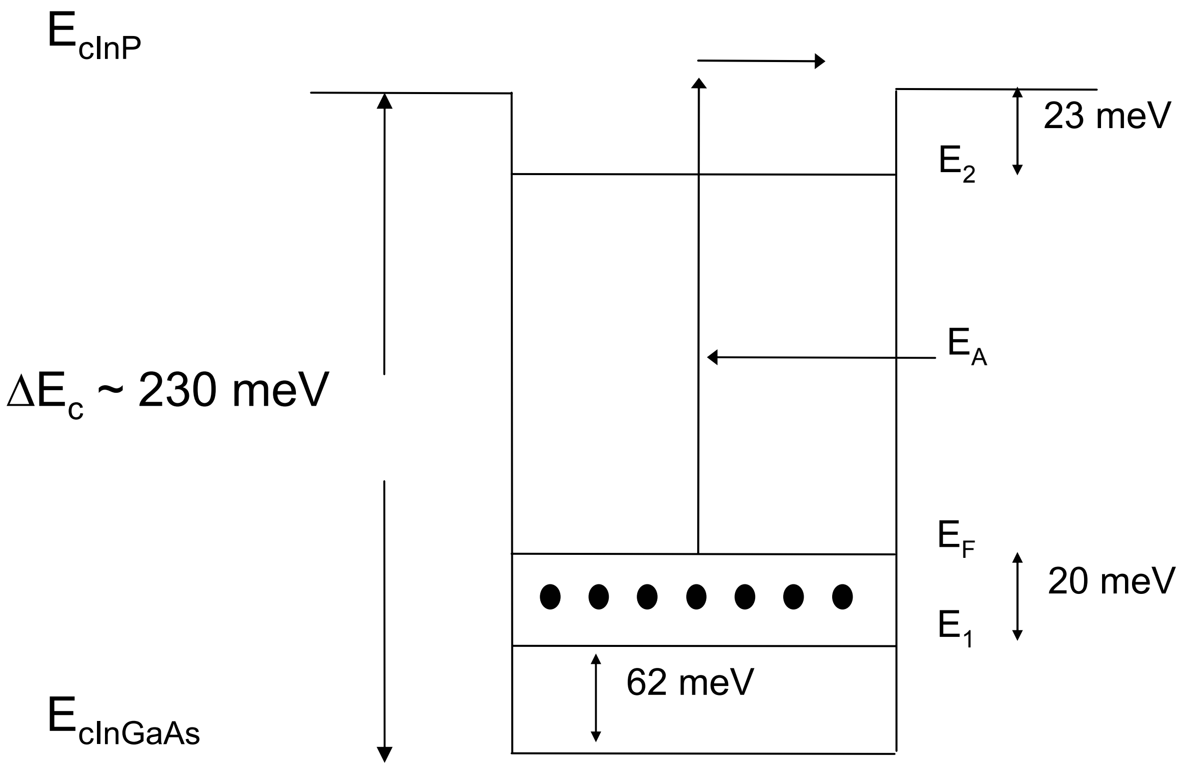


[1]Gunapala et.al.
[3]Andersson et.al.
[4]Pham et.al.
[5]Erdtmann et.al.

Dark I – V Characteristics



Activation energy of InGaAs/InP QWIP



Dark current activation energy

$E_A = \Delta E_c - (E_1 + E_F) \sim 148$ meV

Gain

- Noise gain
  (noise measurement)

  $i_n = \sqrt{4eg_n i_d}$

  g_n = 21.2 at 3.4 V

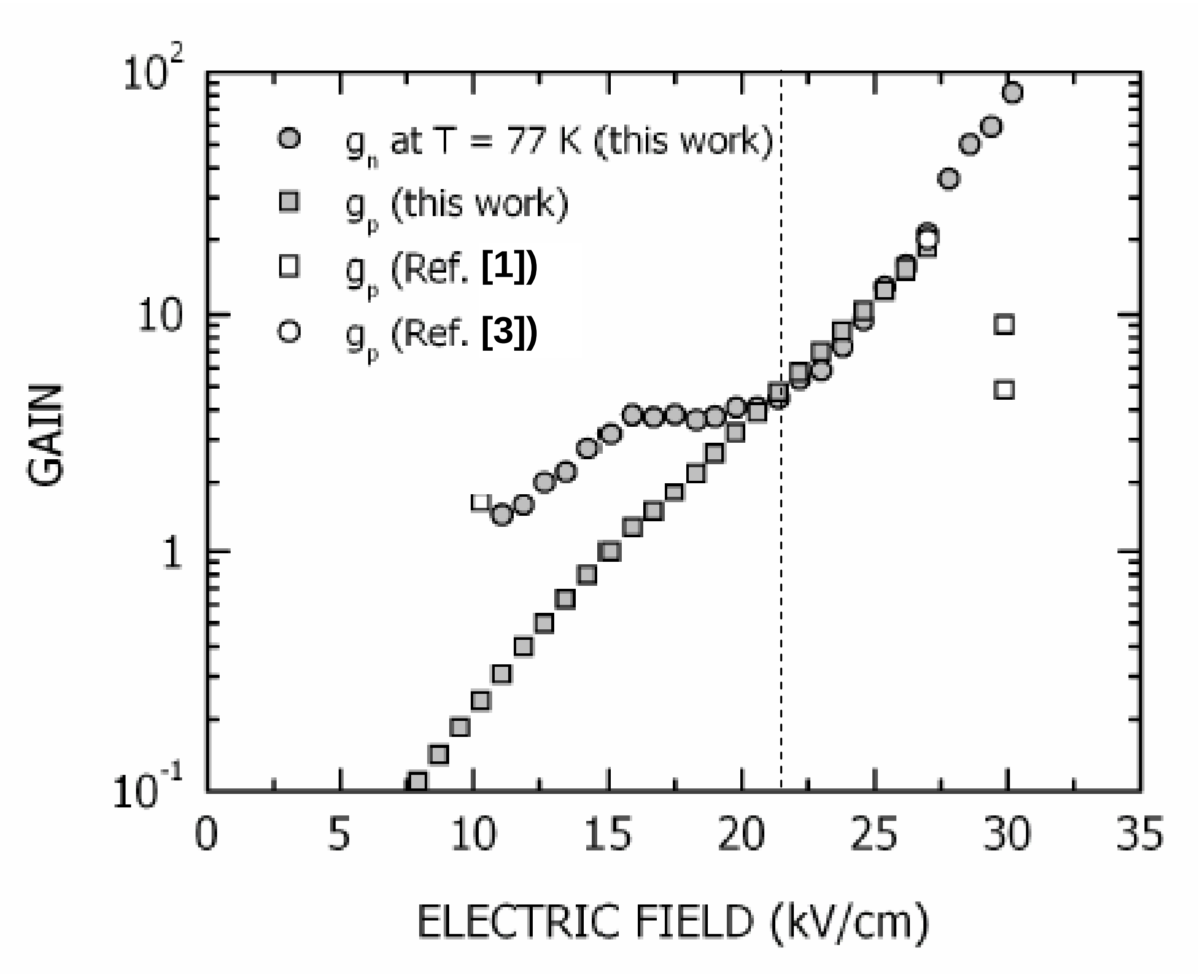
  = 82 at 3.8 V

  Onset of Avalanche
  multiplication at
  E ~ 20 – 25 kV/cm

- Photo Conductive gain
  (Responsivity measurement)

  $$R_{pk} = \left(\frac{e\lambda_{pk}}{hc}\right)\eta g_p$$

  g_p = 18.4 at 3.4 V



Detectivity

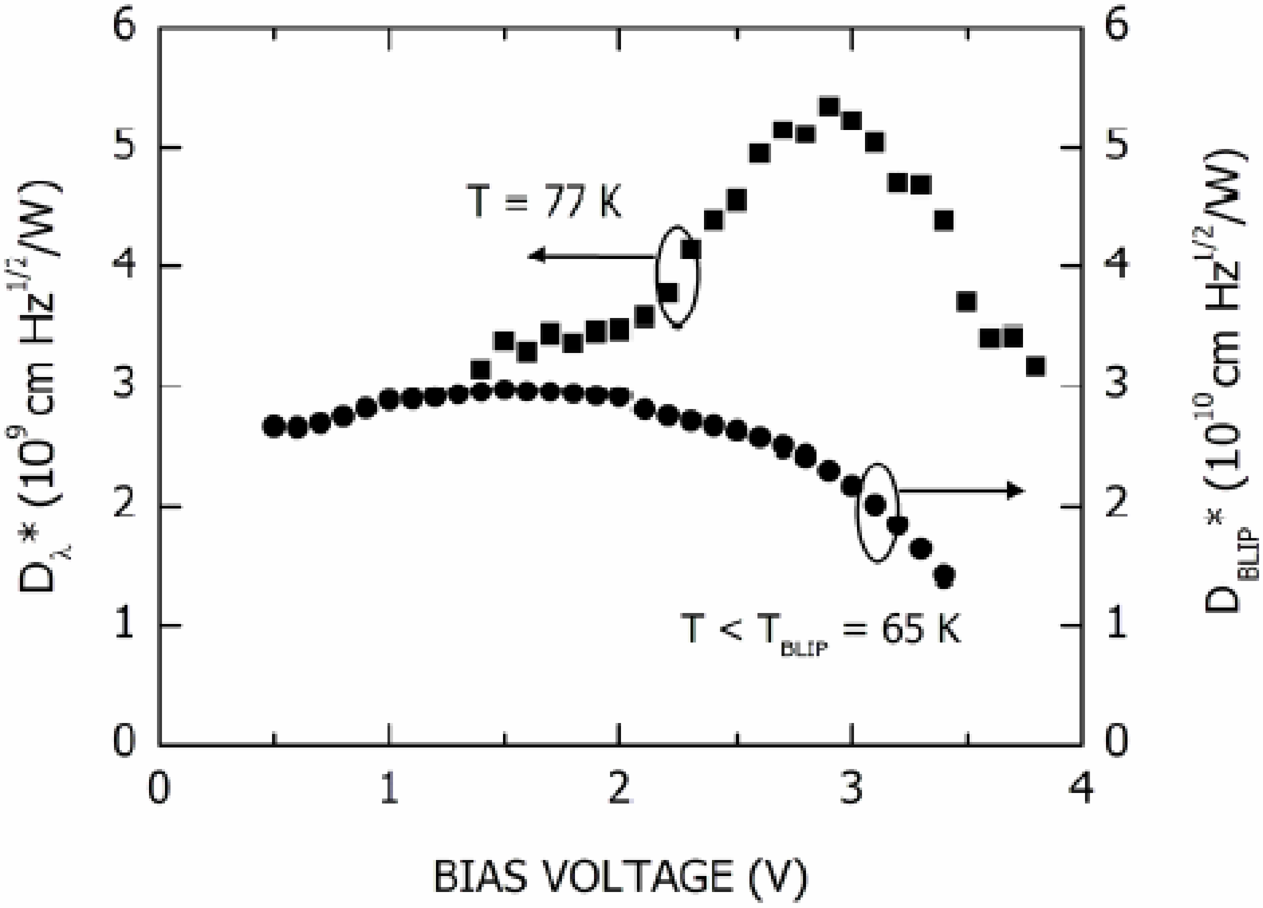
- Peak detectivity

$$D_\lambda^* = \frac{R_{pk}\sqrt{A_d \Delta f}}{i_n}$$

- Background limited detectivity

$$D_{BLIP}^* = \frac{R_{pk}\sqrt{A_d \Delta f}}{i_{pn}}$$

$$i_{pn} = \sqrt{4eg_p I_{bg}}$$



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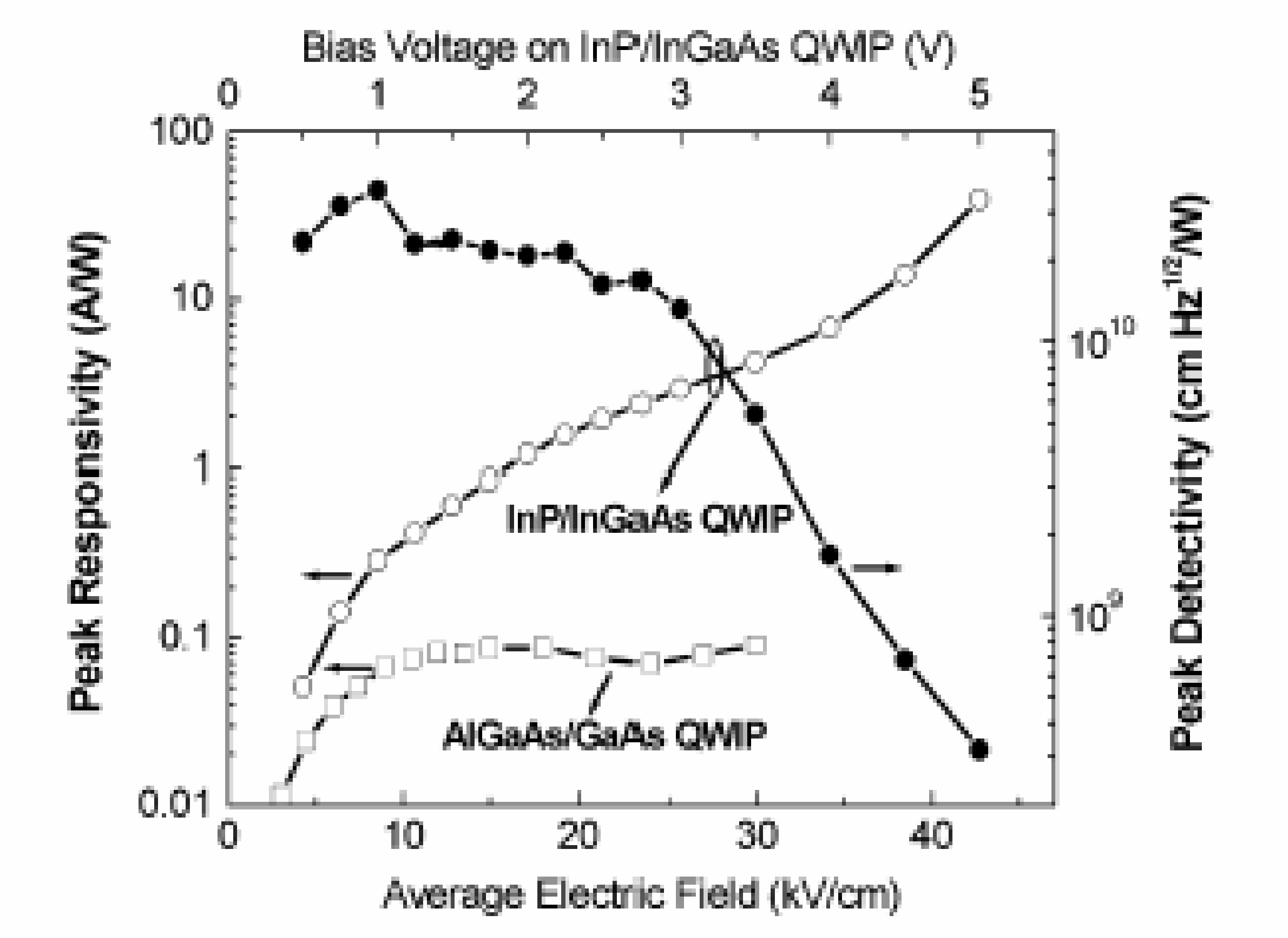
Responsivity

$$R = \frac{e}{h\nu}\eta g = \frac{e}{h\nu}\eta\frac{\tau_c}{\tau_{tr}}$$

- Factors controlling τ_{tr}
  - Electron emission from the excited state in QW into barrier
  - High field electron-velocity in the barrier

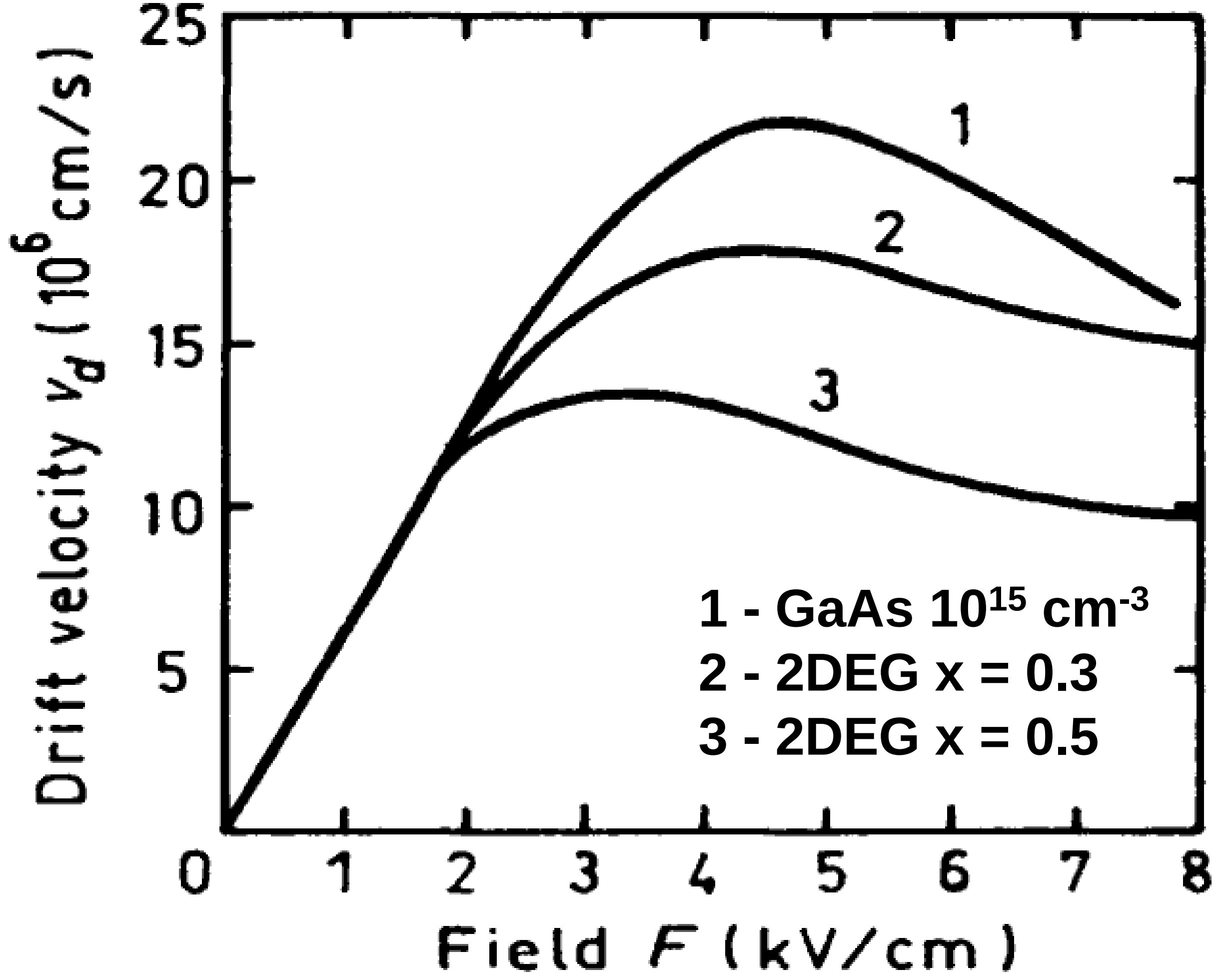
- Factors controlling τ_c
  - Distribution of electrons in Γ, L, X valleys
  - Capture of electrons in the QW
    electron-phonon interaction

Comparison of peak responsivity and detctivity of GaAs/AlGaAs and InGaAs/InP QWIPs



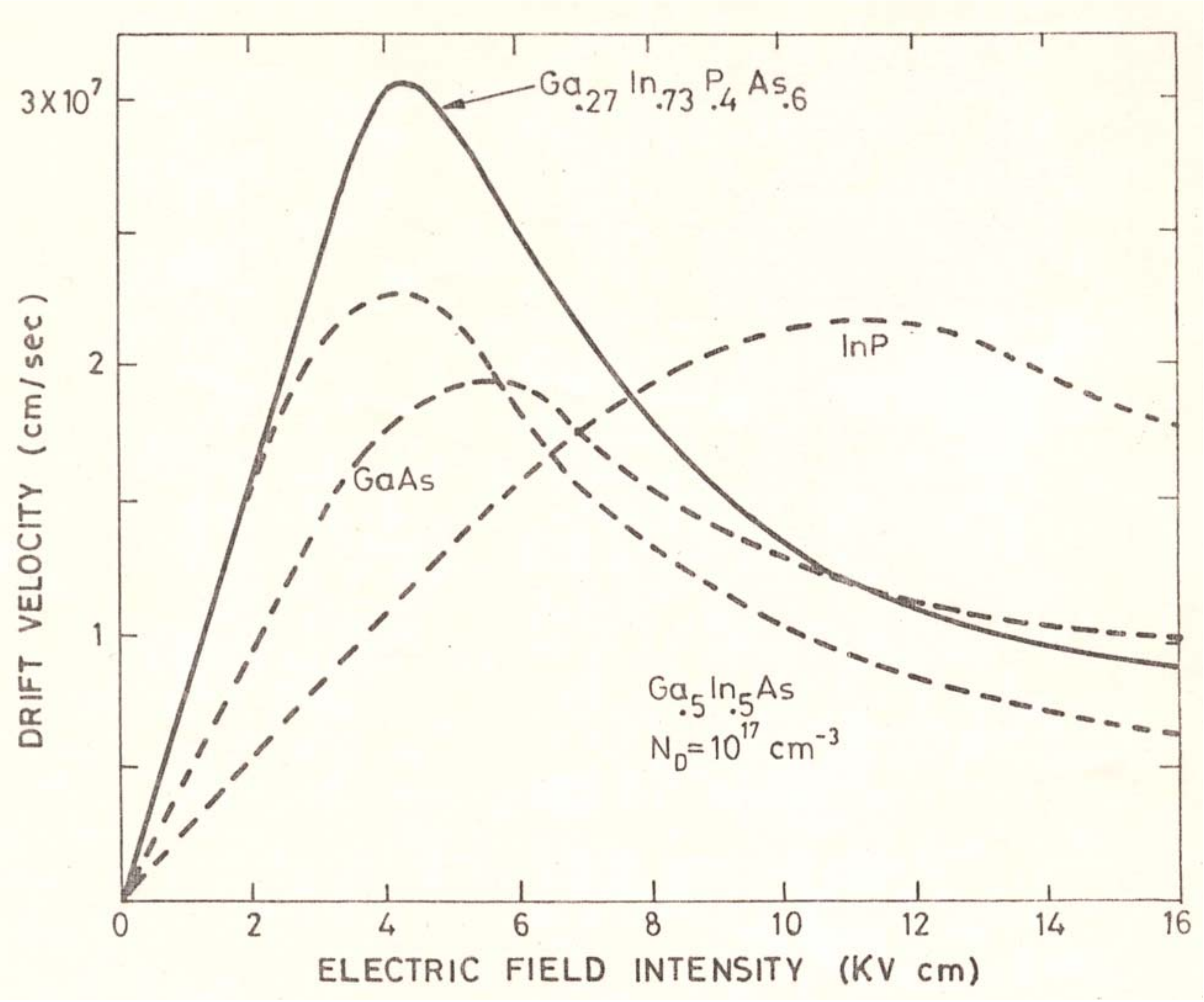
Cellek et.al., IEEE J. Q. E., Vol. 41, No. 7, 980 – 985, July 2005

Velocity-field characteristics of GaAs and $Al_xGa_{1-x}As$

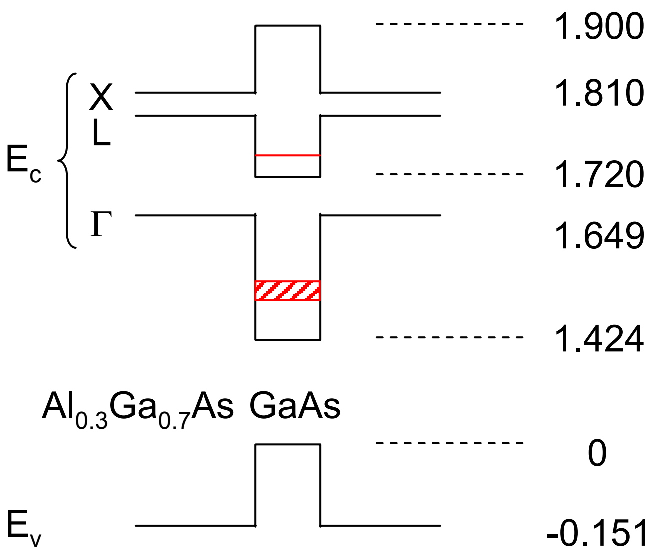


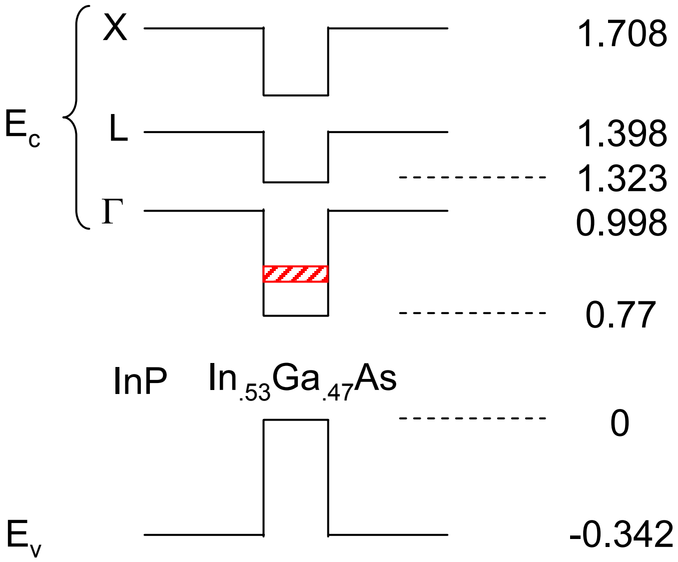
1 - GaAs 10^{15} cm^{-3}
2 - 2DEG x = 0.3
3 - 2DEG x = 0.5

Velocity-field characteristics of InGaAsP, GaAs, InP and InGaAs



GaAs-$Al_{.3}Ga_{.7}As$ and $In_{.53}Ga_{.47}As$-InP Band Diagrams





	GaAs	$Al_{.3}Ga_{.7}As$
E_g^{Γ}	1.424	1.800
E_g^{L}	1.720	1.928
E_g^{X}	1.900	1.961

	$In_{.53}Ga_{.47}As$	InP
E_g^{Γ}	0.77	1.34
E_g^{L}	1.323	1.74
E_g^{X}	1.438	2.05

ΔE_g^{Γ} = 0.376 eV
ΔE_c = 0.225 eV
ΔE_v = 0.151 eV
Assume $\Delta E_c \sim 0.6\ \Delta E_g$

ΔE_g^{Γ} = 0.57 eV
ΔE_c = 0.228 eV
ΔE_v = 0.342 eV
Assume $\Delta E_c \sim 0.4\ \Delta E_g$

Electron Capture in GaAs QW

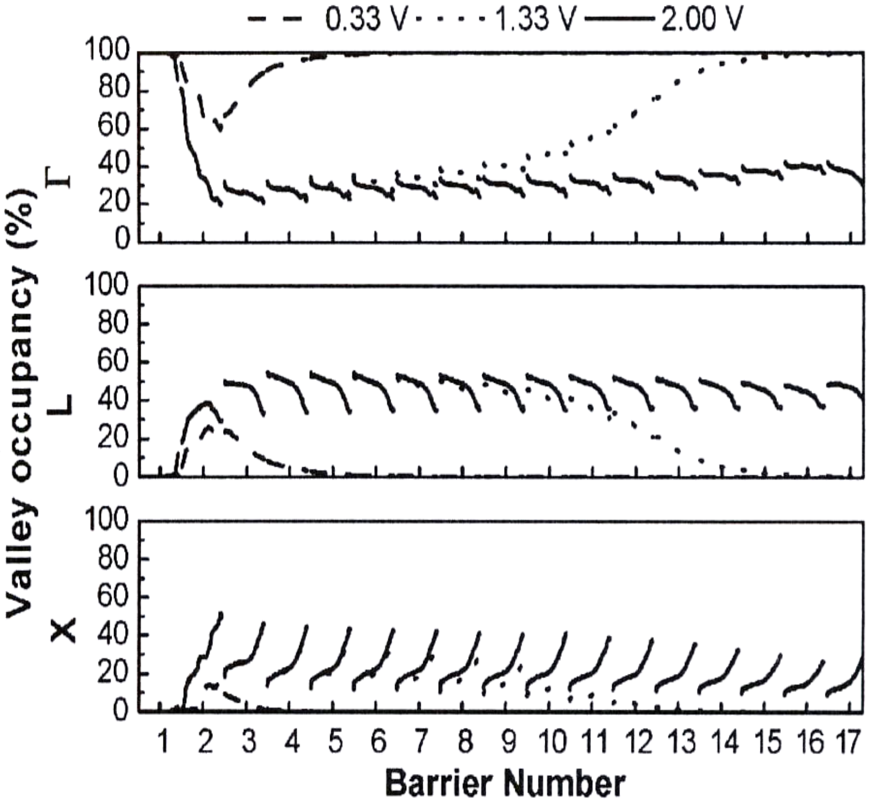


Figure 5. Valley occupancies in the barriers under various bias voltages.

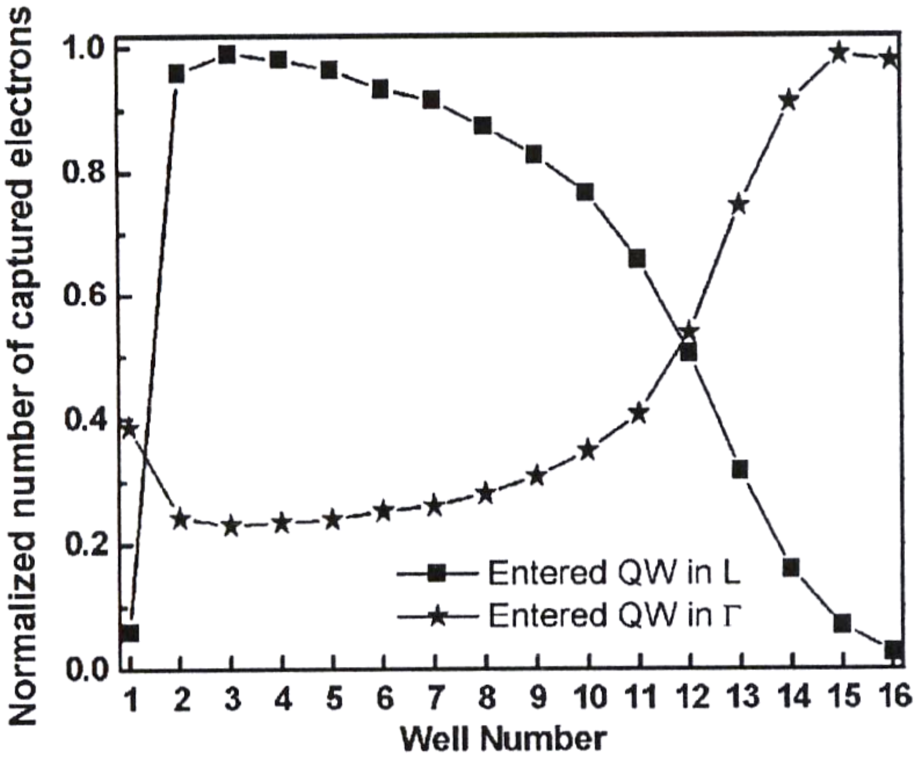


Figure 8. Normalized number of electrons that enter the GaAs QW region in Γ and L valleys and are captured into the same QW of the Γ valley under 1.33 V bias.

Cellek, et. al., Semi. Sci. Tech. 19 (2004) 183-190

Some Questions

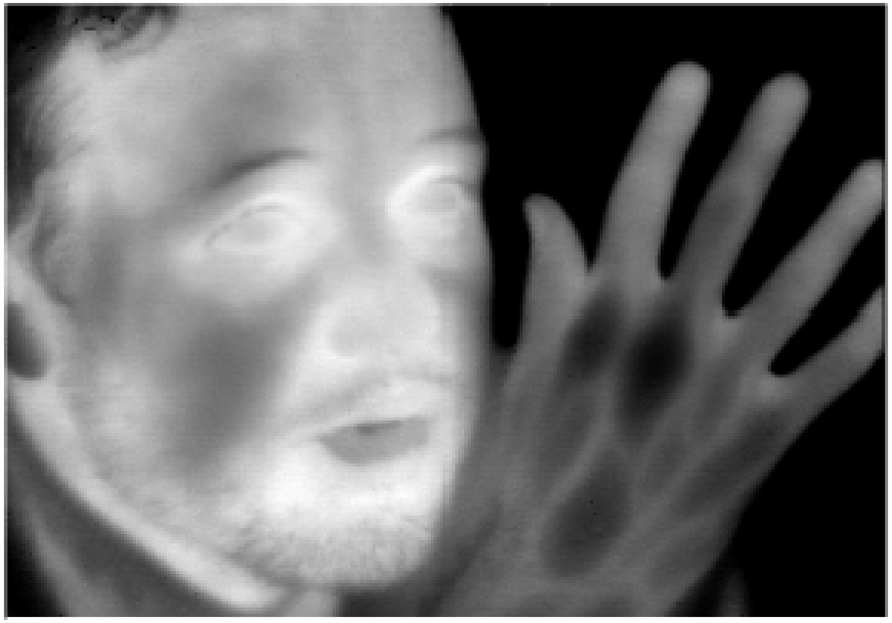
i. What is the origin of asymmetry of dark I – V and photo I – V characteristics ?

ii. Dark current is larger for – ve polarity, while the photo current is larger for + ve plarity. What causes this ?

iii. What is the relation of structural non-uniformities particularly of (i) the compositional & (ii) doping concentration, to the measured characteristics ?

iv. What are the performance limiting aspects of InGaAs / InP QWIPs Vis - a - Vis GaAs / AlGaAs QWIPs ?

Thermal Images from InGaAs/InP QWIP FPA



Indoor Image

Outdoor Image

- Sensor Temperature ~ 70 K

Cellek et.al., IEEE J. Q. E., Vol. 41, No. 7, 980 – 985, July 2005

Summary

- $In_{0.53}Ga_{0.47}As/InP$ B-B QWIPs grown by MOVPE have performance comparable to the devices fabricated from materials synthesized by MBE.
- In order to be able to use the InGaAs / InP QWIP devices for imaging purposes, it is necessary to identify the material aspects such as non-uniformities, interfaces, which limit the uniformity and performance over the arrays, particularly their dark current and noise characteristics.