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SMR.998d - 11

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
11 - 22 AUGUST 1997

"Optical Properties and Tunnelling Spectroscopy of self-assembled InAs Quantum Dots"

PART I

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Lecture I

OPTICAL PROPERTIES AND TUNNELLING SPECTROSCOPY OF SELF-ASSEMBLED InAs QUANTUM DOTS

L. Eaves

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Collaborators:

Nottingham: T. Ihn, S. T. Stoddart, I. E. Itskevich, A. Thornton, M. Henini, H. A. Carmona, P. C. Main

Grenoble: D. K. Maude, J. C. Portal

- Overview of optical and structural properties of quantum dots and their energy levels
- Reducing the PL linewidth
- Resonant tunnelling through individual dot states
- Using quantum dots to probe many-electron effects in a 2D electron gas at fractional Landau filling factors

Zur Theorie der orientierten Ausscheidung von Ionenkristallen aufeinander

Von

I. N. Stranski und L. Krastanow

Aus dem Phys.-chem. Institut der Universität Sofia

Mit 8 Figuren im Text

(Eingegangen am 14. 2. 1938. Vorgelegt in der Sitzung am [illegible])

1. Einleitung und Problemstellung.

Die Vorgänge bei der orientierten Ausscheidung von Ionenkristallen aufeinander wurden vor einigen Jahren von dem einen von uns einer genaueren theoretischen Untersuchung unterzogen [1]. Es ergab sich dabei, daß man einer jeden einzelnen Netzebene des über fremder Unterlage wachsenden Kristalls einen gesonderten Sublimationsdruck (bzw. Löslichkeit) zuschreiben muß. Mit Hilfe dieser Sublimationsdrucke (bzw. Löslichkeiten) ließen sich dann die Bildungsmöglichkeiten der einzelnen Netzebenen genauer angeben und daraus auch eine Reihe weiterer einfacher und übersichtlicher Schlüsse ziehen [2].

Das wichtigste Ergebnis davon soll hier an Hand des folgenden einfachen Beispiels, das uns auch weiter unten dienen wird, erläutert werden. Es seien die Ionenkristalle $Kt^{\cdot}An'$ und $Kt^{\cdot\cdot}An''$ gegeben, die beide das NaCl-Gitter und die gleichen Gitterkonstanten haben sollen. Die Ladungen der Ionen sollen aber in beiden Fällen verschieden sein (beim $Kt^{\cdot}An'$ einfach und beim $Kt^{\cdot\cdot}An''$ doppelt), d. h. die Kristalle sind im Grimmschen Sinne isomorph.

Scheidet sich nun $Kt^{\cdot}An'$ über einem $Kt^{\cdot\cdot}An''$-Kristall aus, und zwar über der Würfelfläche, die in diesem Falle die einzige Gleichgewichtsformfläche ist, so wird die erste Netzebene einen bedeutend kleineren Dampfdruck p_1 als den Dampfdruck p_∞

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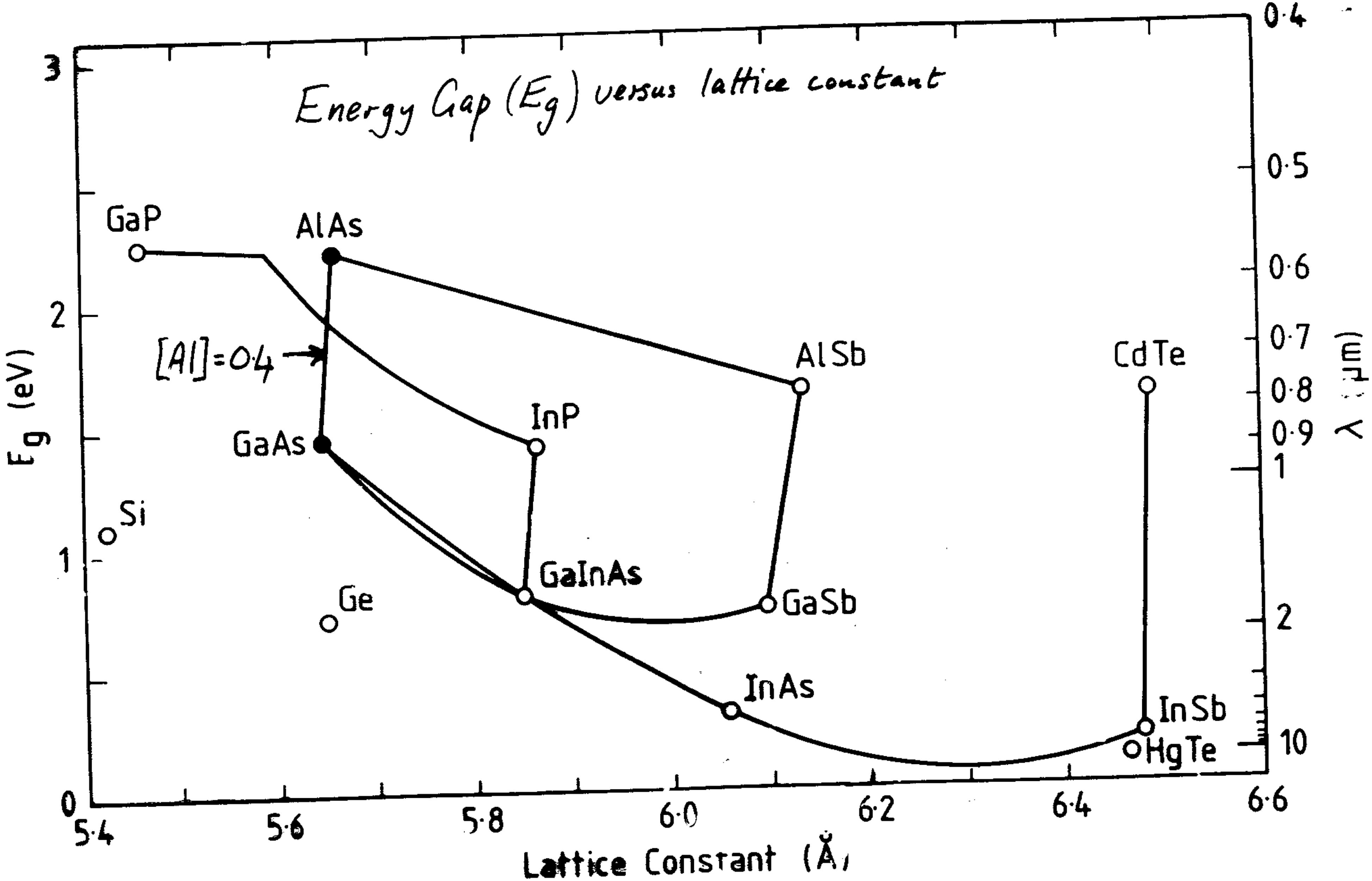
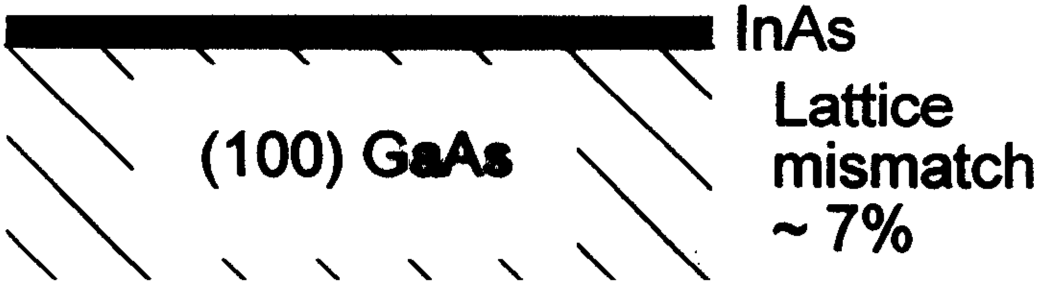
[1] I. N. Stranski, Z. physik. Chem. A 142 (1929) 453; Bodenstein-Festbd. (1931) 230.

[2] Hier sei insbesondere auf den Bericht von H. Seifert über „Die anomalen Mischkristalle" verwiesen, erschienen in Fortschr. d. Min., Krist. u. Petrogr. 19 (1935) 103—182 (I. Teil); 20 (1936) 324—455 (II. Teil); 22 (1937) 185—488 (III. Teil). In diesem Bericht sind die vielfachen Erfahrungen aus dem Gebiete der Mischkristallbildung und Kristallaufwachsung in ausgezeichneter Weise zusammengestellt und auch durch eigene Untersuchungen ergänzt.

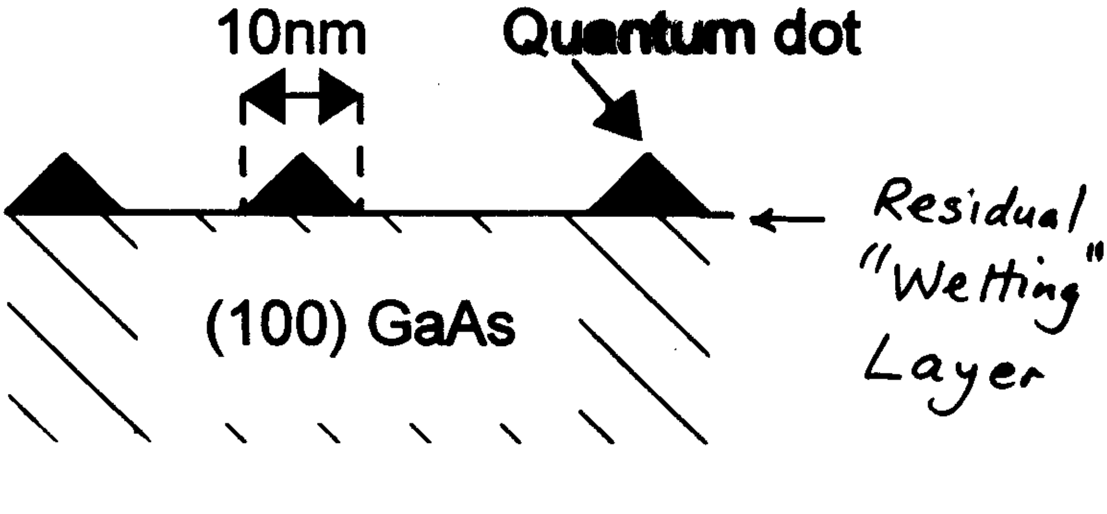

Energy Gap (Eg) versus lattice constant
3
2
1
0
Eg (eV)
5·4
5·6
5·8
6·0
6·2
6·4
6·6
Lattice Constant (Å)
0·4
0·5
0·6
0·7
0·8
0·9
1
2
10
λ (μm)
GaP
AlAs
AlSb
CdTe
InP
GaAs
Si
GaInAs
GaSb
Ge
InAs
InSb
HgTe
[Al]=0·4

Stranski-Krastanov (Self-Organised) MBE Growth of InAs Quantum Dots on (100) GaAs

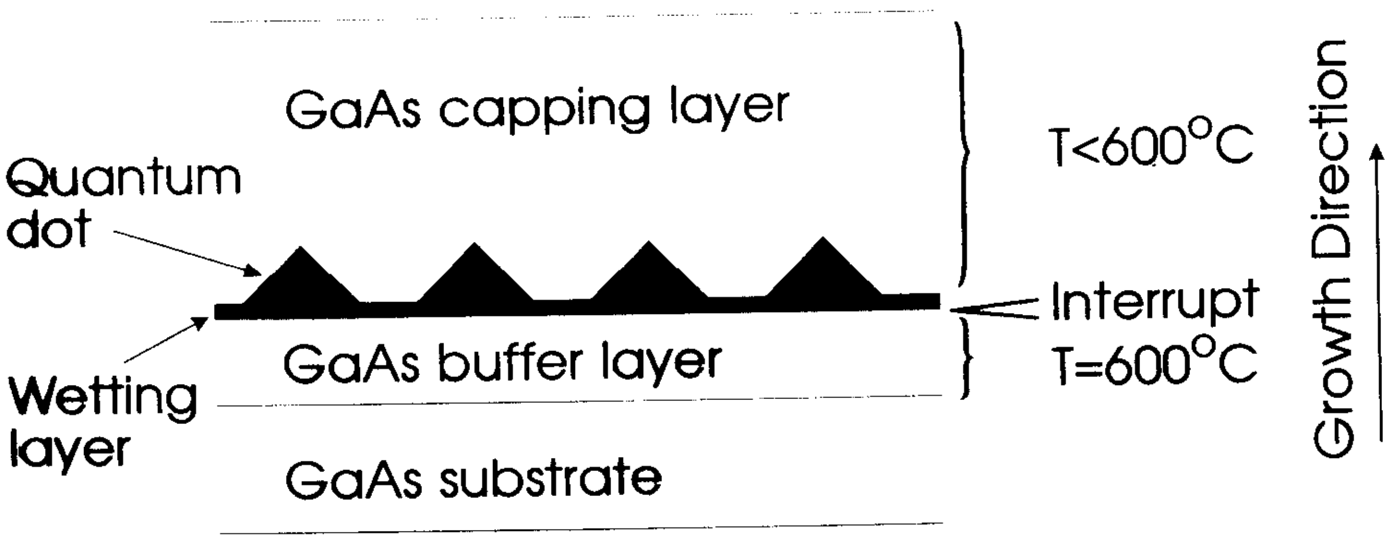
No islands at ~1 monolayer InAs

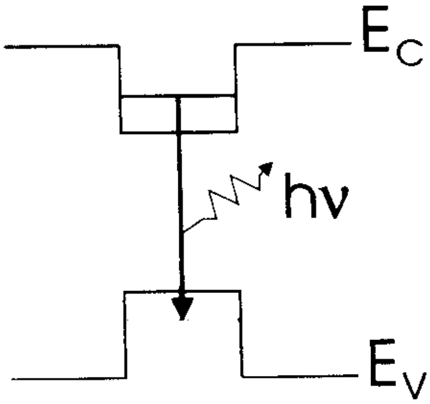


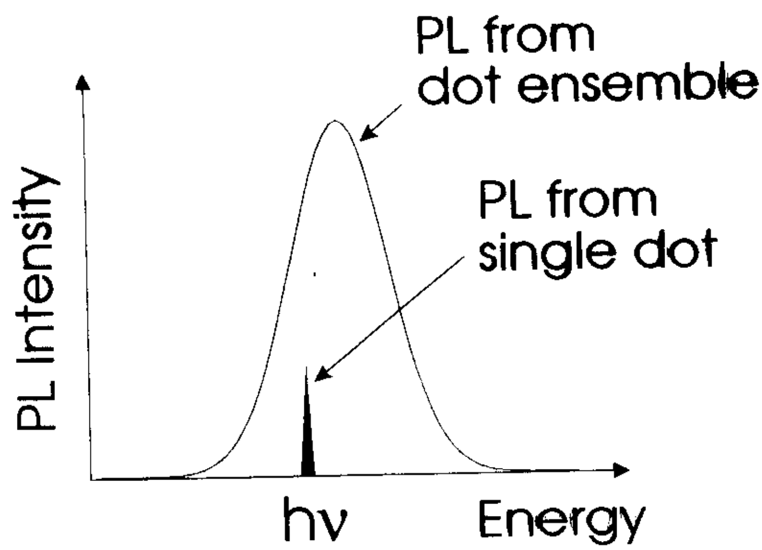
Islands form at ~ 1.7 InAs monolayers

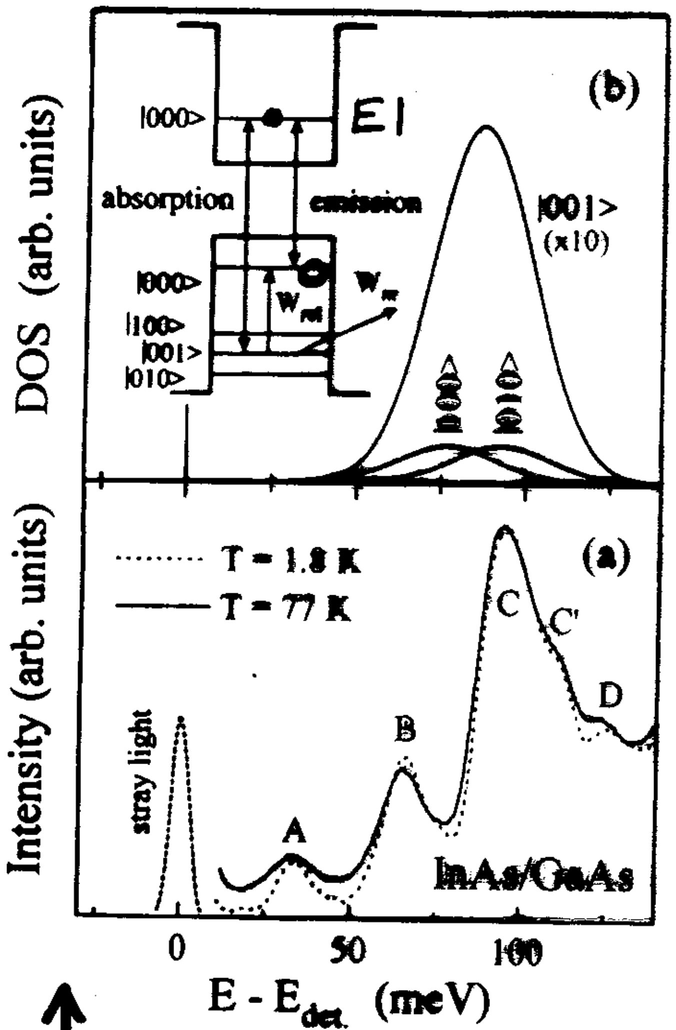


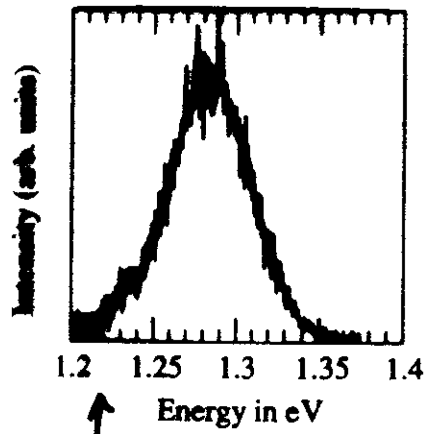
Dot growth and PL



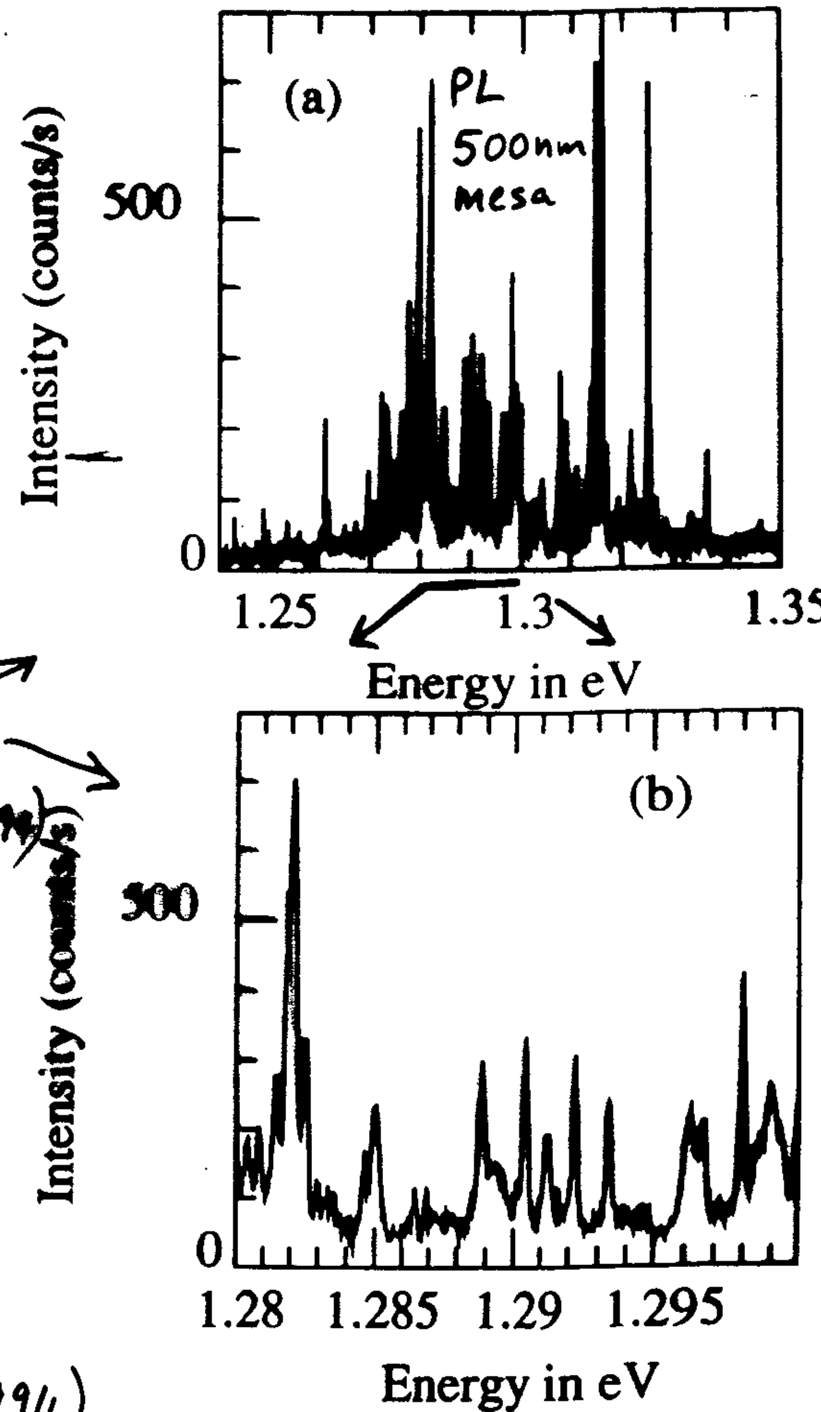








↑ PL, 10K,
"large" 5μm diameter mesa
↑
Marzin et al
P.R.L. 73, 718 (1994)



↑

- Heitz et al
  A.P.L. 68, 361 (1996)
- Also Capacitance Spectroscopy
  eg Drexler et al P.R.L. 73, 2252 (1994)

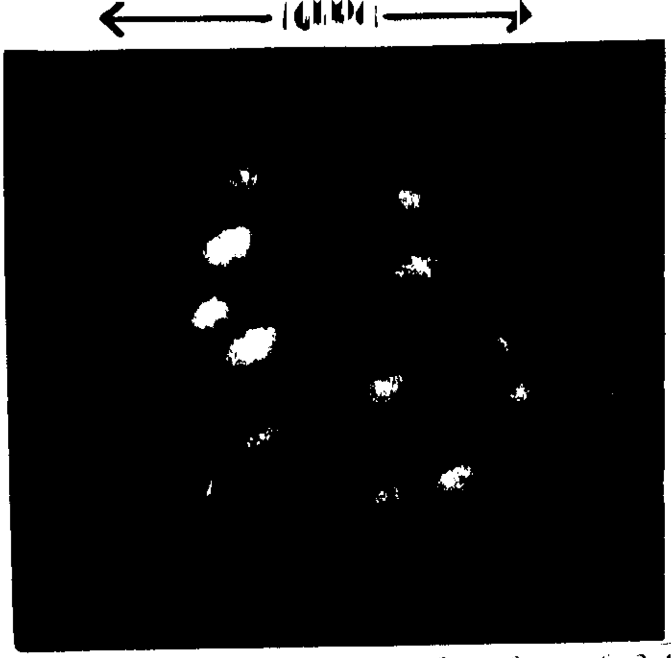


Figure 1(a) STM image of surface of 2.4 monolayers of InAs on GaAs (square size 1000 Å × 1000 Å).

STM: P. Moriarty
P. H. Beton

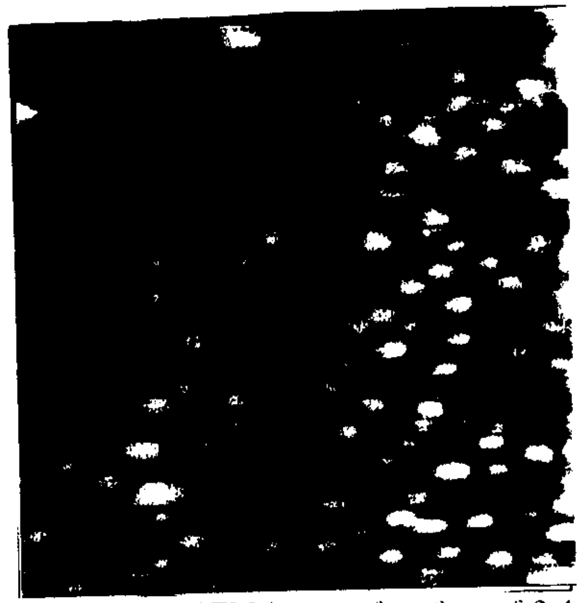


Figure 1(b) STM image of surface of 2.4 monolayers of InAs on GaAs (square size 2000 Å × 2000 Å), showing uniformity of island coverage.

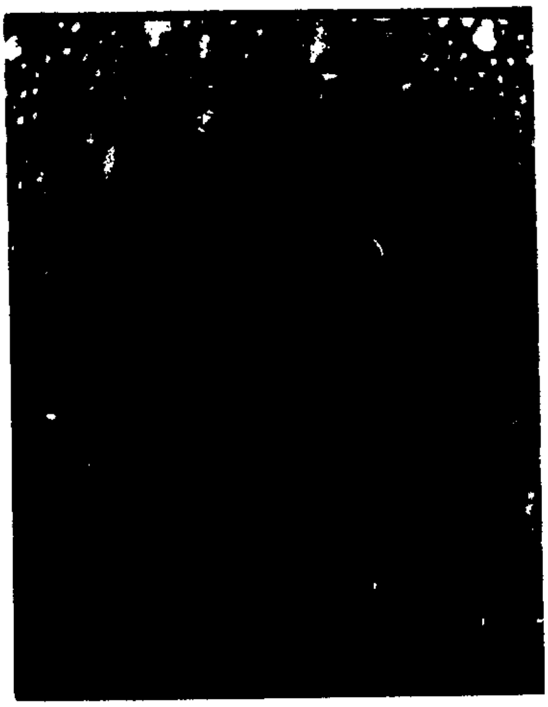


Figure 1(c) SEM image of surface of 2.4 monolayers of InAs on GaAs (square size ~4500 Å × 4500 Å). This shows merging of the islands to form larger clusters.

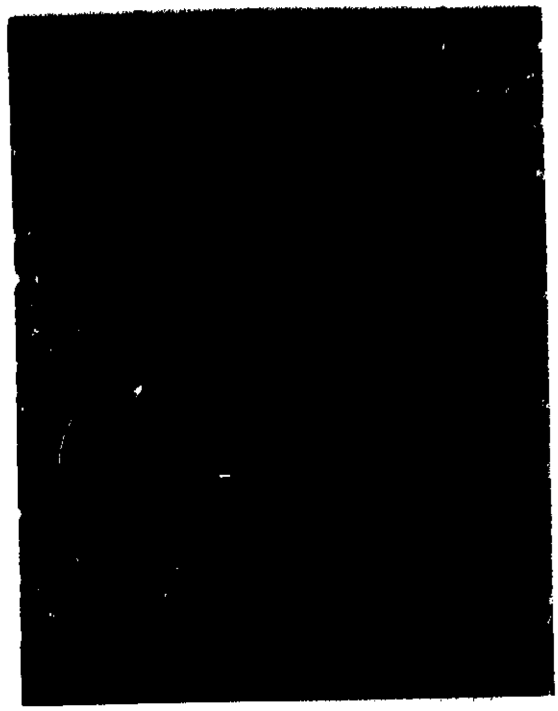
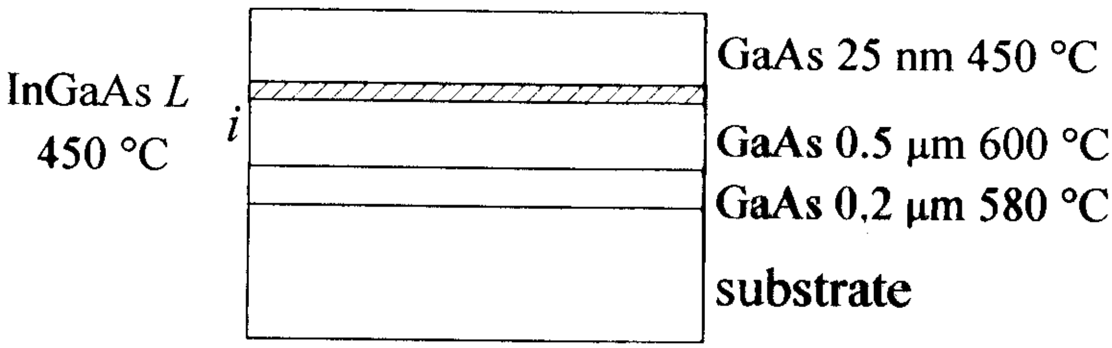


Figure 1(d) SEM image of surface of 1.7 monolayers of InAs on GaAs (square size ~4500 Å × 4500 Å). This is close to the critical thickness to obtain a uniform coverage of dots and narrow size distribution.

SEM: A. Nogaret
(on Glasgow High Res. Instrument)

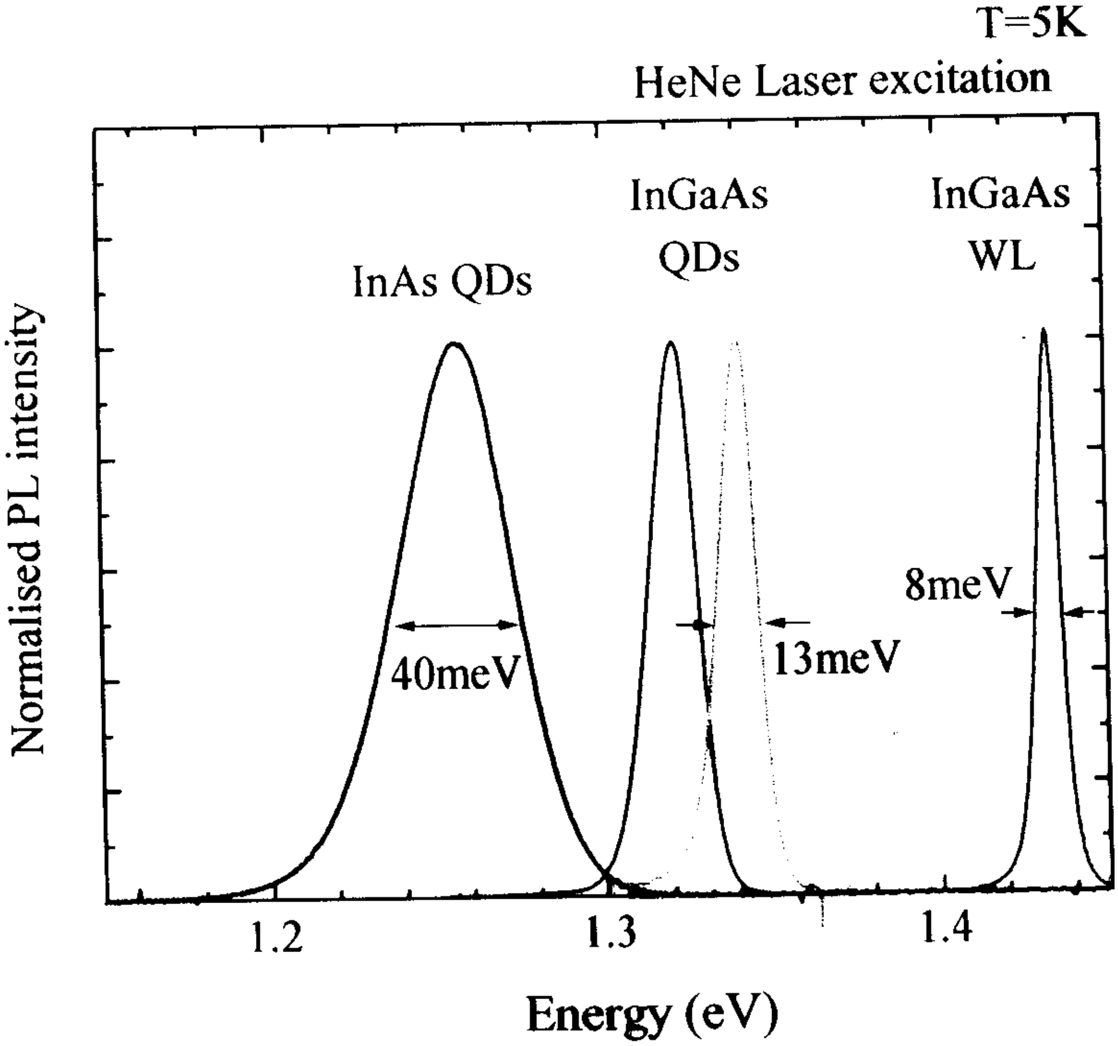
Samples

$In_{0.5}Ga_{0.5}As/GaAs$ heterostructures **grown on**
(100), (311)B, (311)A substrates



L=11.3 Å	RHEED 2D - 3D	QD
L=6.8 Å	RHEED 2D	WL

PL Spectra



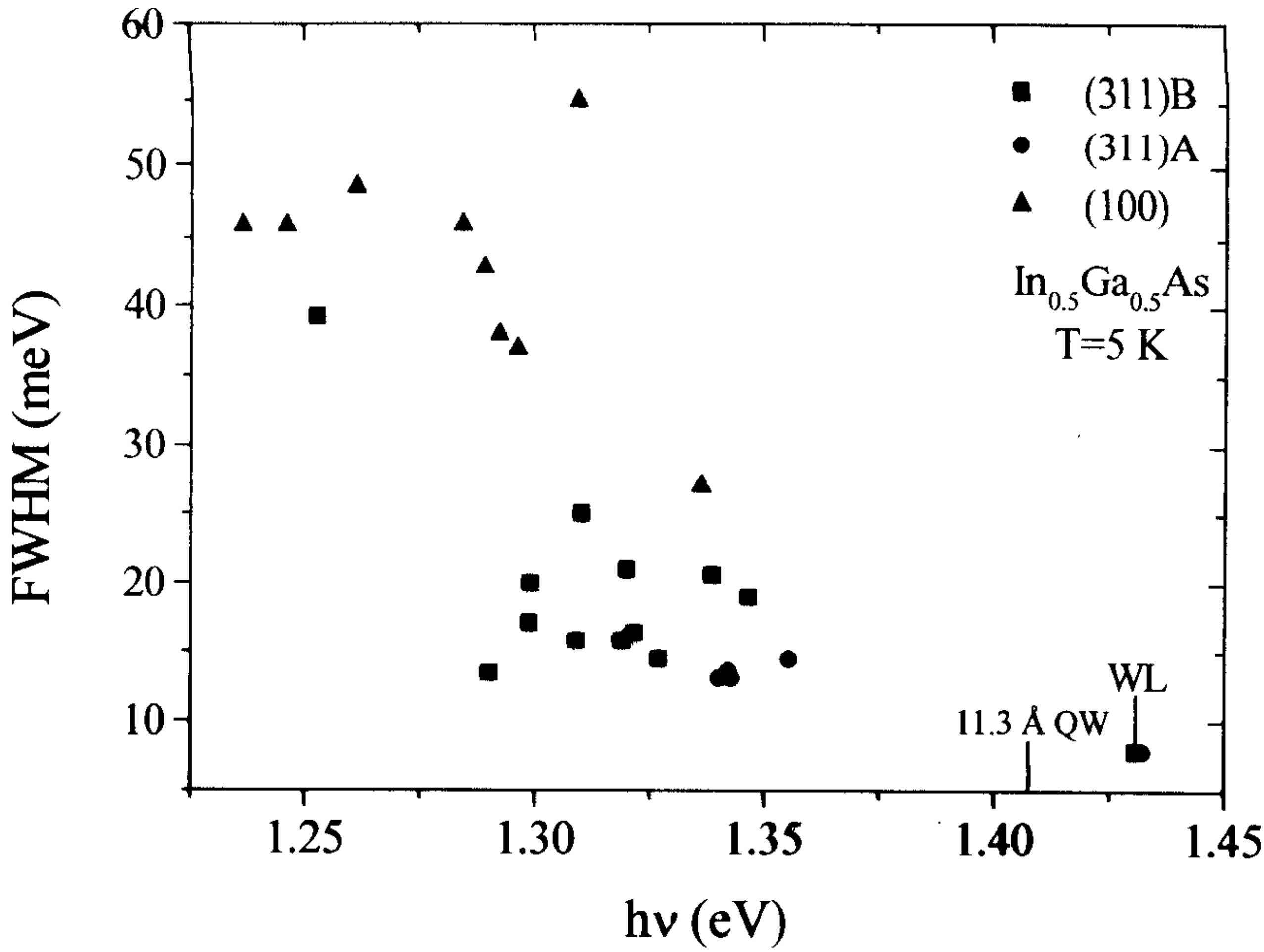
InAs QDs on GaAs (100)

$In_{0.5}Ga_{0.5}As$ QDs on GaAs (311)B

$In_{0.5}Ga_{0.5}As$ QDs on GaAs (311)A

$In_{0.5}Ga_{0.5}As$ WL on GaAs (311)A

Nottingham samples



Good reproducibility and small linewidth

$\langle h\nu \rangle_{(311A)} = 1.346$ eV $\quad \langle FWHM \rangle_{(311A)} = 13.6$ meV

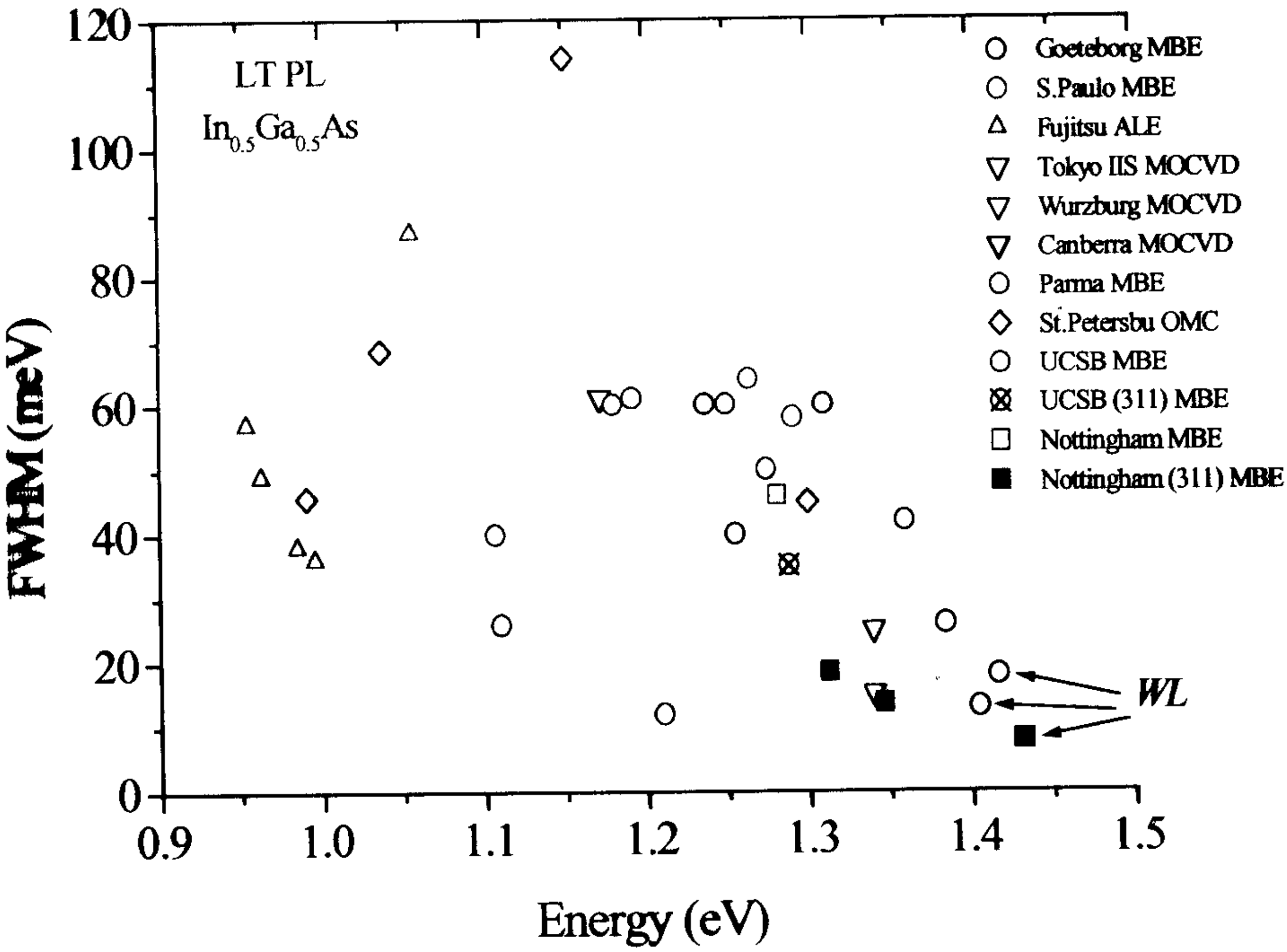
$\langle h\nu \rangle_{(311B)} = 1.312$ eV $\quad \langle FWHM \rangle_{(311B)} = 18.5$ meV

$\langle h\nu \rangle_{(100)} = 1.281$ eV $\quad \langle FWHM \rangle_{(100)} = 40$ meV

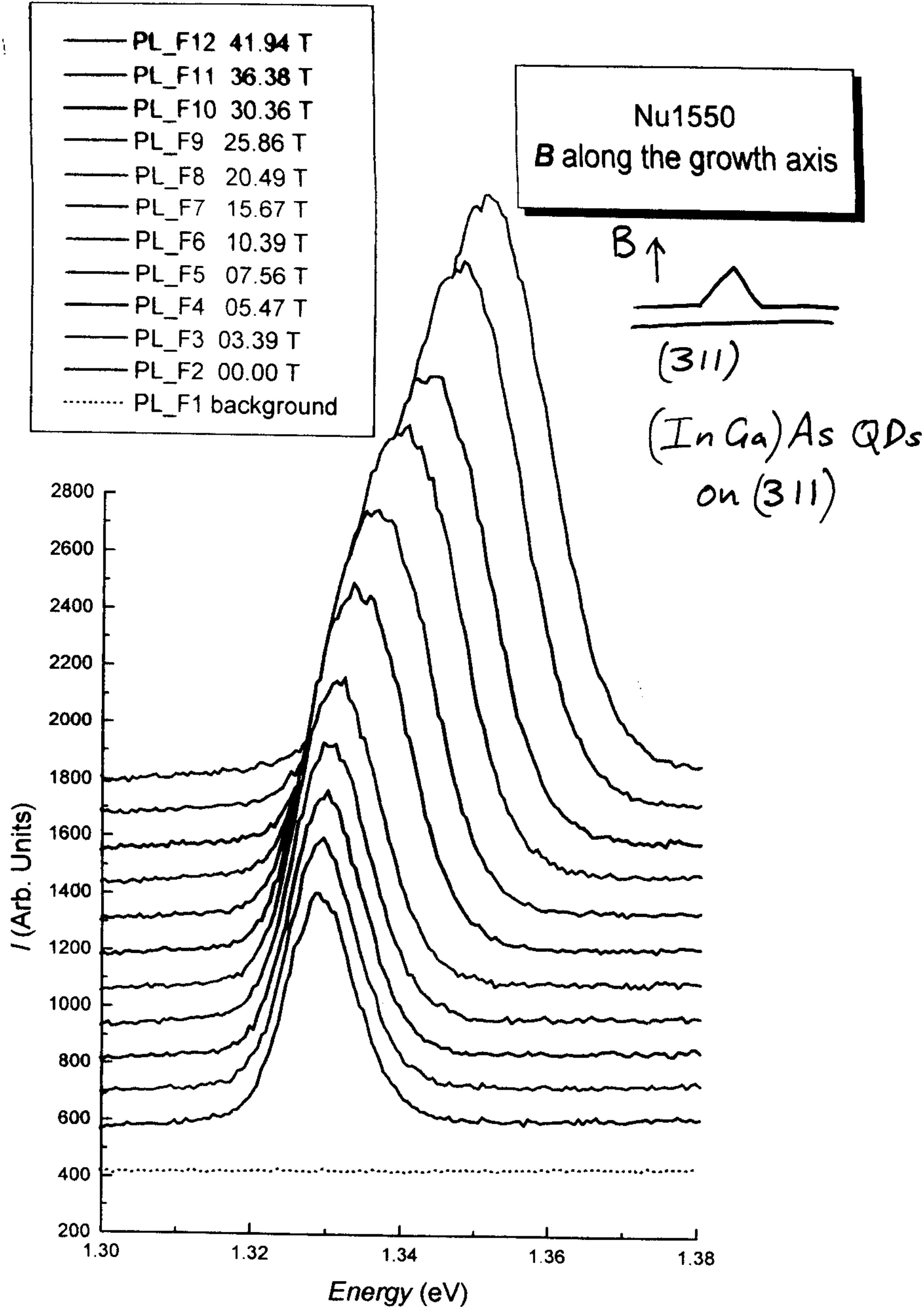
60% of strain release for (311)B
40% " (311)A
is to be supposed for explaining a WL red-shift

NO PL efficiency decrease has been observed

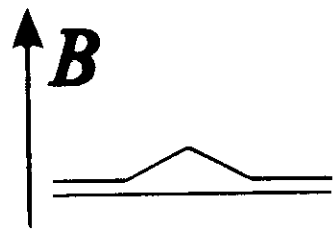
Different groups and growth tecniques

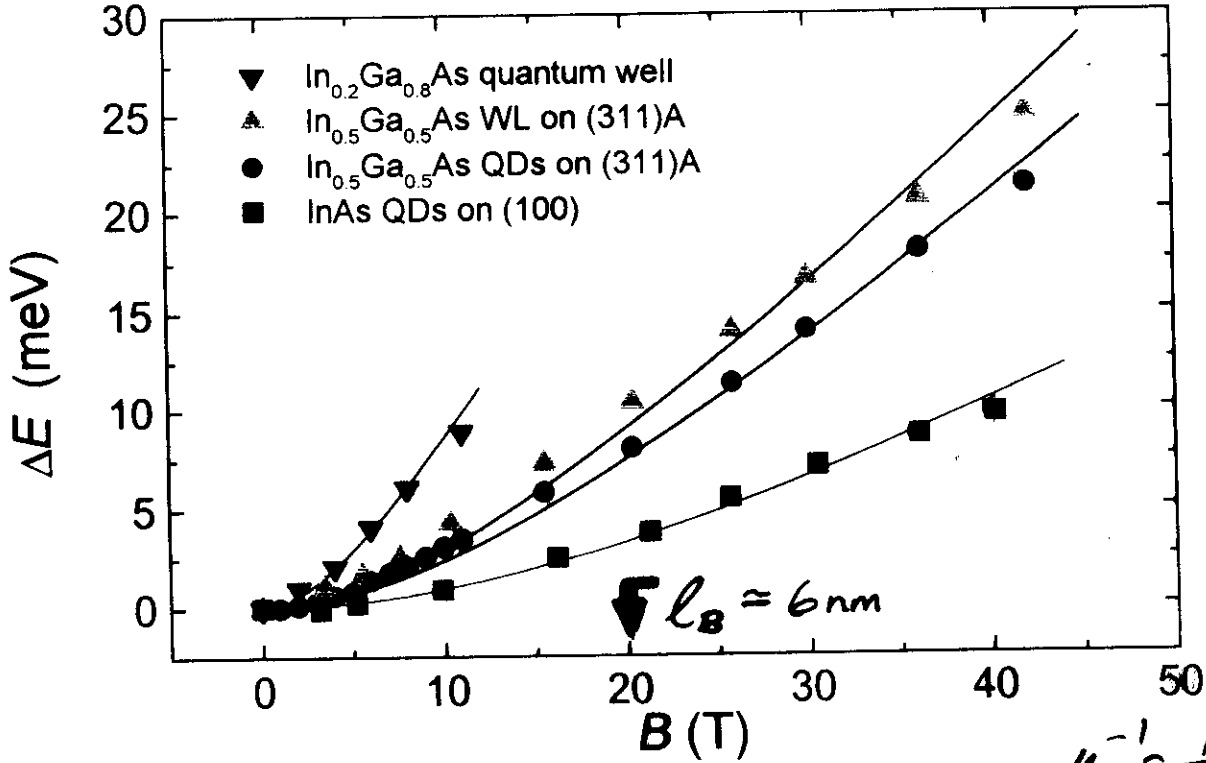


The spectra do not show the WL emission


PL_F12 41.94 T
PL_F11 36.38 T
PL_F10 30.36 T
PL_F9 25.86 T
PL_F8 20.49 T
PL_F7 15.67 T
PL_F6 10.39 T
PL_F5 07.56 T
PL_F4 05.47 T
PL_F3 03.39 T
PL_F2 00.00 T
PL_F1 background
Nu1550
B along the growth axis
B
(311)
(InGa)As QDs
on (311)
I (Arb. Units)
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
1.30
1.32
1.34
1.36
1.38
Energy (eV)

B parallel to growth direction



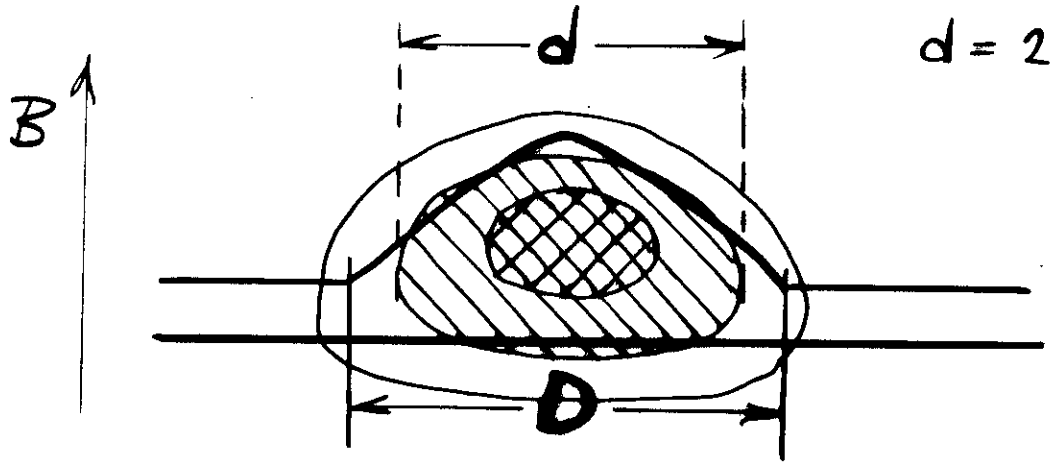


$\mu^{-1} = \frac{1}{m_e} + \frac{1}{m_h}$
$= 0.05$

- Low field :
  Diamagnetic shift $\Delta E = \frac{1}{4}\frac{e^2\langle x^2\rangle}{\mu}B^2$
- High field :
  Landau level $\Delta E = \frac{1}{2}\hbar\omega_c = \frac{1}{2}\frac{\hbar e}{\mu}B$

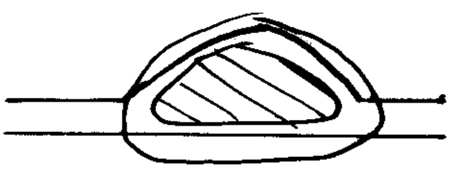
- Magnetic length : $l_B = \left(\frac{\hbar}{eB}\right)^{1/2}$

B parallel to growth direction

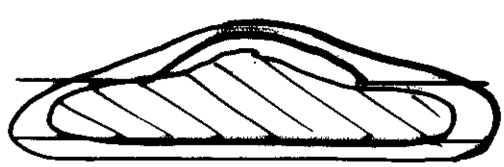


$d = 2\sqrt{\langle x^2 \rangle}$

	d (nm)	D (nm)
InAs QDs on (100)	6	10-12
$In_{0.5}Ga_{0.5}As$ QDs on (311)A	13	5-8
$In_{0.5}Ga_{0.5}As$ WL on (311)A	14	-

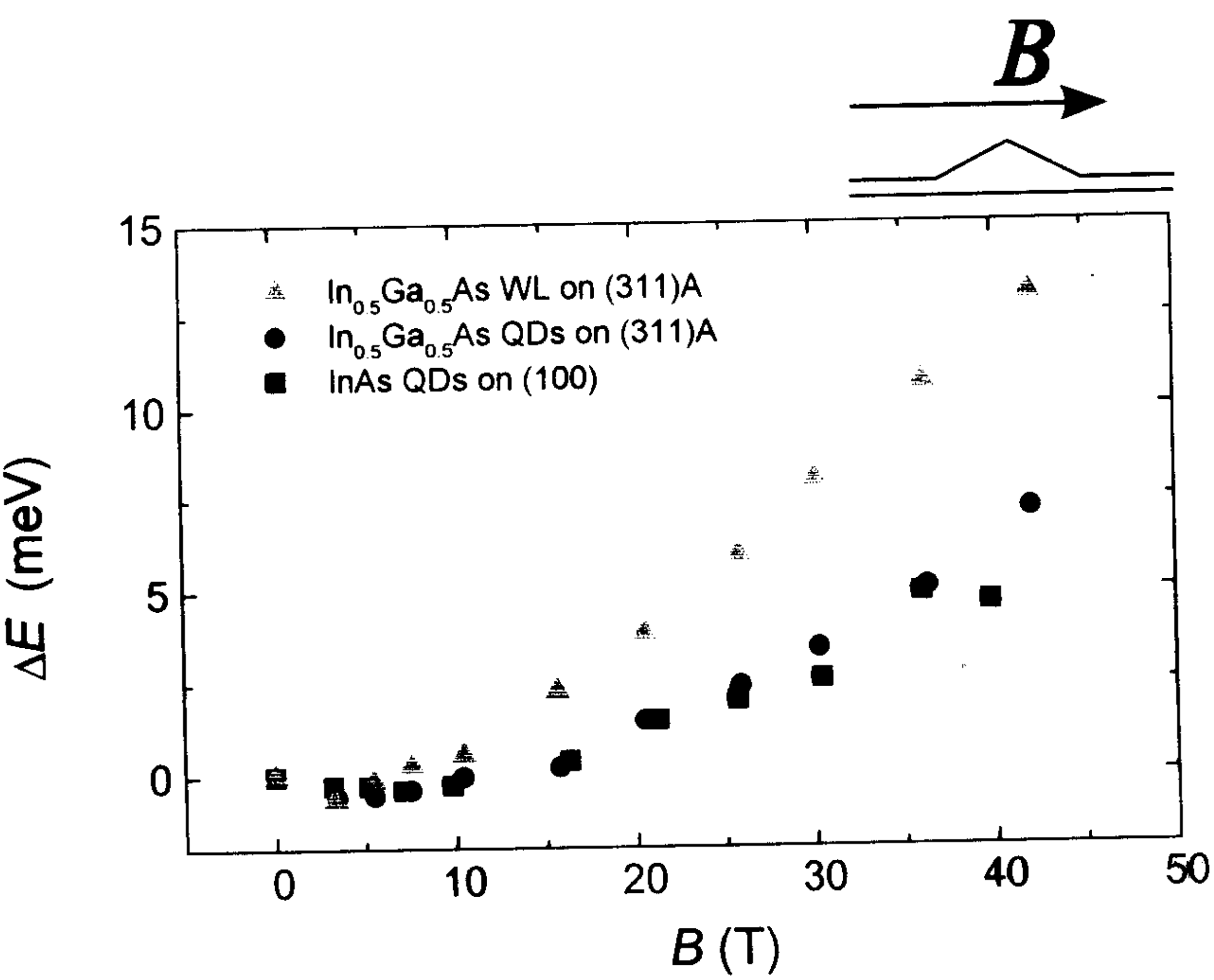


InAs QD on (100)



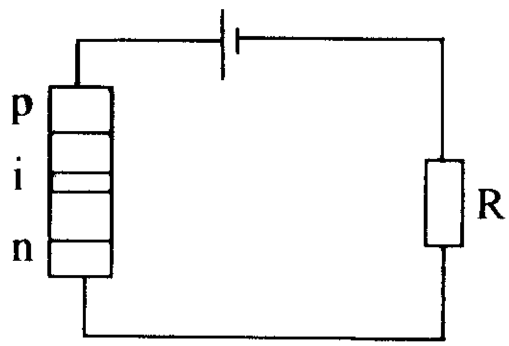
$In_{0.5}Ga_{0.5}As$ QD on (311)A/B

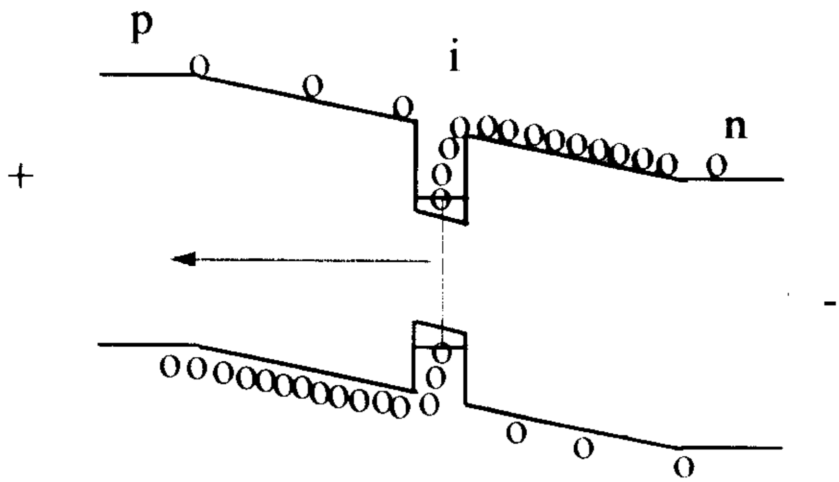
B perpendicular to growth direction



- Diamagnetic shift strongly anisotropic.
- $\Delta E < 0$ for $B < 10$T.
- No difference between InAs and $In_{0.5}Ga_{0.5}As$ dots.

EL on p-i-n diodes



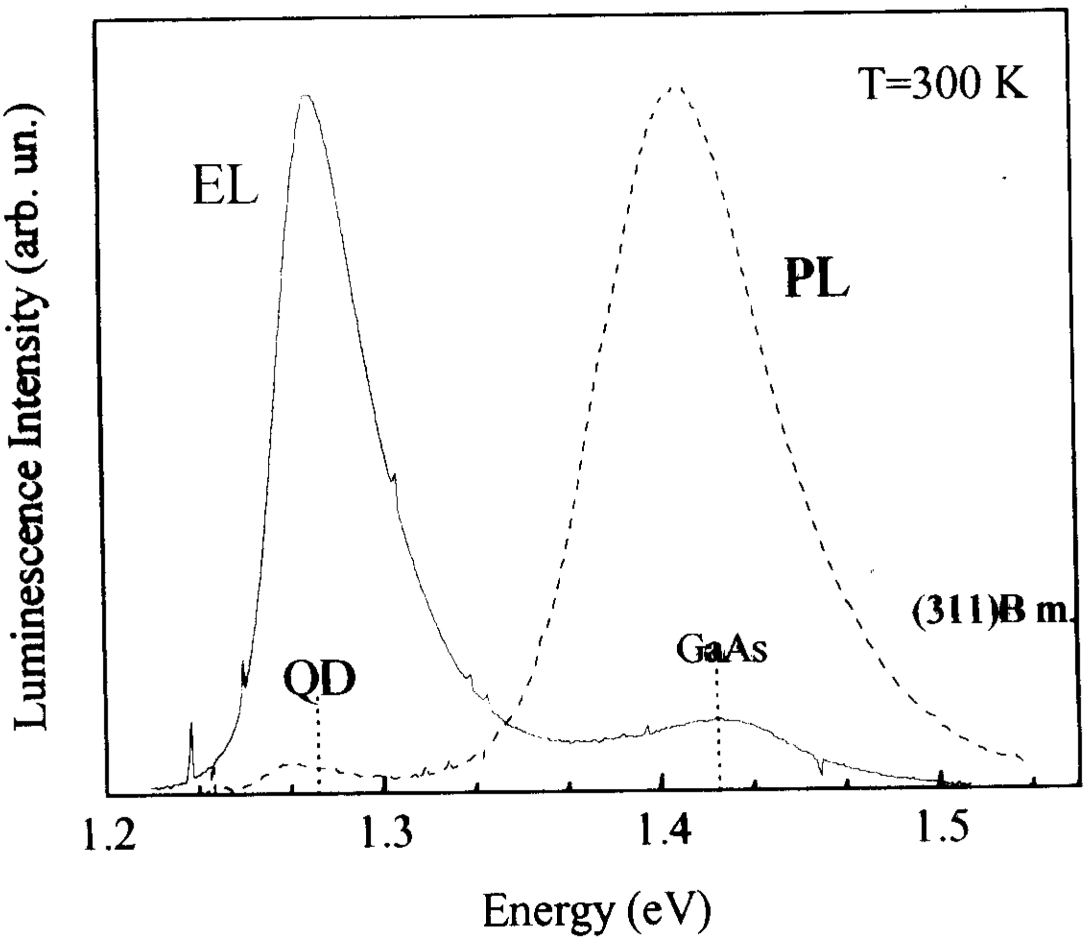


- More than 40 diodes measured

- Luminescence as a function of I and T

In collaboration with G. Hill
University of Sheffield

EL and PL
at room tempereture
$In_{0.5}Ga_{0.5}As$ QD



Light sources at RT

PROCESSING OF RIB WAVEGUIDE LASERS

Evaporate front p-type contact stripes and anneal

Reactive ion etch waveguide ribs using contacts as mask

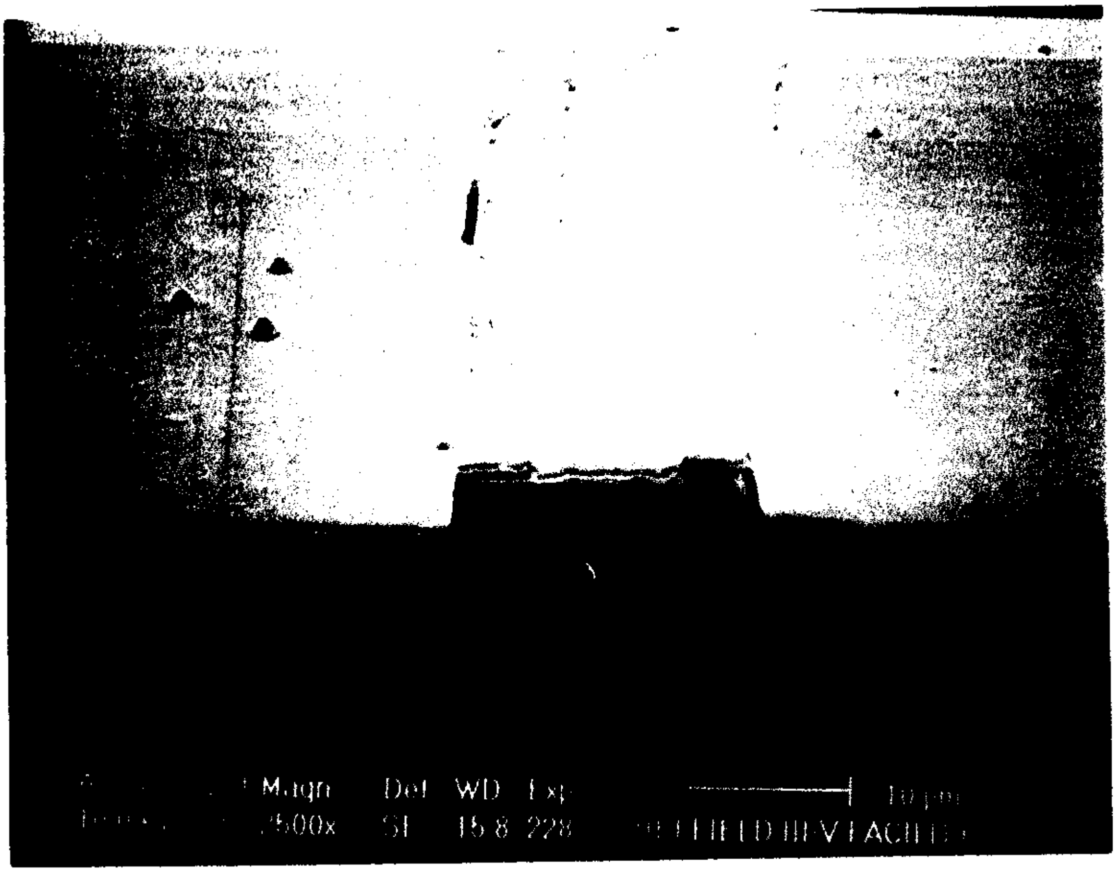
Deposit silicon nitride and pattern windows on rib contacts

Evaporate bond pads over ribs

Thin sample to 100um

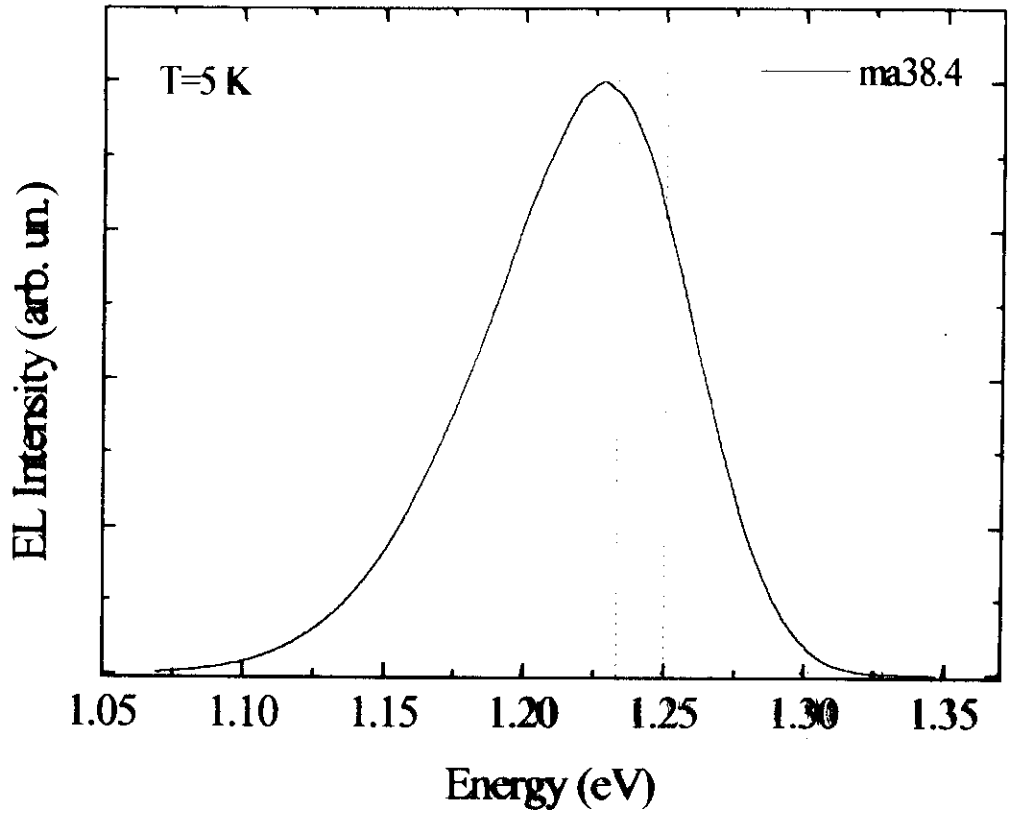
Evaporate rear n-contact and anneal

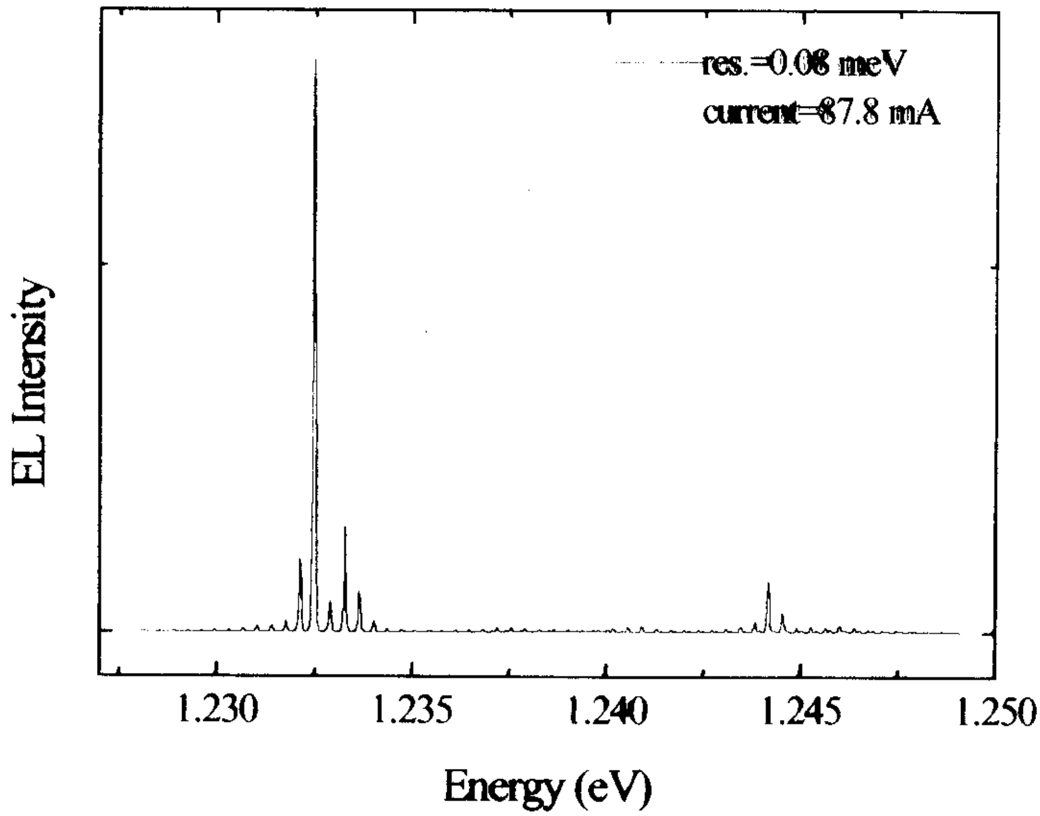
QUANTUM DOT WAVEGUIDE LASER



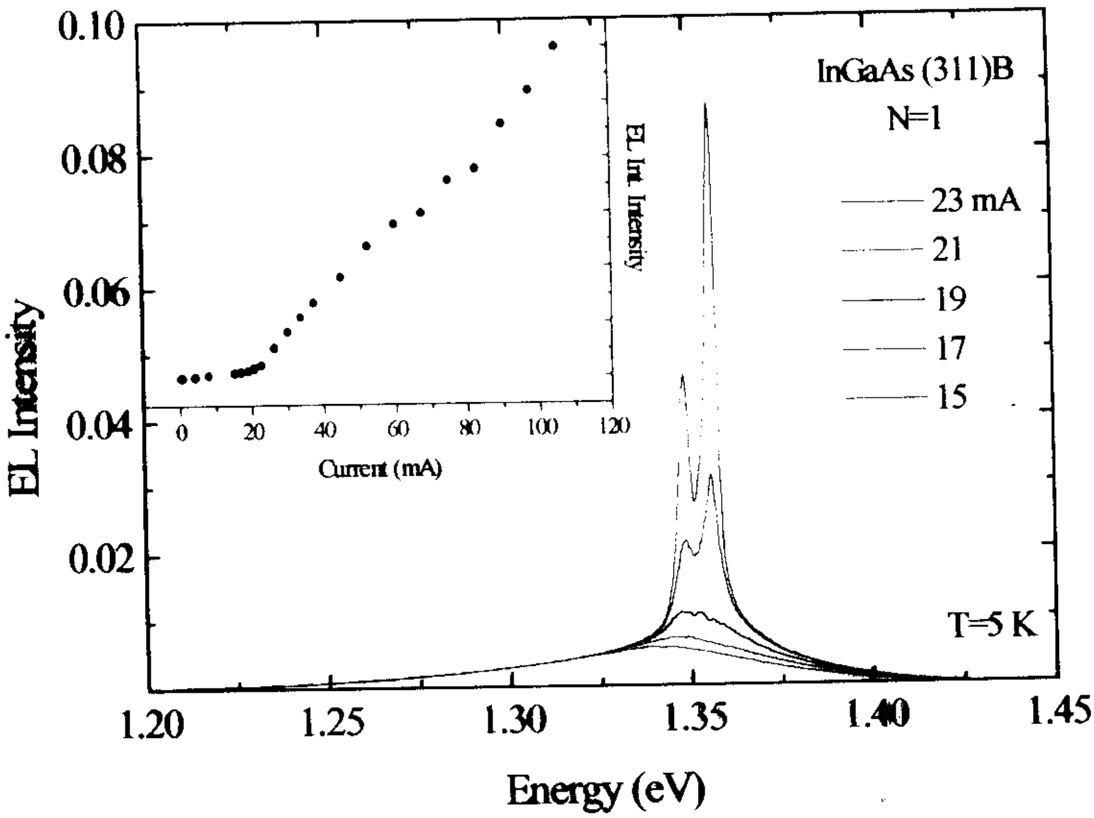
EPSRC III-V Central Facility

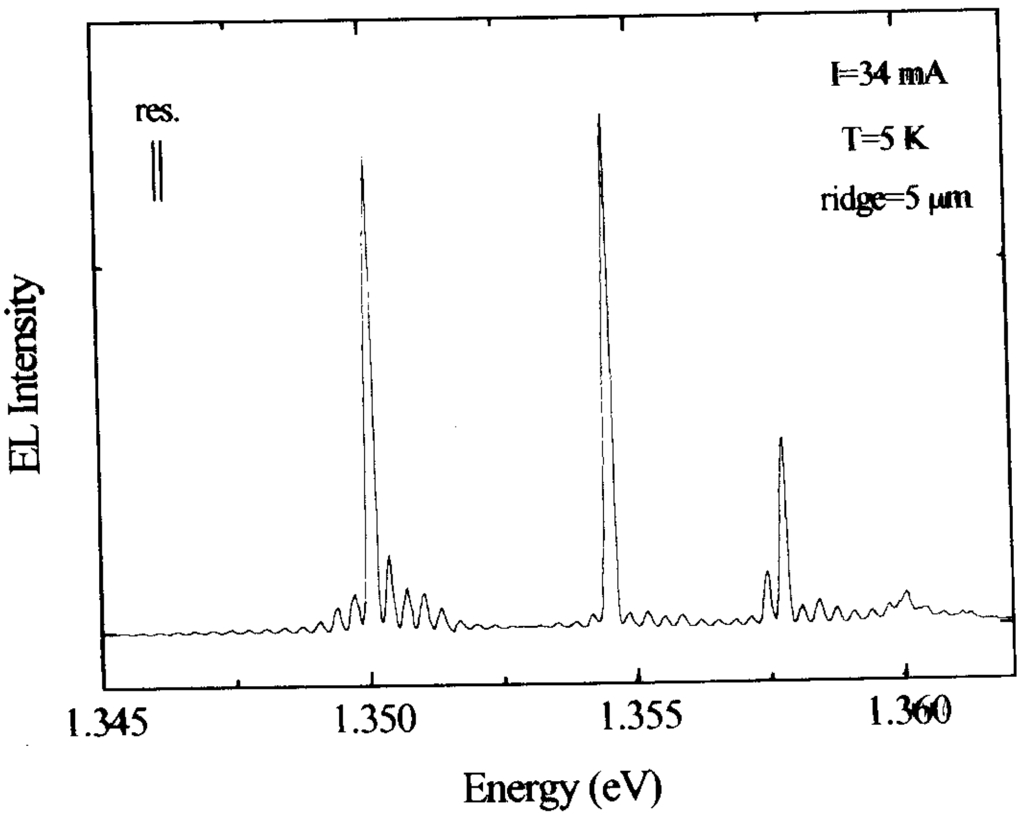
$In_{0.5}Ga_{0.5}As$ QD LASER on (100)
10 layers





InGaAs QD LASER
single layer on (311)B

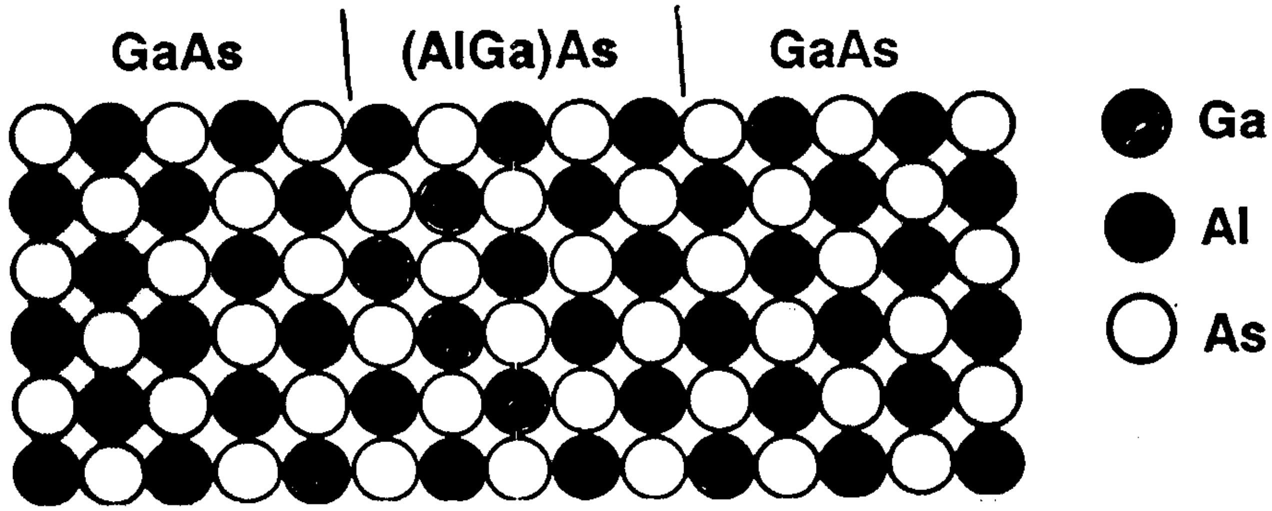


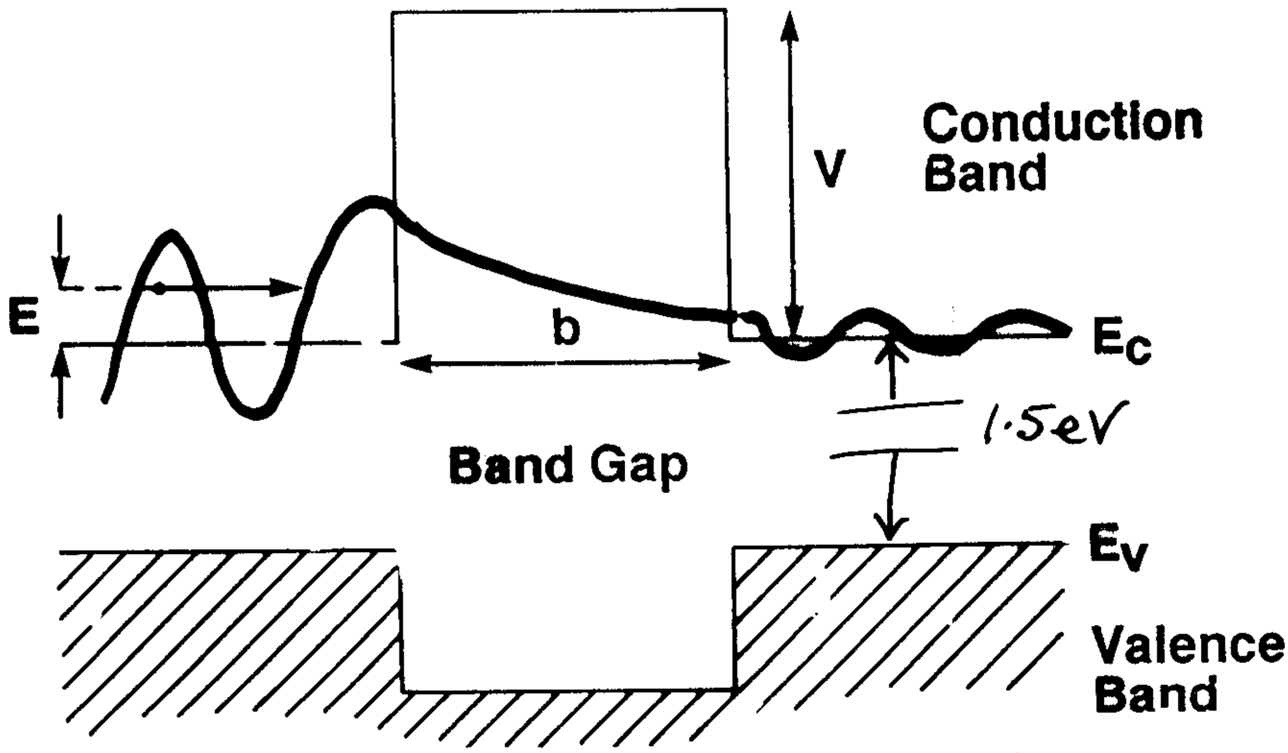


Conclusions

- Bright and narrow PL from $In_{0.5}Ga_{0.5}As$ QDs on (311)A/B substrates.
- Exciton strongly confined in InAs QDs.
- $In_{0.5}Ga_{0.5}As$ QD exciton spreads into wetting layer.
- $In_{0.5}Ga_{0.5}As$ QDs promising for laser applications.

- a tunnel barrier for conduction electrons





Transmission Coefficient $T \simeq \exp(-2Kb)$ — $T \sim 10^{-2}$ to 1(typically

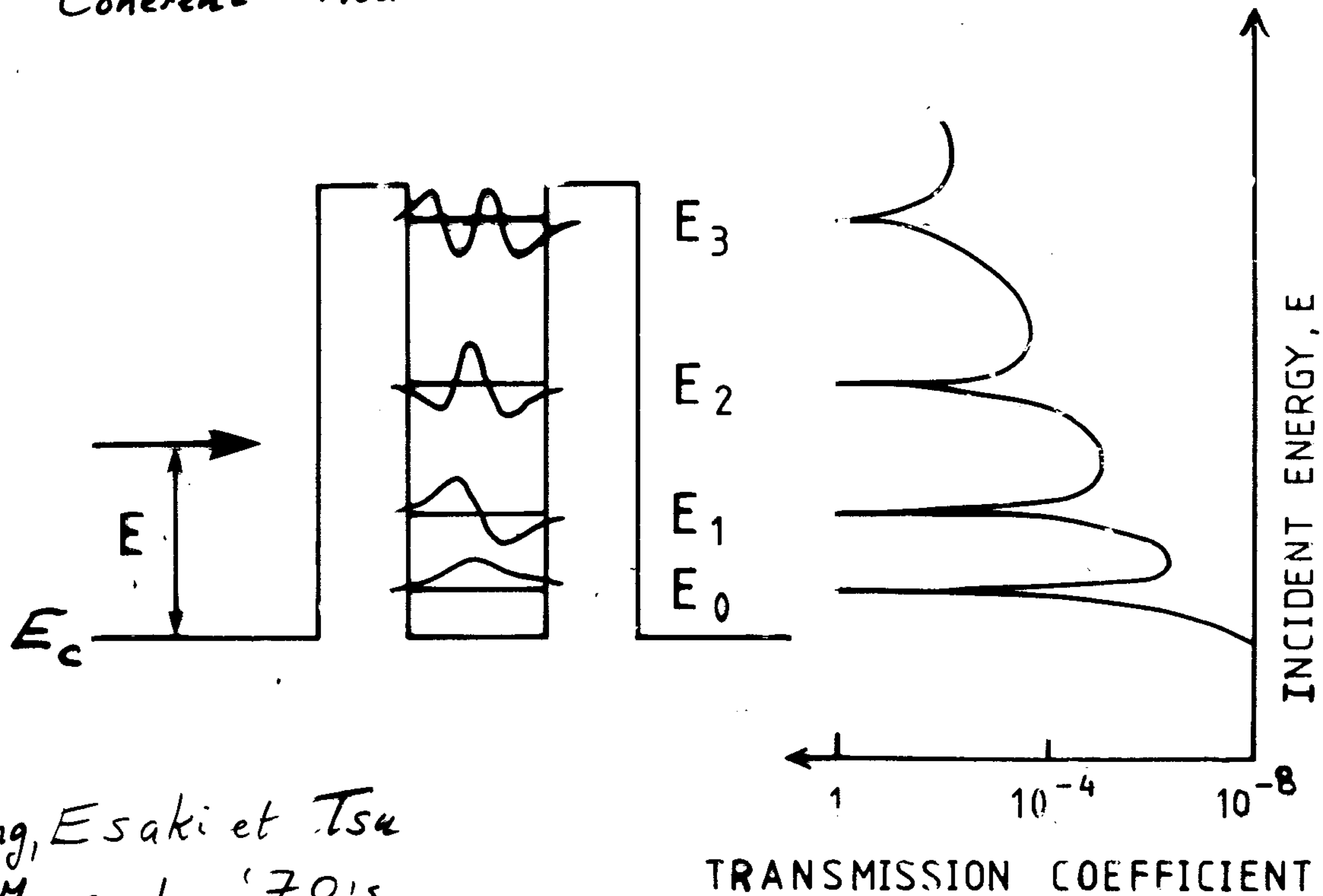
$K = [2m^*(V - E)]^{1/2}/\hbar$

$m^* = 0.1\ m_e$

$V = \Delta E_C \simeq 0.3$ eV for $x = 0.4$

b = 1 - 10 nm typically

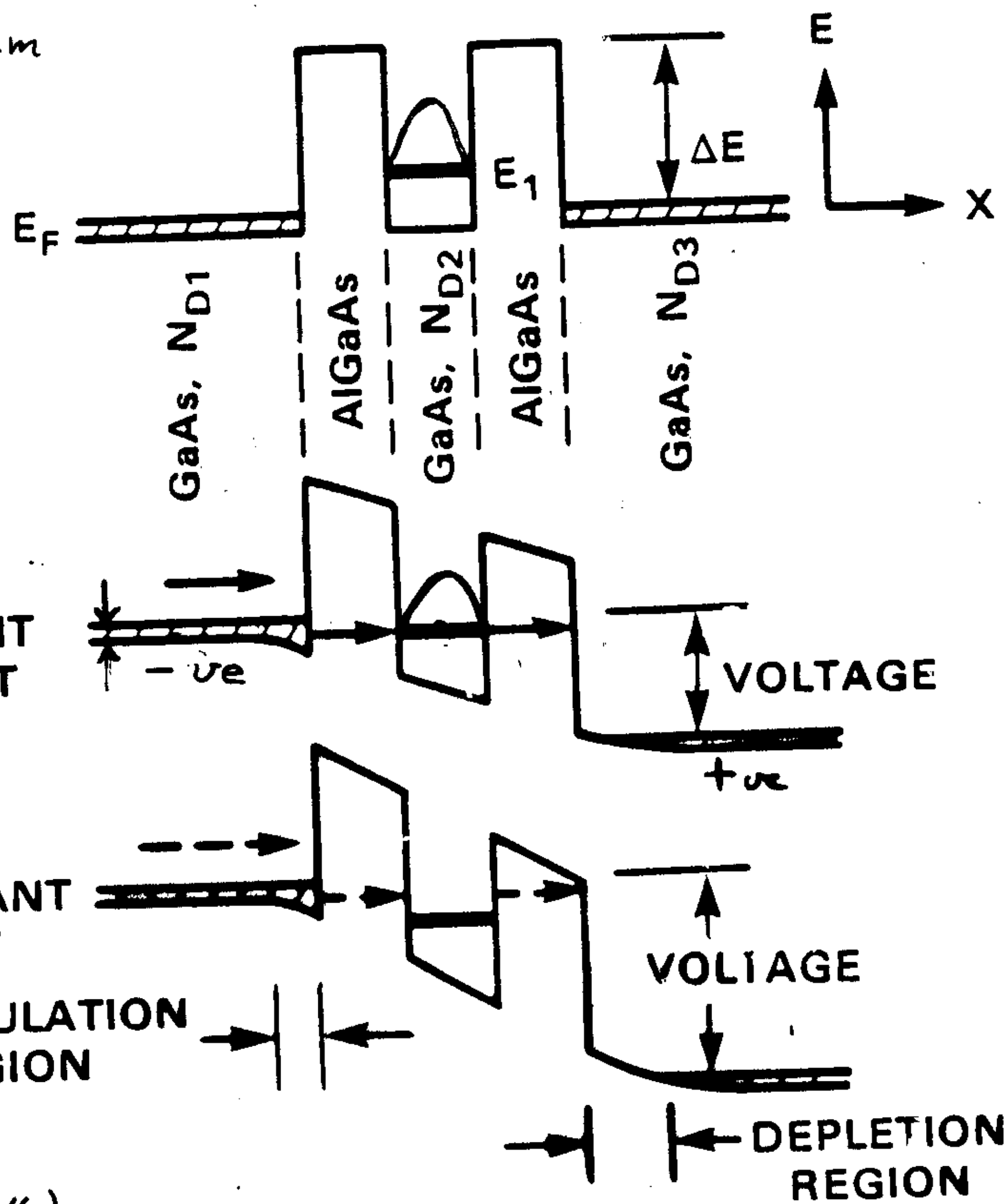
"Coherent" Model



Chang, Esaki et Tsu
IBM, early '70's

$(AlGa)As = Al_{0.4}Ga_{0.6}As$

Barrier and Well Thicknesses ~ 5nm



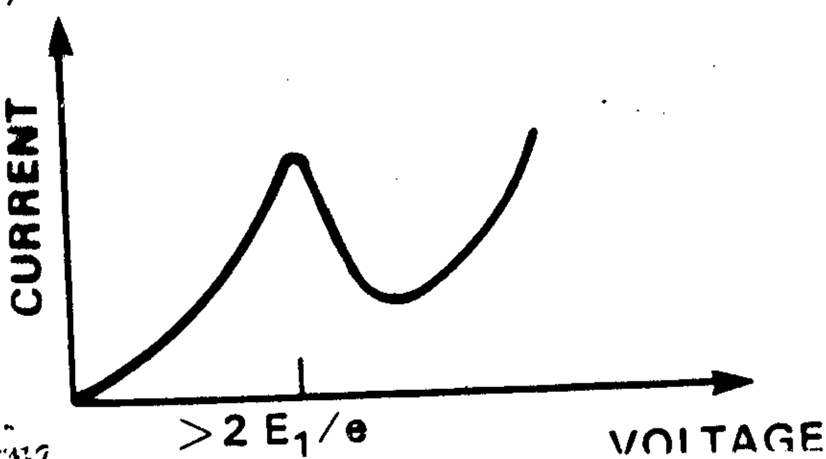
$$\mathcal{H} = \frac{p_x^2 + p_y^2 + p_z^2}{2m} + V(x)$$

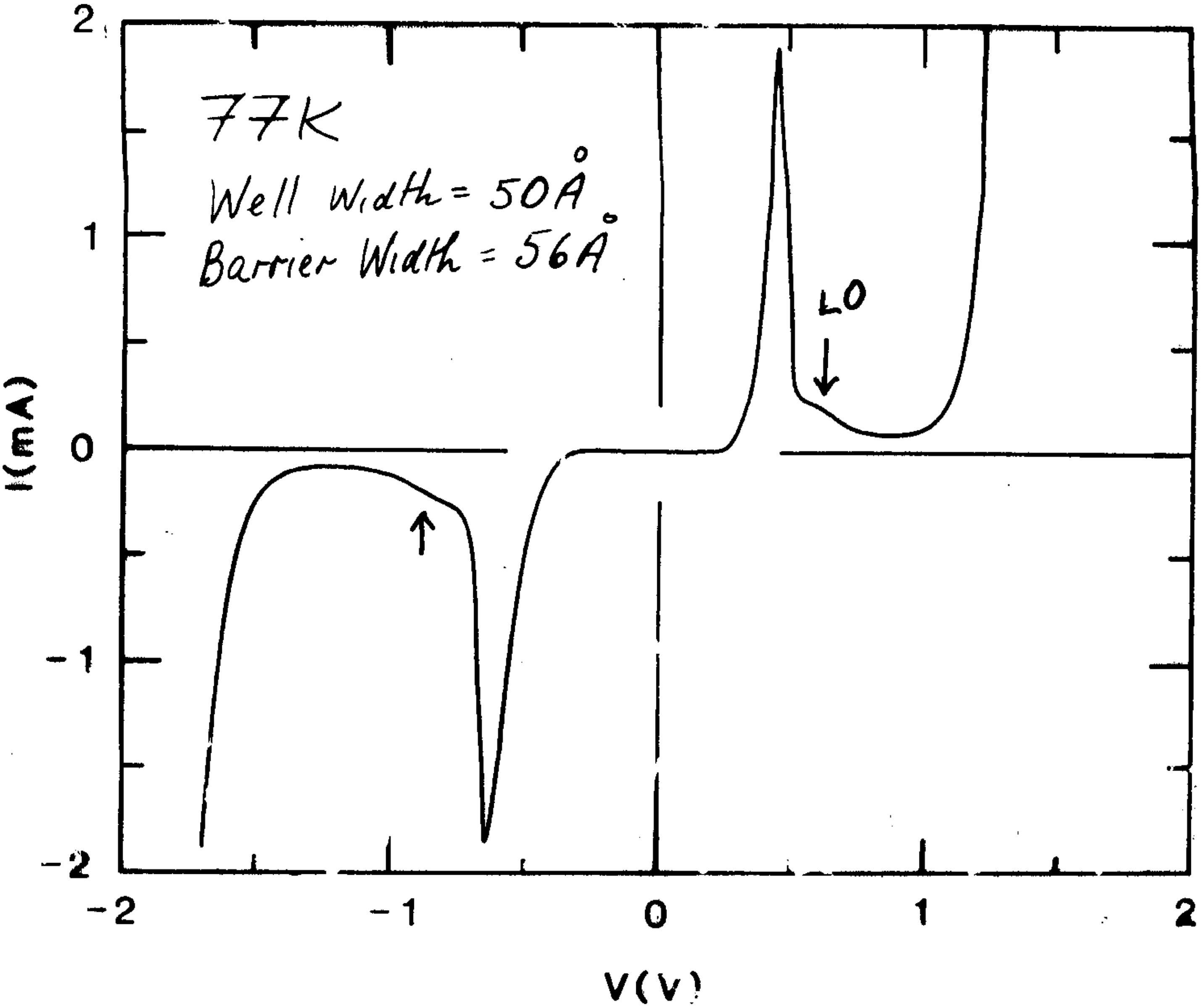
$$[\mathcal{H}, p_y] = [\mathcal{H}, p_z] = 0$$

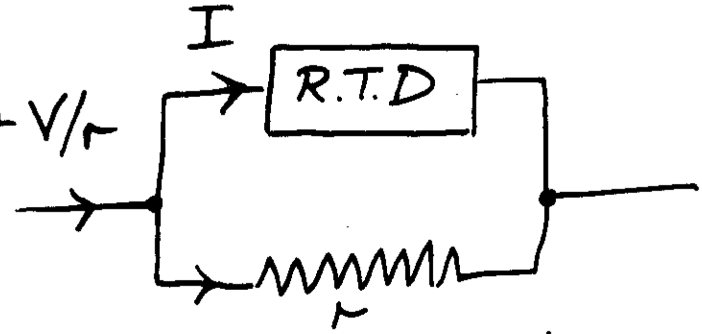
p_y, p_z are good quantum numbers

∴ $p_\perp$ is conserved

in absence of scattering





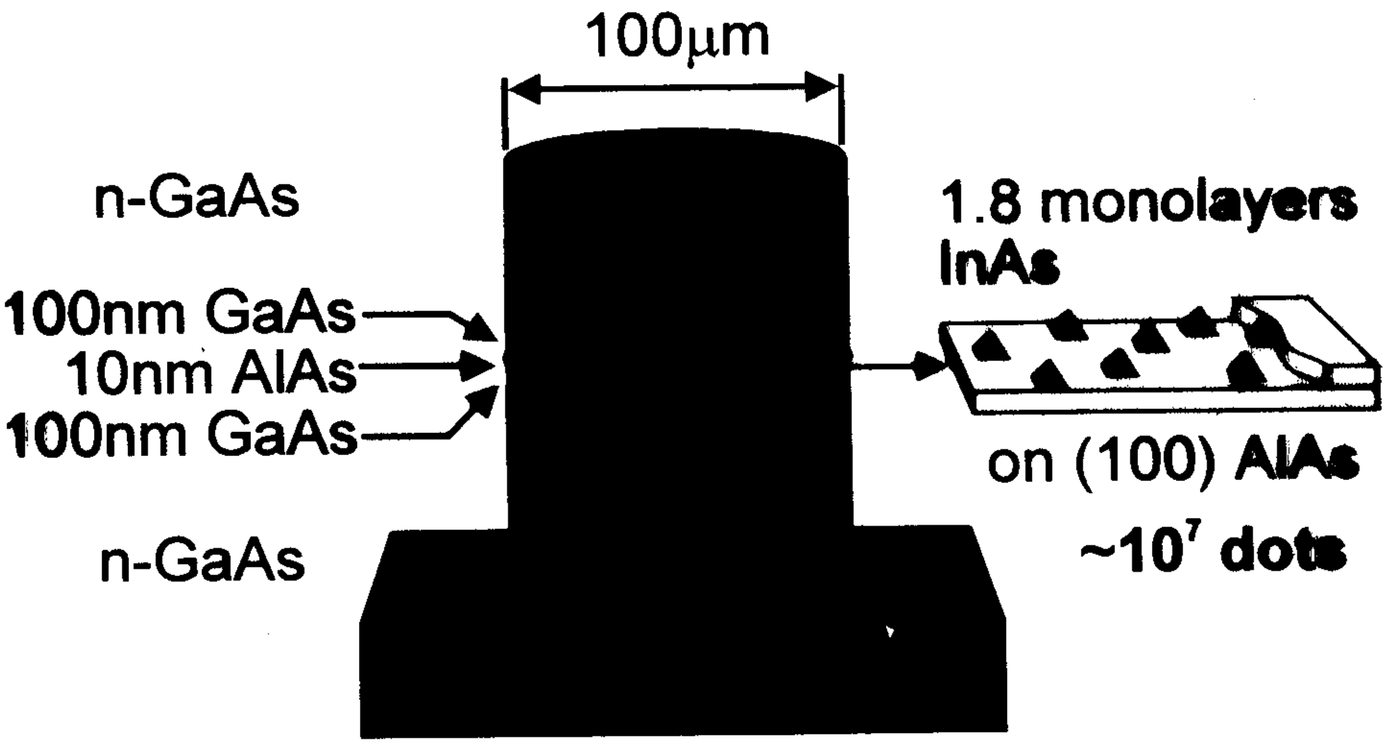


$I_{tot.} = I + V/r$

$$r < \left| \frac{dV}{dI} \right|$$

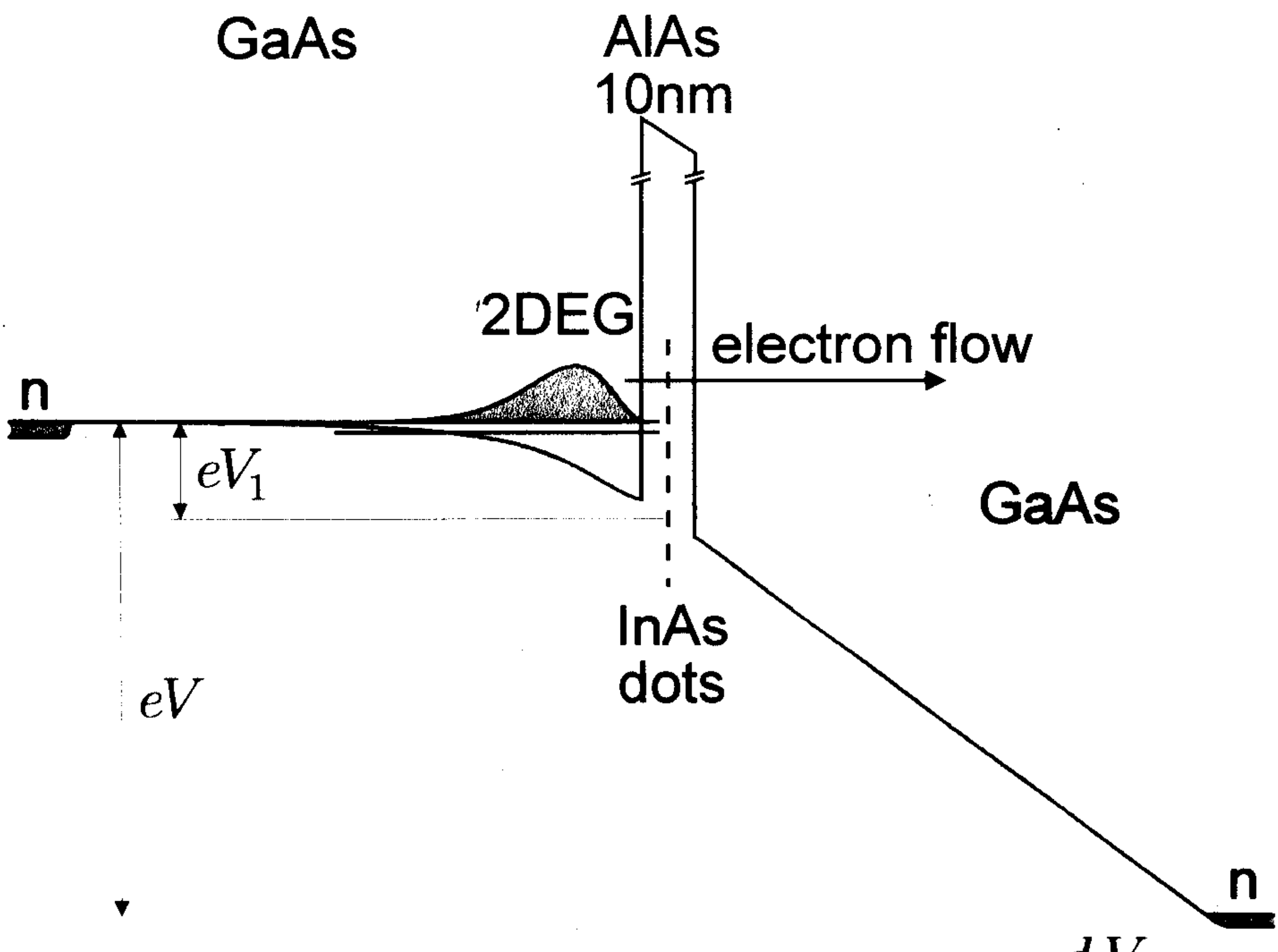
$(r = 25\Omega)$

The Single-Barrier Tunnelling Resonant Device Incorporating InAs Quantum Dots



Itskevich et al Phys Rev B
Narihiro et al A.P.L.

Conduction band profile



electrostatic lever factor: $f^{-1} := \frac{dV_1}{dV}$

Single electron tunnelling through an individual InAs dot

$I = ne\nu \frac{T_1 T_2}{T_1 + T_2}$

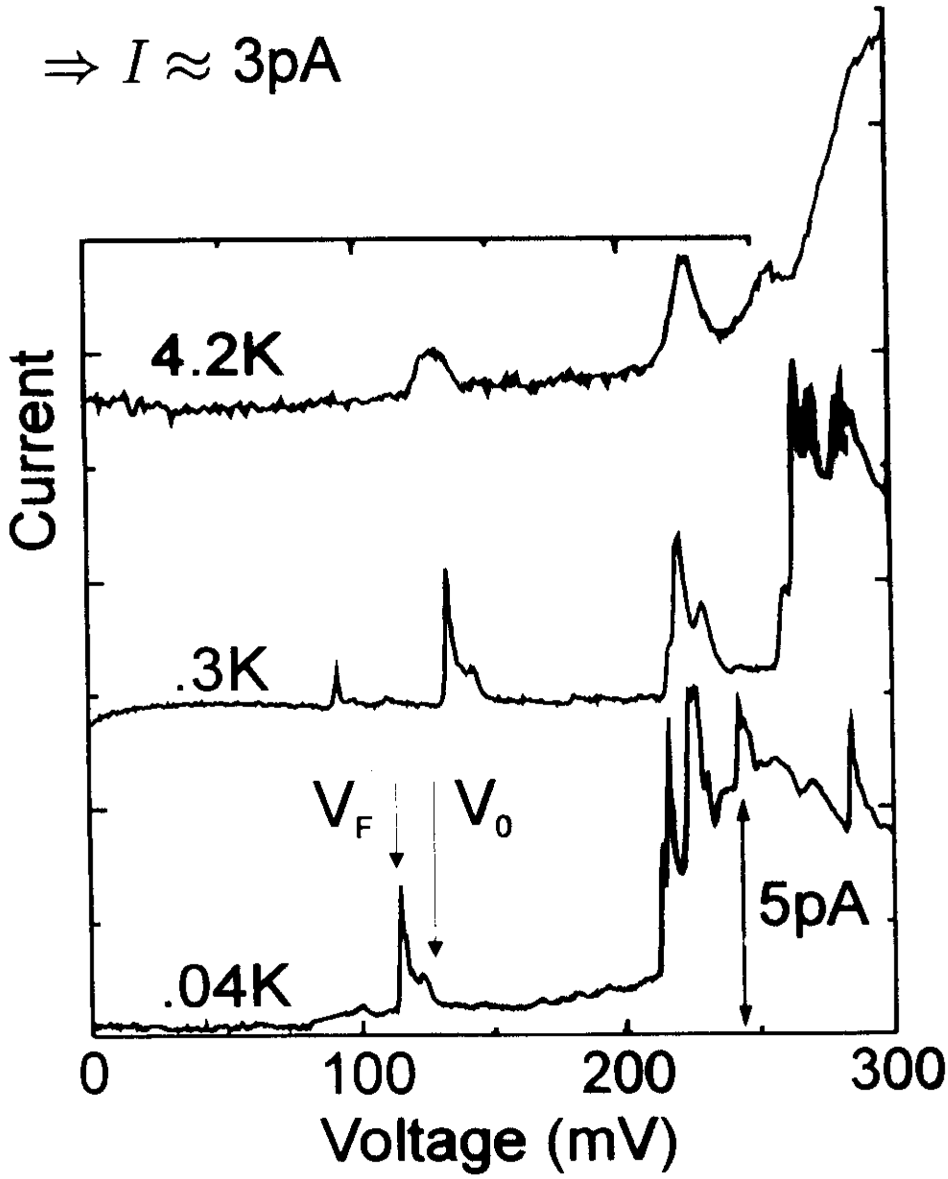
Single electron tunnelling current:

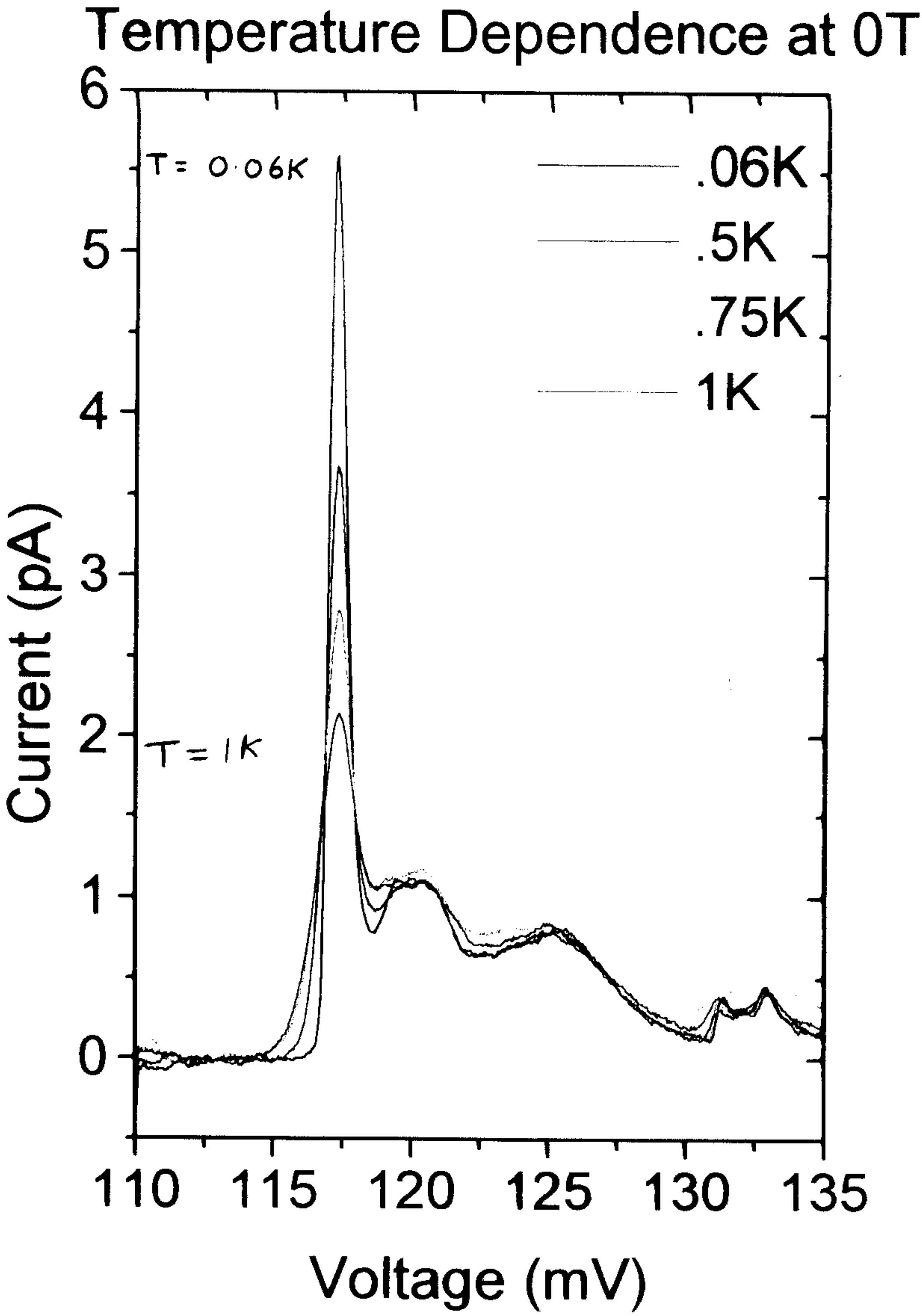
$I = e\nu \exp(-2\kappa d)$ $\quad T = e^{-2\kappa d}$

take 800meV barrier, d=50Å ,

$\nu \sim E_{conf}/h \sim 2.5$THz

$\Rightarrow I \approx 3$pA




Temperature Dependence at 0T
T= 0.06K
T= 1K
.06K
.5K
.75K
1K
Current (pA)
Voltage (mV)
0
1
2
3
4
5
6
110
115
120
125
130
135