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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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SECOND WORKSHOP ON
SCIENCE AND TECHNOLOGY OF THIN FILMS

(11 - 29 March 1996)

" Fabrication of quantum wells and superlattices by molecular beam epitaxy. " (PART III)

presented by:

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Fabrication of Quantum Wells and Superlattices by Molecular Beam Epitaxy

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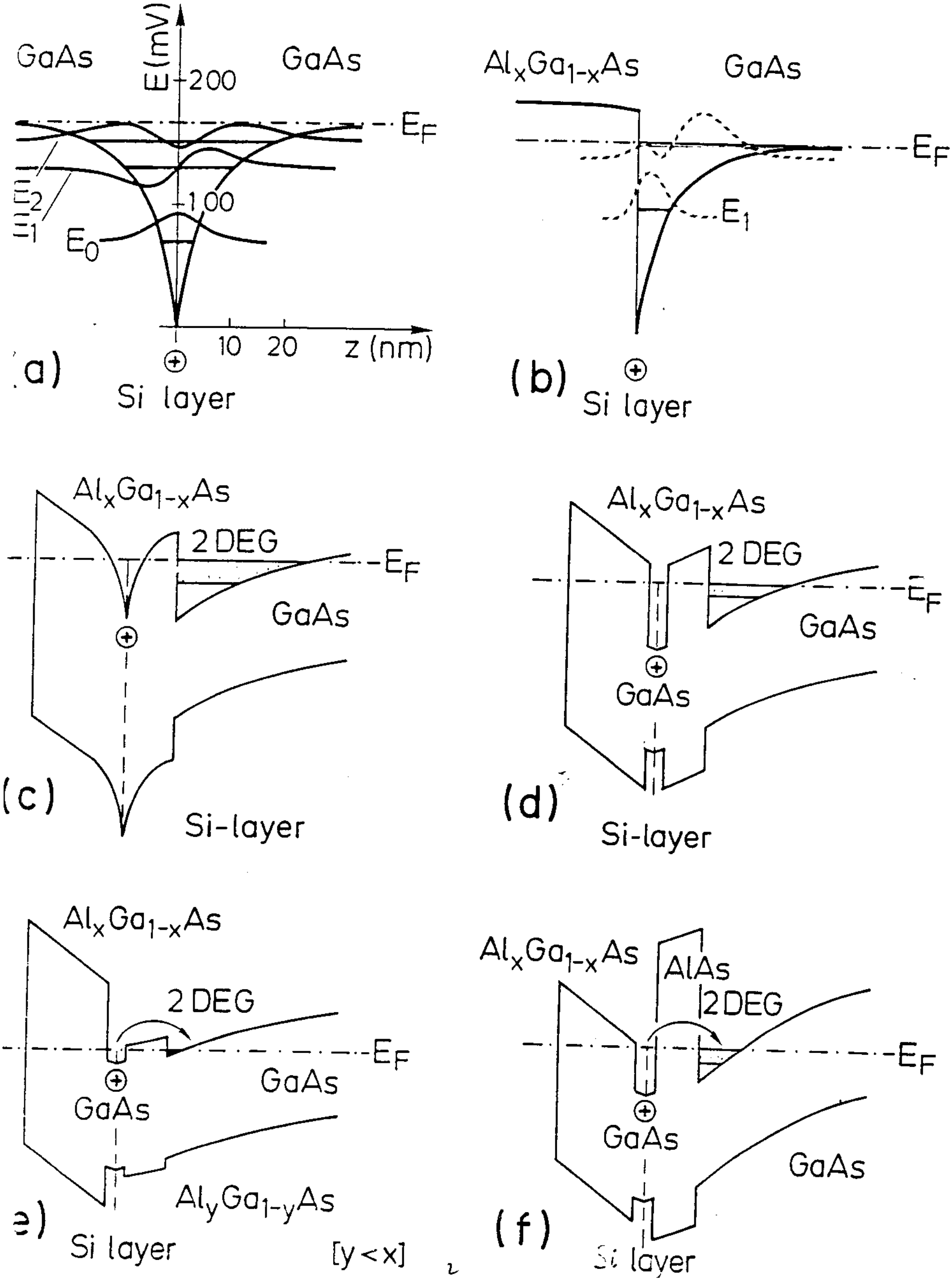
Outline

MBE--Method and equipment
Growth mechanism of III-V-compounds

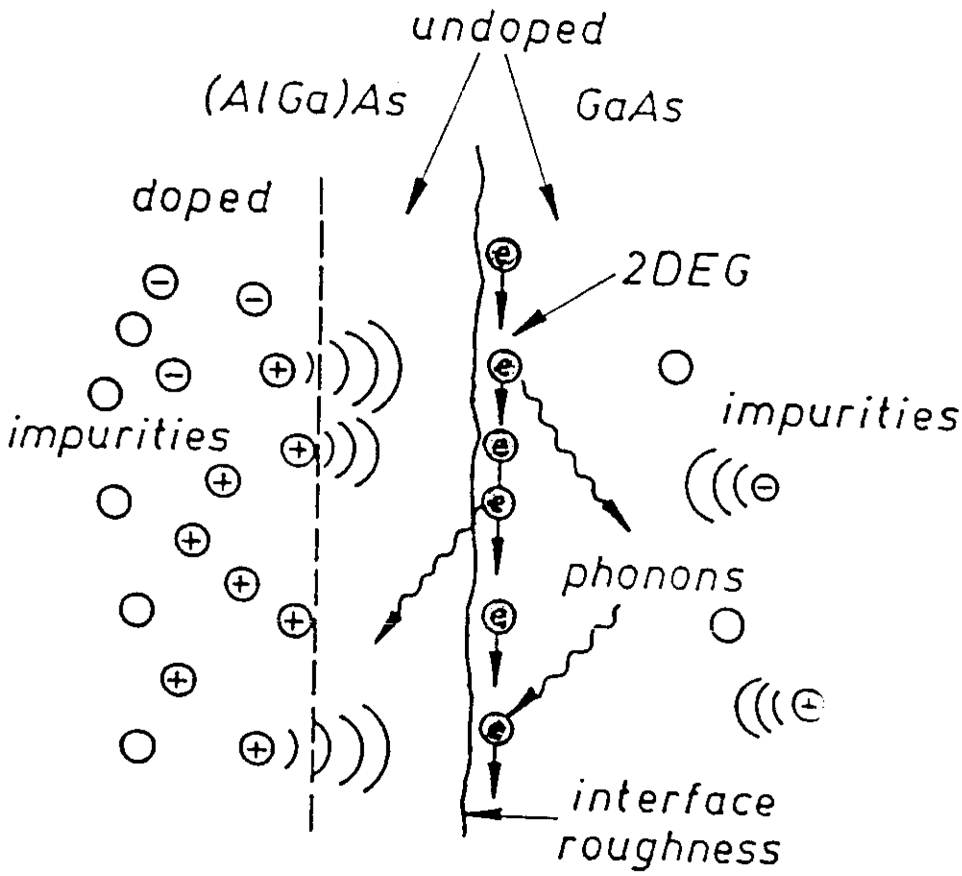
Homoepitaxy GaAs
Heteroepitaxy I--AlAs/GaAs
Single quantum wells

Part III Heteroepitaxy II--doped structures
Superlattices
Strained layers

δ-Doping


GaAs
E(mV)
200
GaAs
E_F
E_2
E_1
100
E_0
10
20
z (nm)
(a)
Si layer
$Al_xGa_{1-x}As$
GaAs
E_F
E_1
(b)
Si layer
$Al_xGa_{1-x}As$
2 DEG
E_F
GaAs
(c)
Si-layer
$Al_xGa_{1-x}As$
2 DEG
E_F
GaAs
GaAs
(d)
Si-layer
$Al_xGa_{1-x}As$
2 DEG
E_F
GaAs
GaAs
$Al_yGa_{1-y}As$
(e)
Si layer
[y < x]
$Al_xGa_{1-x}As$
AlAs
2 DEG
E_F
GaAs
GaAs
(f)
Si layer

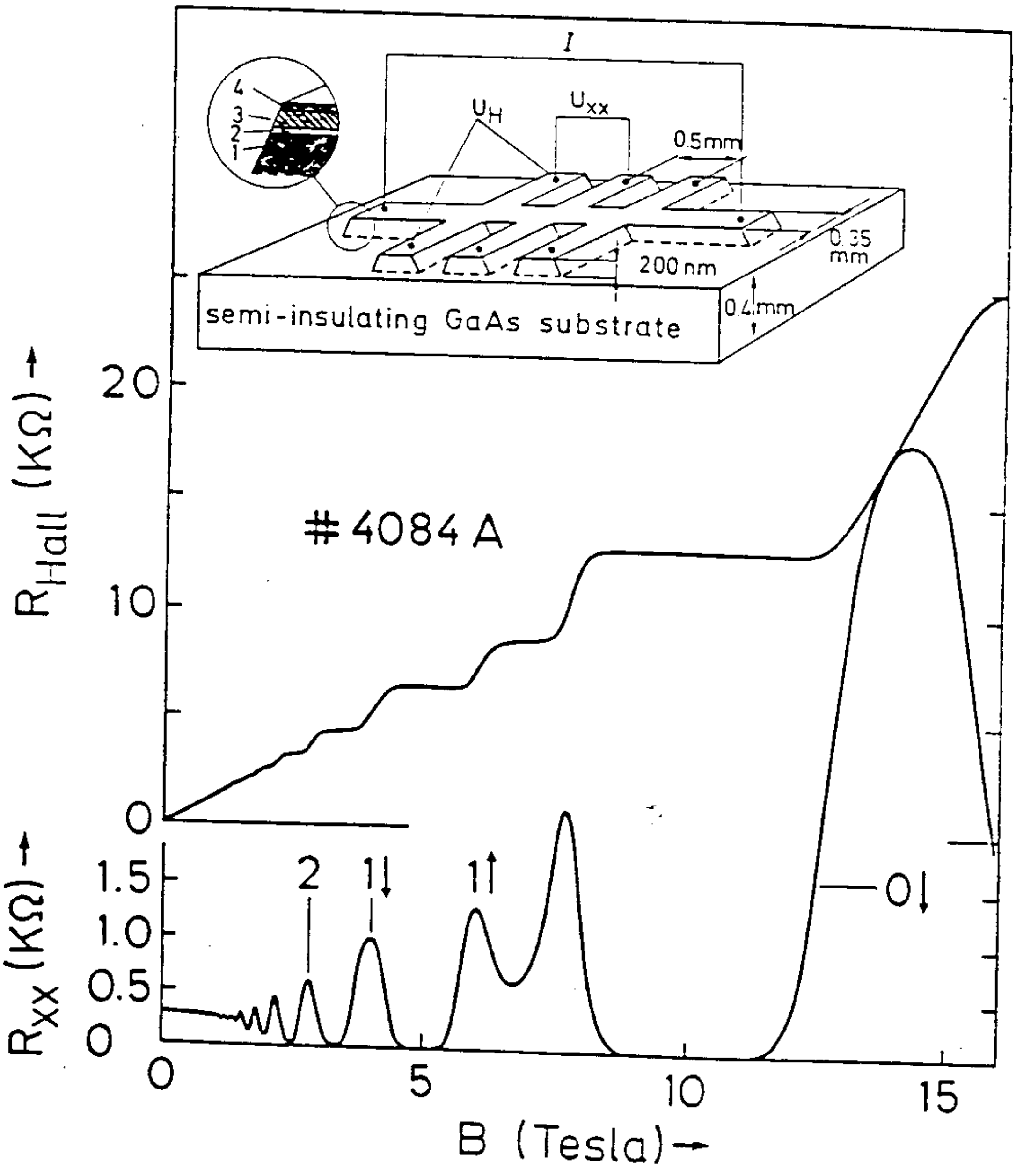
Scattering Processes of 2D Electron gas
In selectively Doped n-Al$_x$Ga$_{1-x}$As/GaAs Heterostructure



- optical and acoustic bulk phonons
- interface phonons
- alloy scattering
- remote ionized impurity scattering
- neutral and ionized impurity scattering (residual impurities in GaAs)
- interface roughness

Quantum Hall Effect

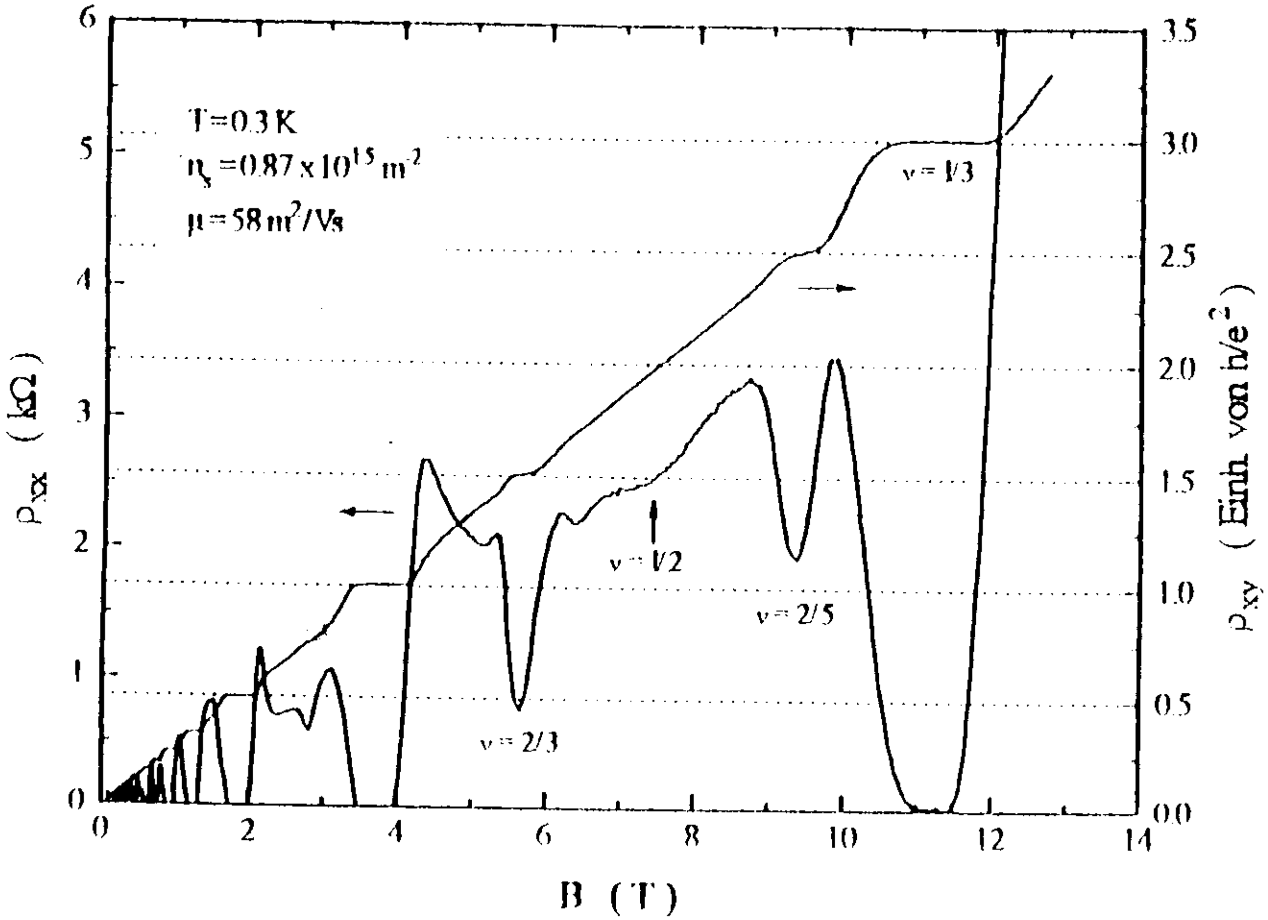
The resistance plateaus appearing at values of h/ie^2 are independent on the geometry of the Hall bar and on the material parameters.



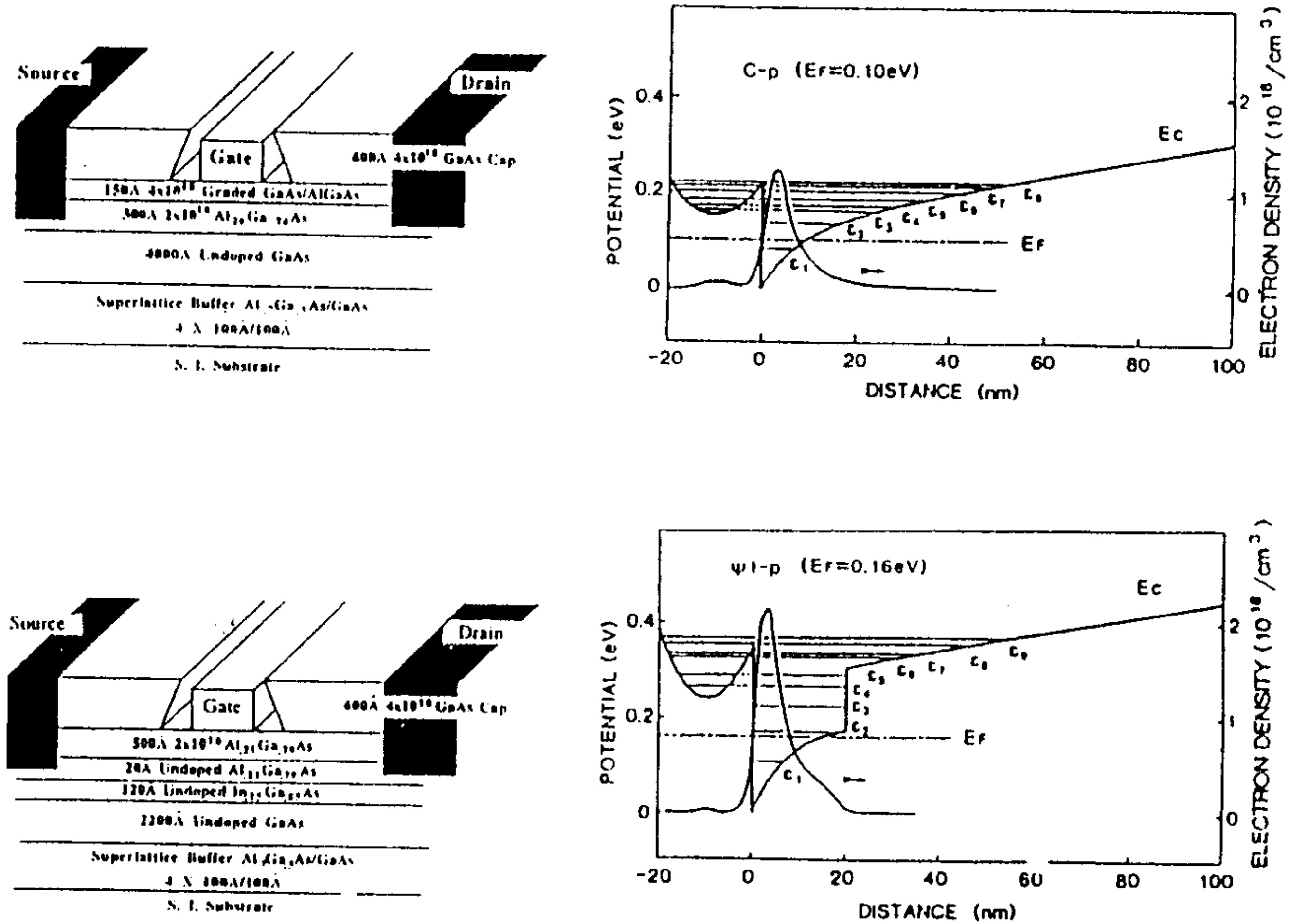
$$R_H = \frac{h}{i \cdot e^2} \qquad i = 1, 2, 3 \ldots$$

(classical: $R_H = \frac{B}{e \cdot n_s}$) 4

FQHE

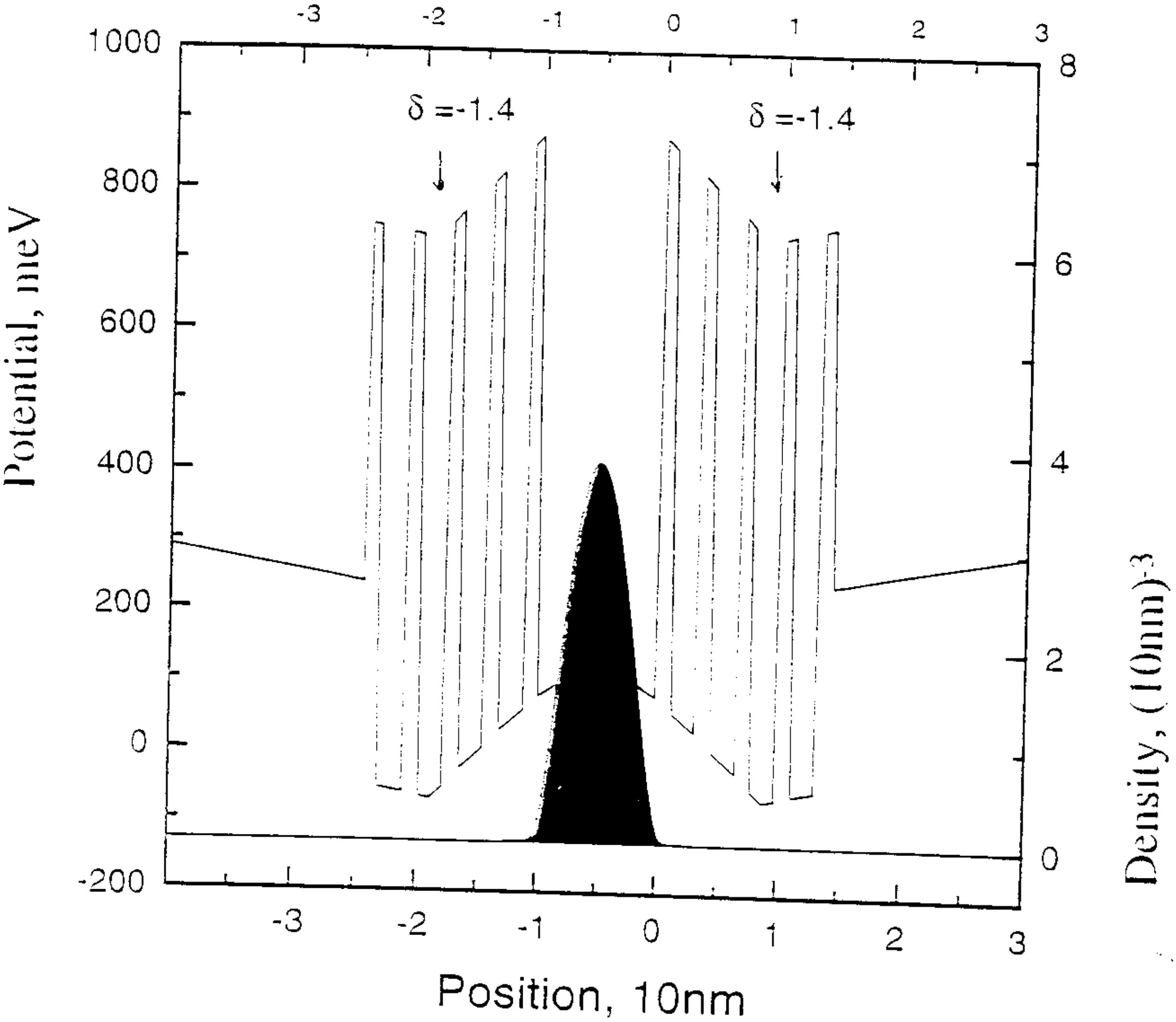


T=0.3 K
$n_s = 0.87 \times 10^{15}\ m^{-2}$
$\mu = 58\ m^2/Vs$
ρ_{xx} (kΩ)
ρ_{xy} (Einh. von h/e^2)
B (T)
ν = 1/3
ν = 2/5
ν = 1/2
ν = 2/3



Schematic layer sequence of two prototype structures for HEMT applications (left) and corresponding conduction band diagrams, electron subbands and electron wavefunction (right).

Remote δ-doped QW with AlAs/GaAs SPSL barriers



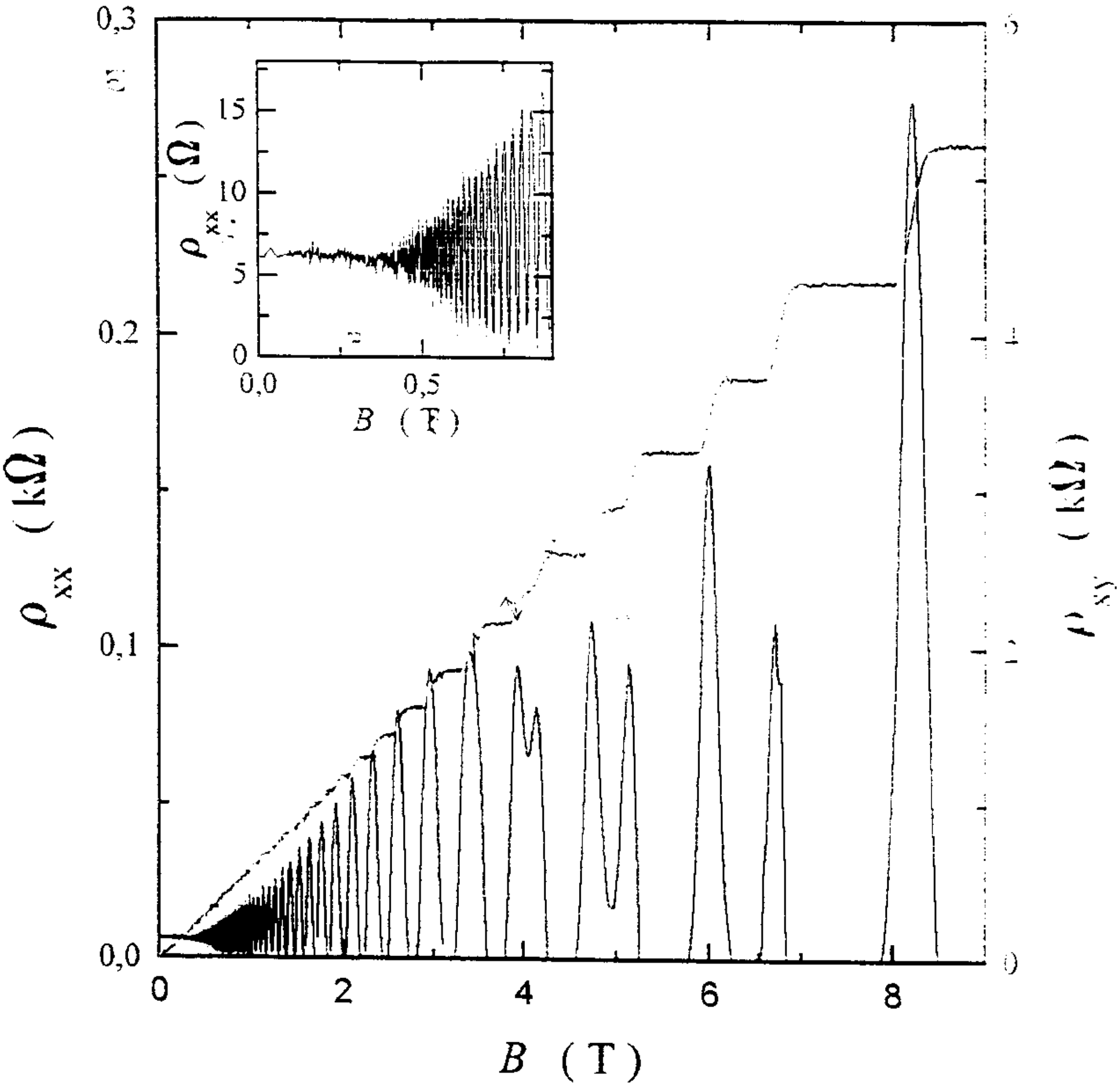
E_f=208.453 meV

n

E_0=152.3258 meV / 2.3166 $(10nm)^{-2}$

E_1=264.5620 meV / 0.0000 $(10nm)^{-2}$

E_2=276.6833 meV / 0.0000 $(10nm)^{-2}$



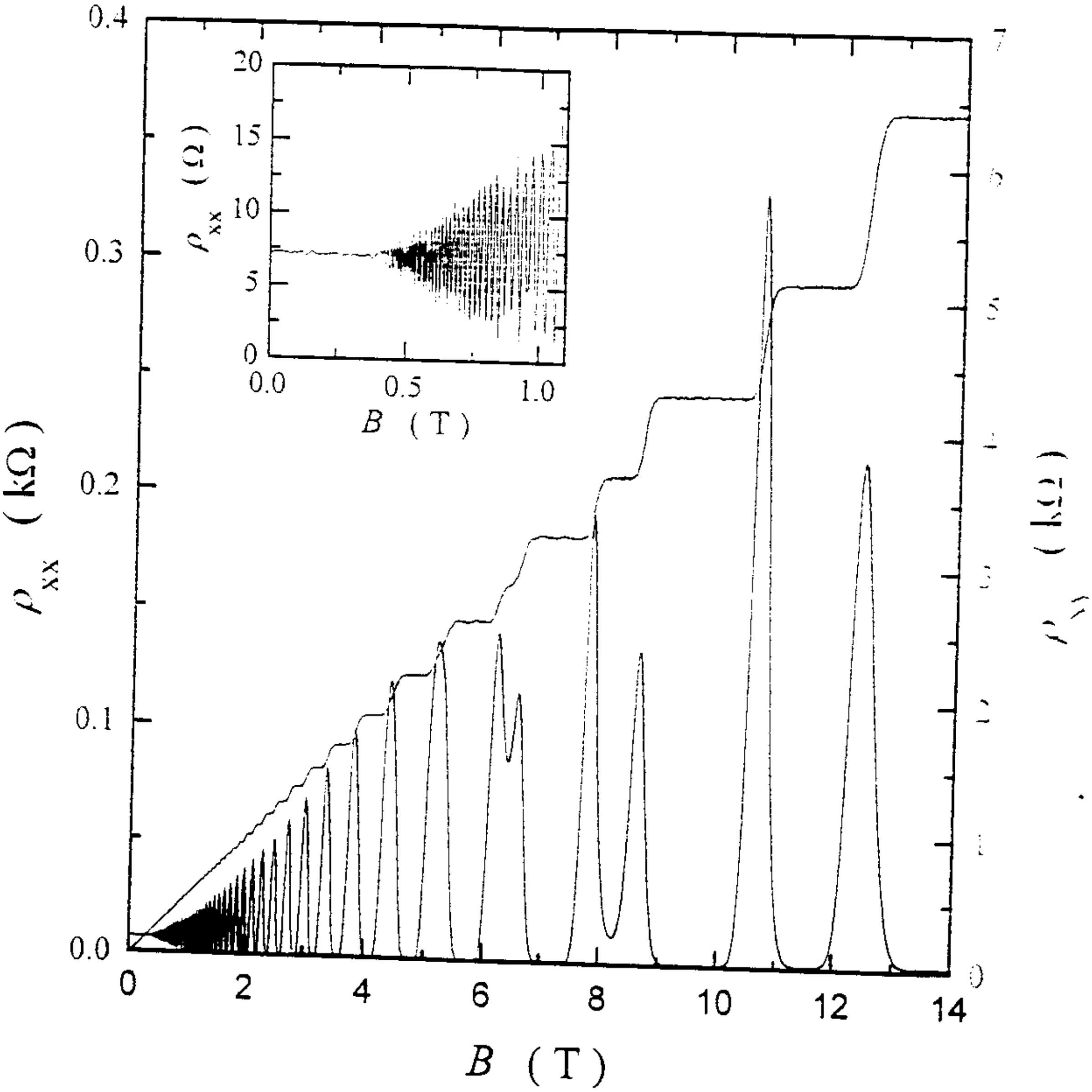
M 4.574.1.1

$T = 0.3$ K, dark

$n_H = \quad 1.08 \times 10^{16}$ m^{-2}

$\mu_H = \quad 94$ m^2/Vs

m457401.org
©Friedland-30.1.1996



M 4.579.1.1

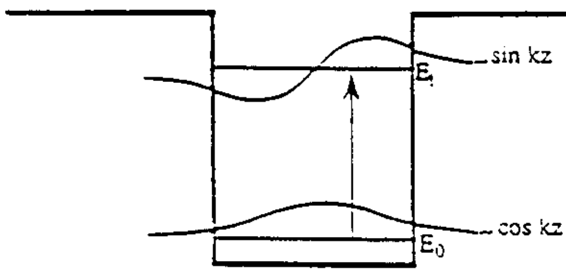
$T = 0.3$ K

$n_H = 1.4 \times 10^{12}$ cm^{-2}

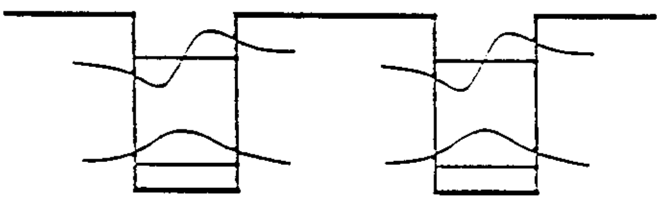
$\mu_H = 0.63 \times 10^6$ cm^2/Vs

ρ

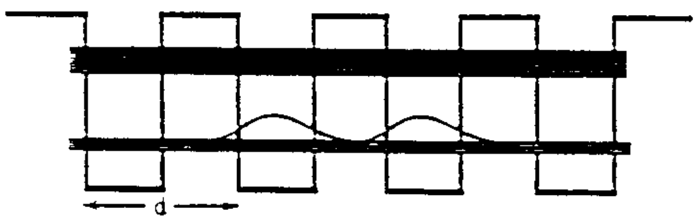
SQW, MQW, SL: level schemes



(a)



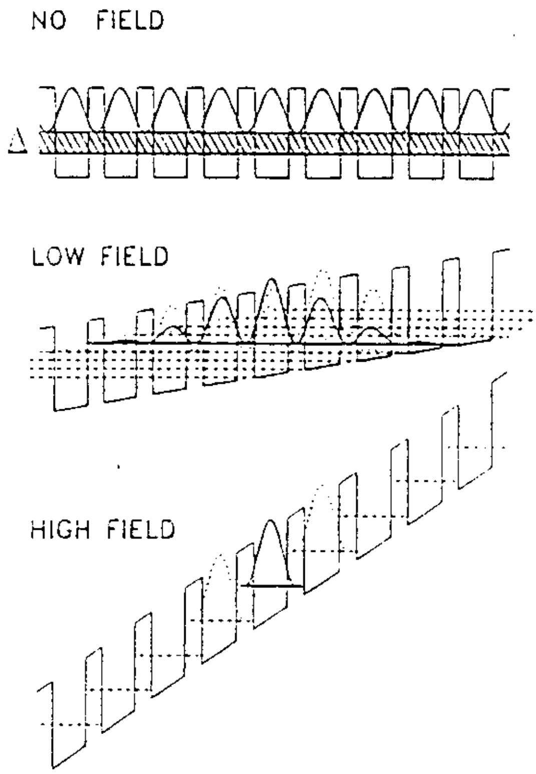
(b)



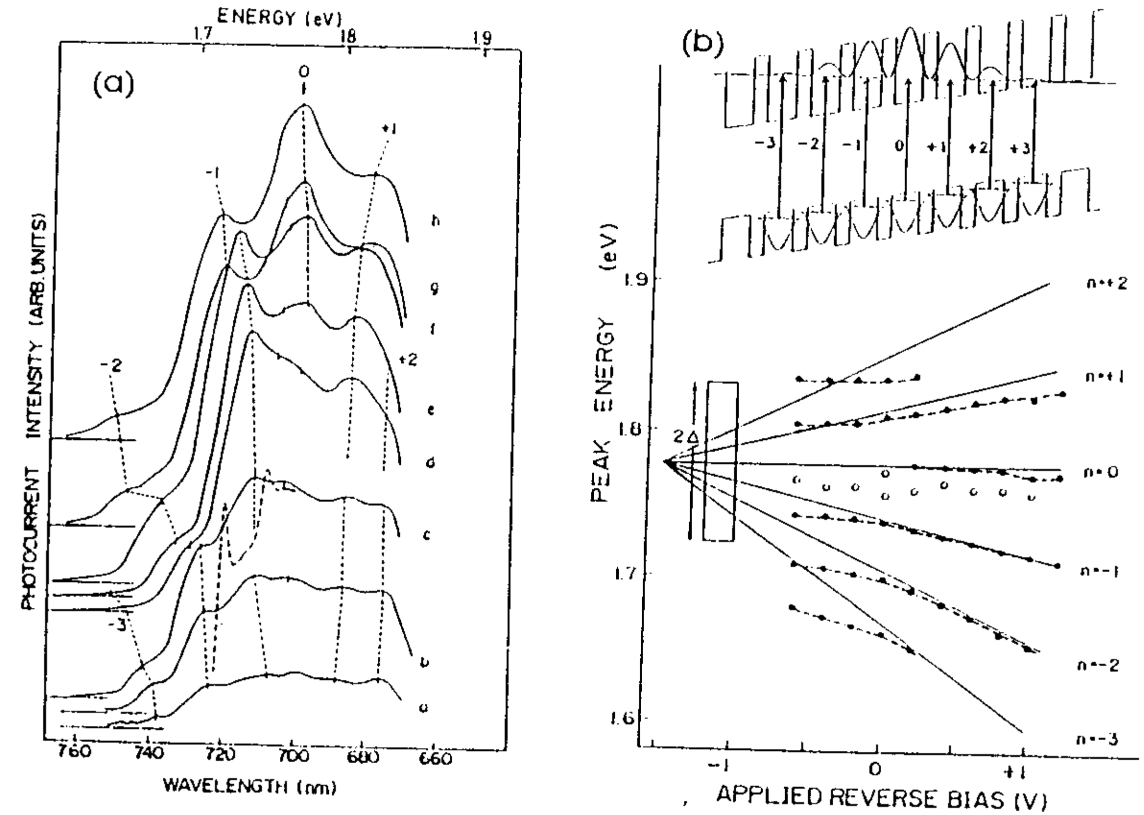
(c)

Confined energy levels and wave functions. a) Single quantum well. b) Multiquantum well structure with thick barrier layers. c) Formation of minibands in superlattice.

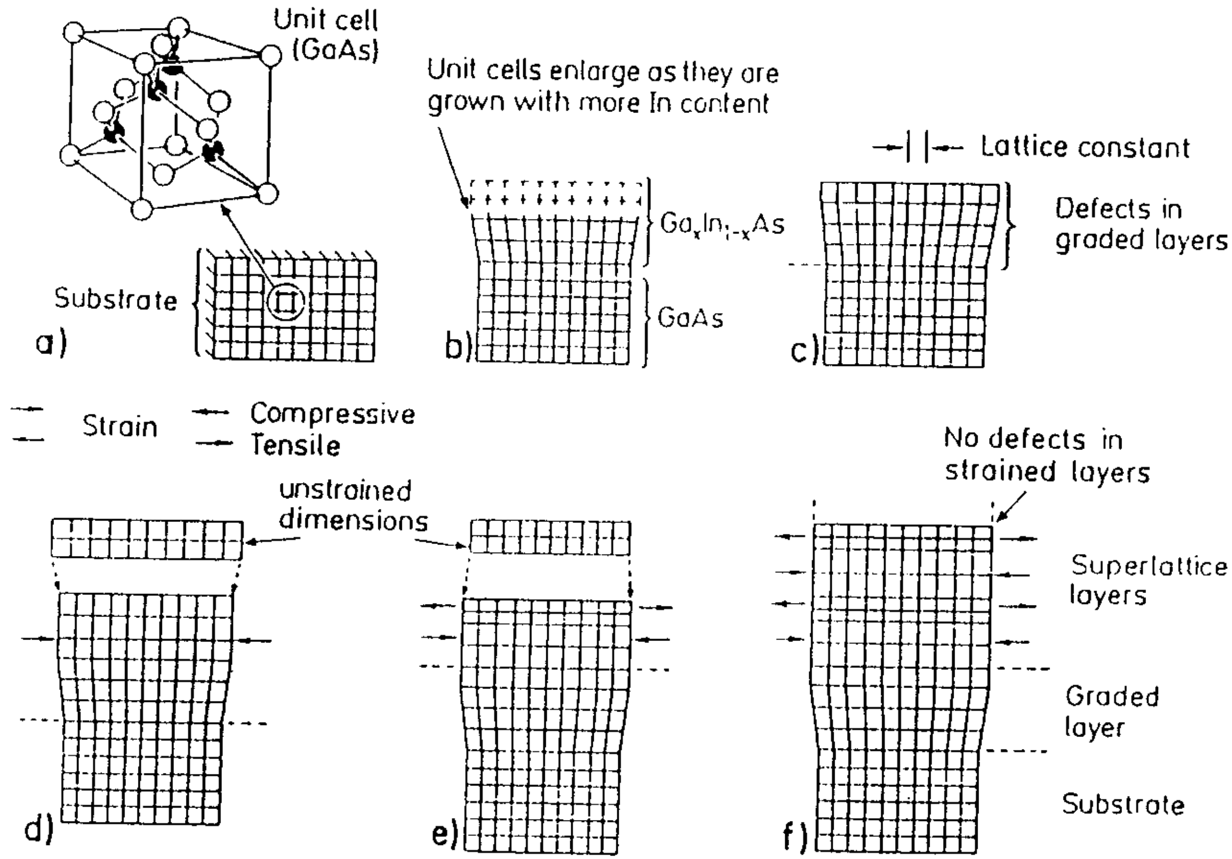
G. A. Sarov NATO ASI Series 3 High Tech. Vol.



Schematic illustration of electric-field induced localization (Stark localization) of electron wavefunctions in the periodic conduction band potential of a $Al_xGa_{1-x}As/GaAs$ superlattice.

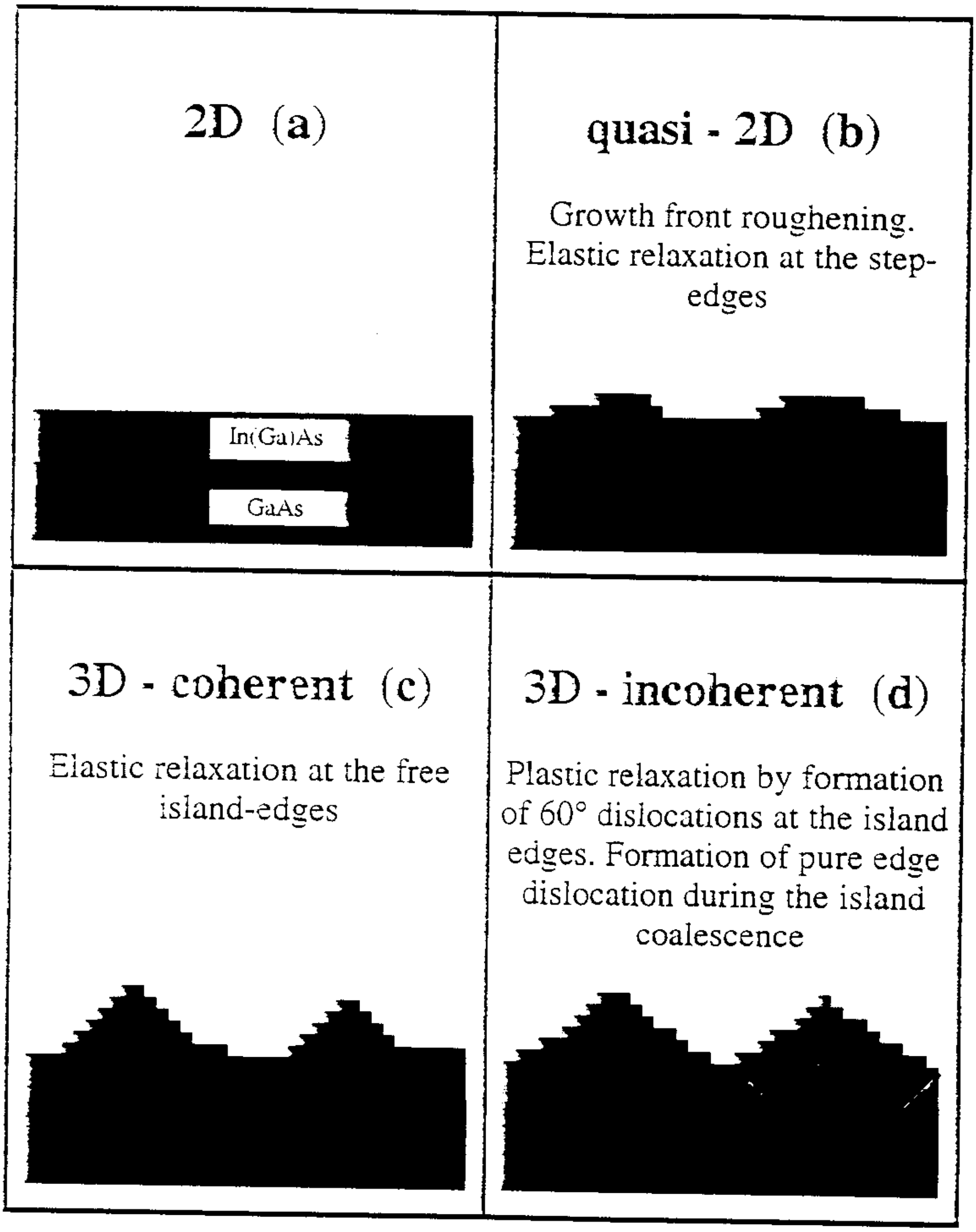


(a) Photocurrent spectra of 9-Å AlAs/32-Å GaAs superlattice taken at 8 K as a function of applied bias voltage V_b (V_b = +1.0 V for a and -1.0 V for h). (b) Variation of peak energies of photocurrent spectra with bias voltage. The inset shows interband transitions between electron and hole states involving the Stark ladder.

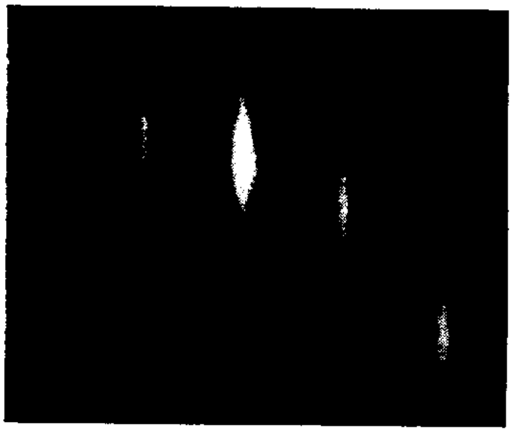


Schematic illustration of the formation of a strained $GaAs/Ga_yIn_{1-y}As$ multilayer structure on a (001)GaAs substrate with an intermediate graded $Ga_xIn_{1-x}As$ buffer layer

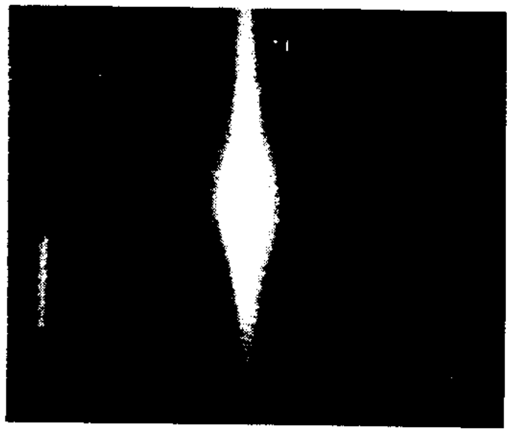
PRINCIPLE



Different growth regimes of $In_xGa_{1-x}As$ ($x > 0.25$) strained layers on GaAs as a function of coverage

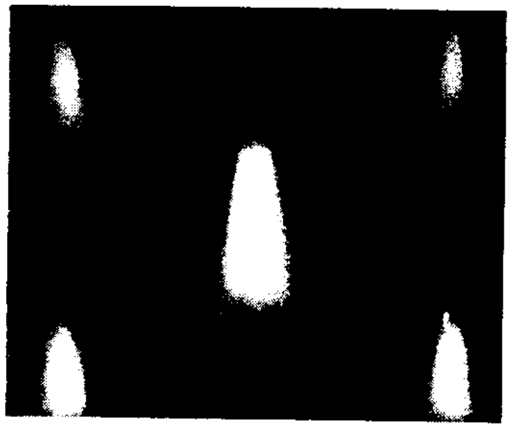


(a) c(4x4) , Θ = 0

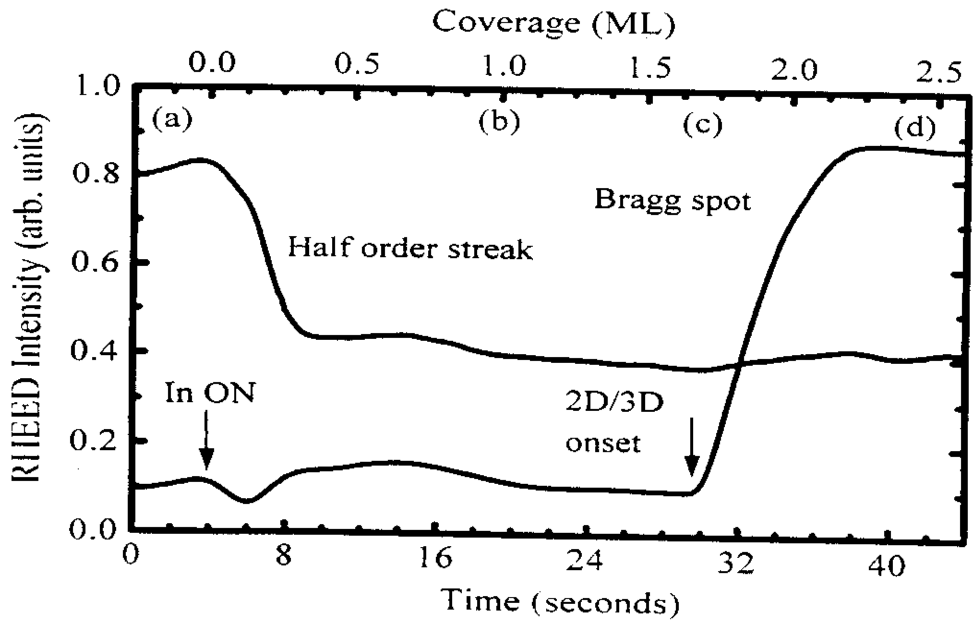


(b) (2x3) , Θ = 1 ML

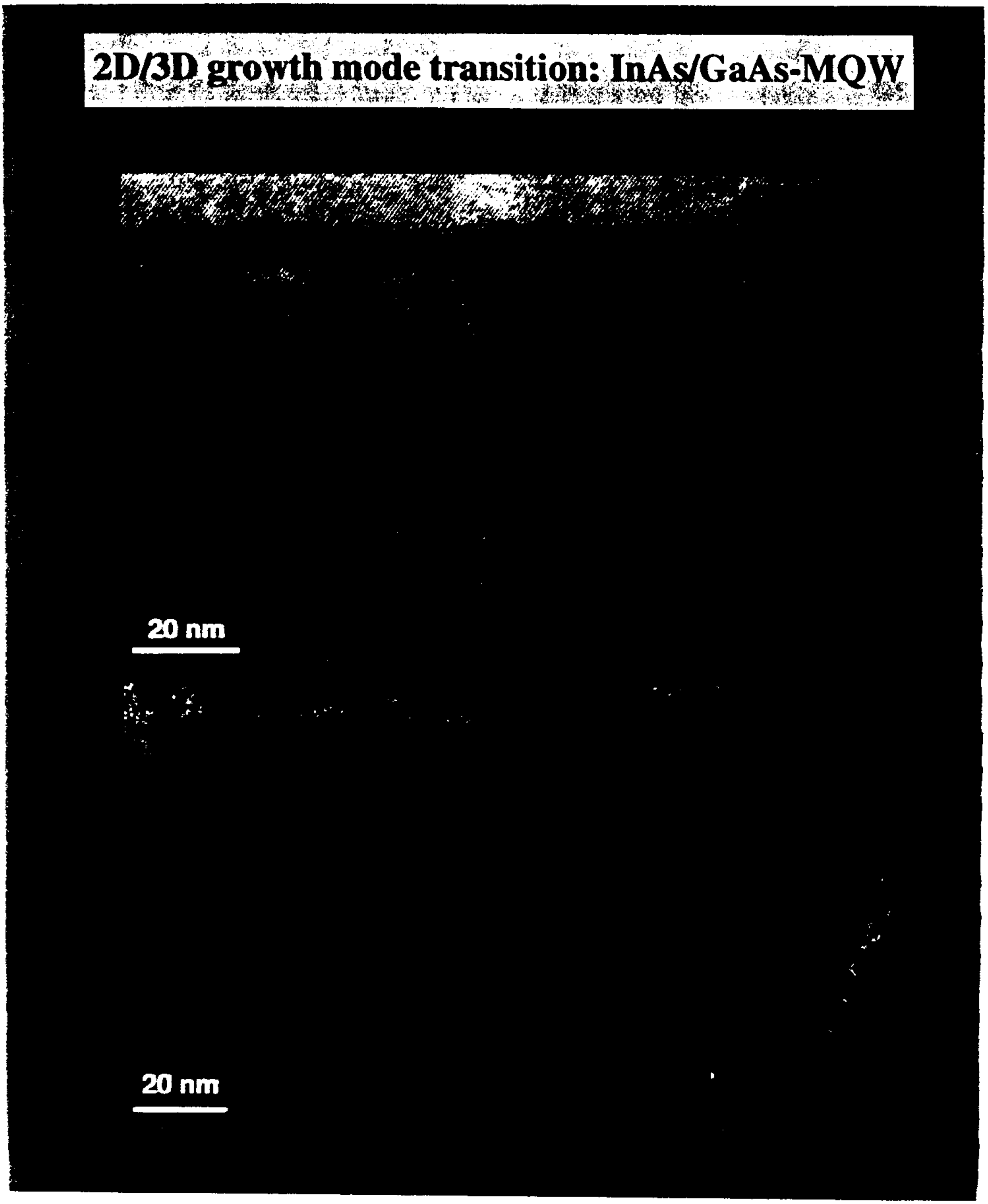
(c) Θ = 1.7 ML



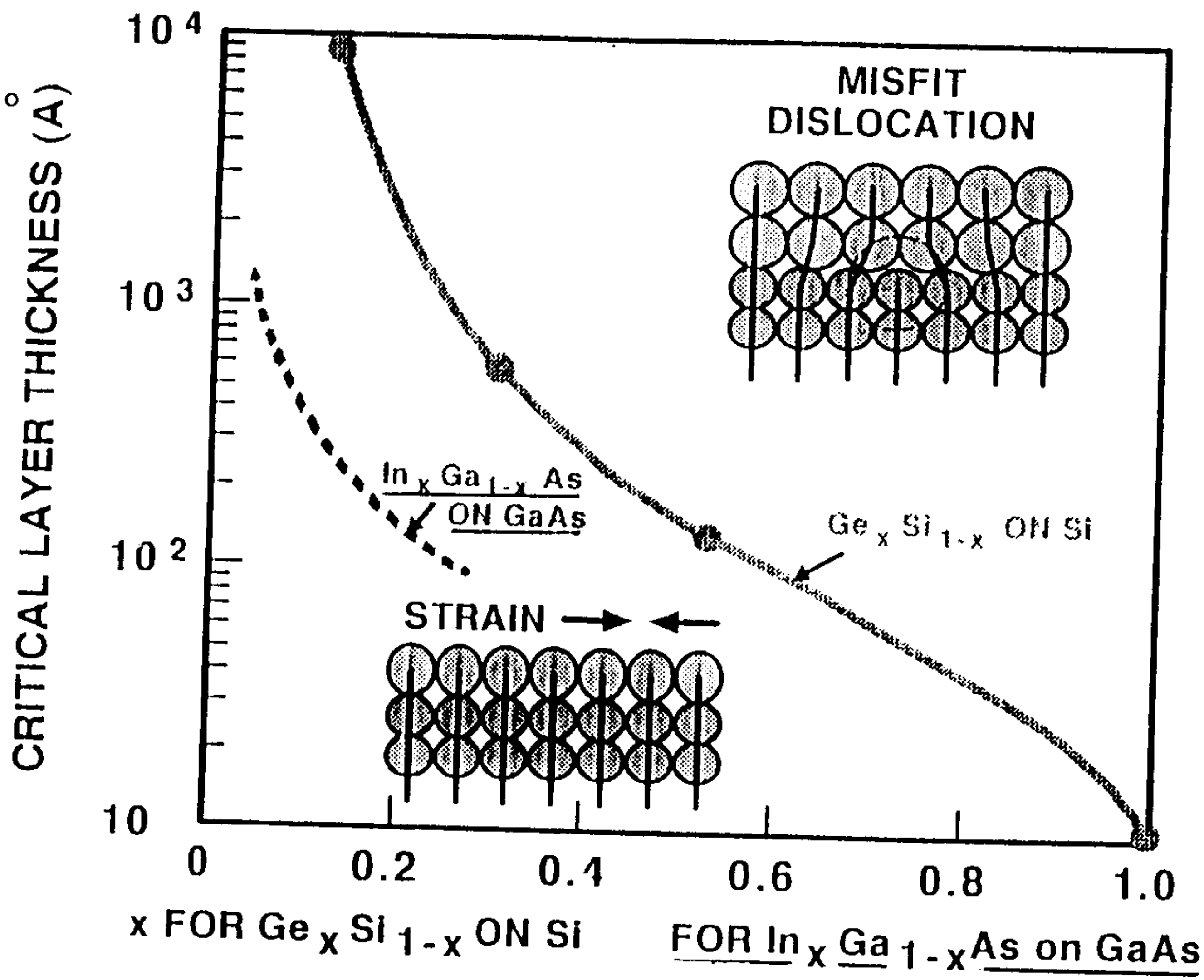
(d) Θ = 2.5 ML



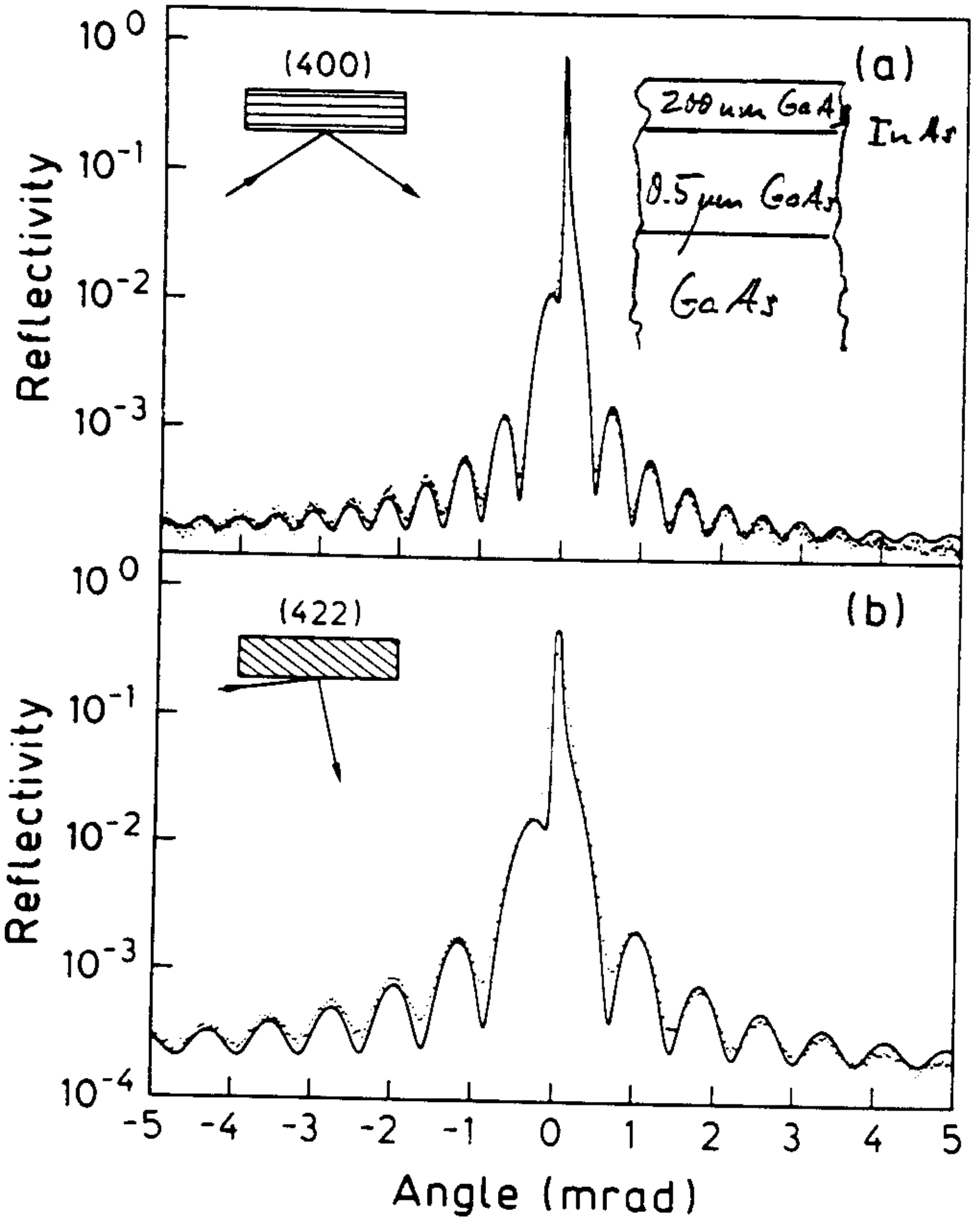
RHEED pattern and RHEED intensity time scans recorded along the [1-10] azumuth during InAs deposition at 480°C $\Theta_{2D/3D} = 1.7 \pm 0.1$ ML

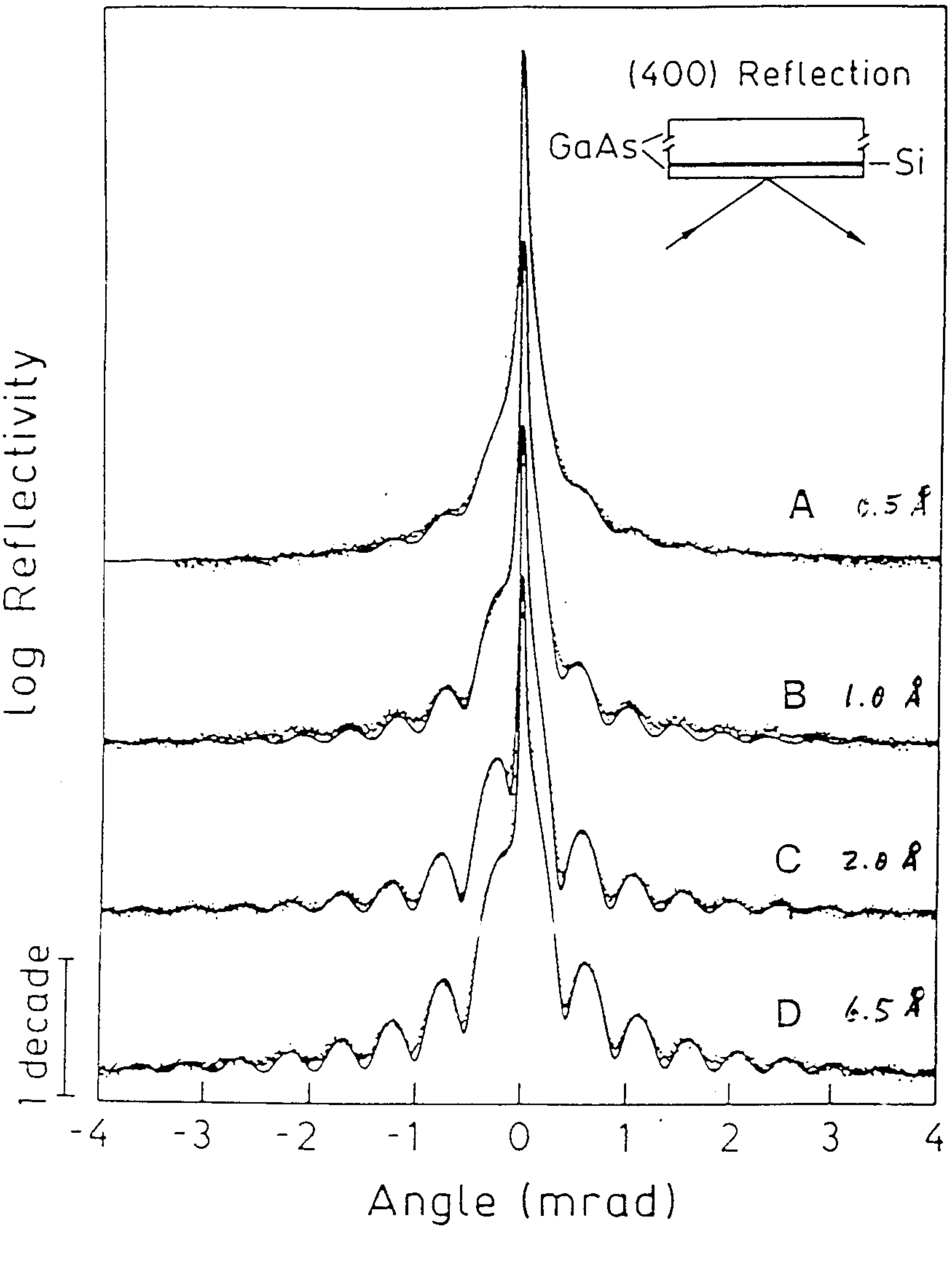

2D/3D growth mode transition: InAs/GaAs-MQW
20 nm
20 nm

CRITICAL LAYER THICKNESS FOR DEFECT FREE STRAINED LAYER GROWTH

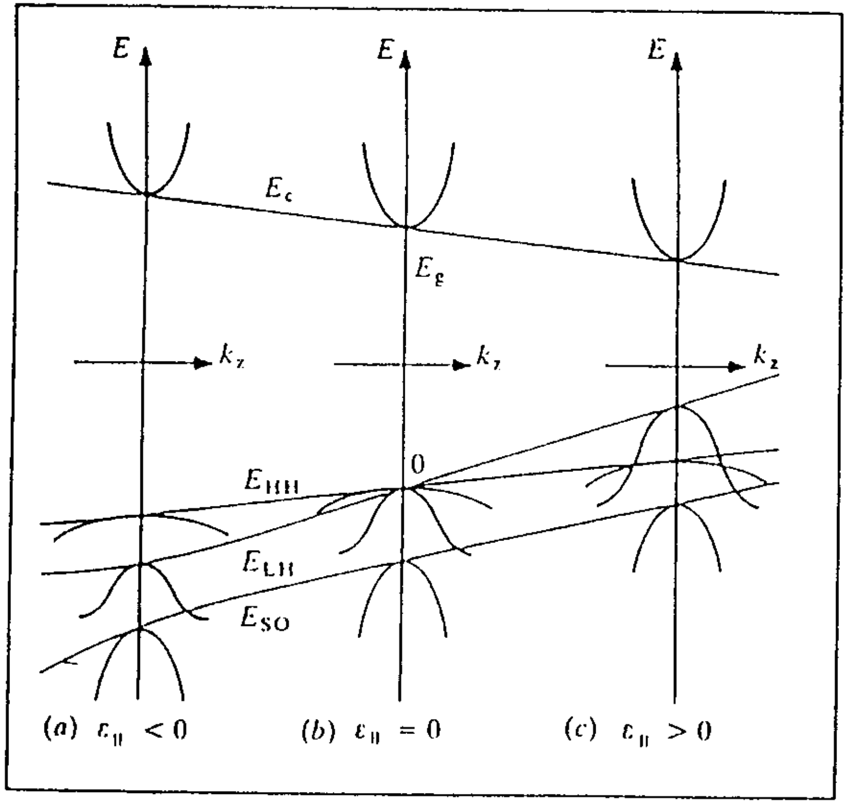


1.5 ML InAs (100) in GaAs



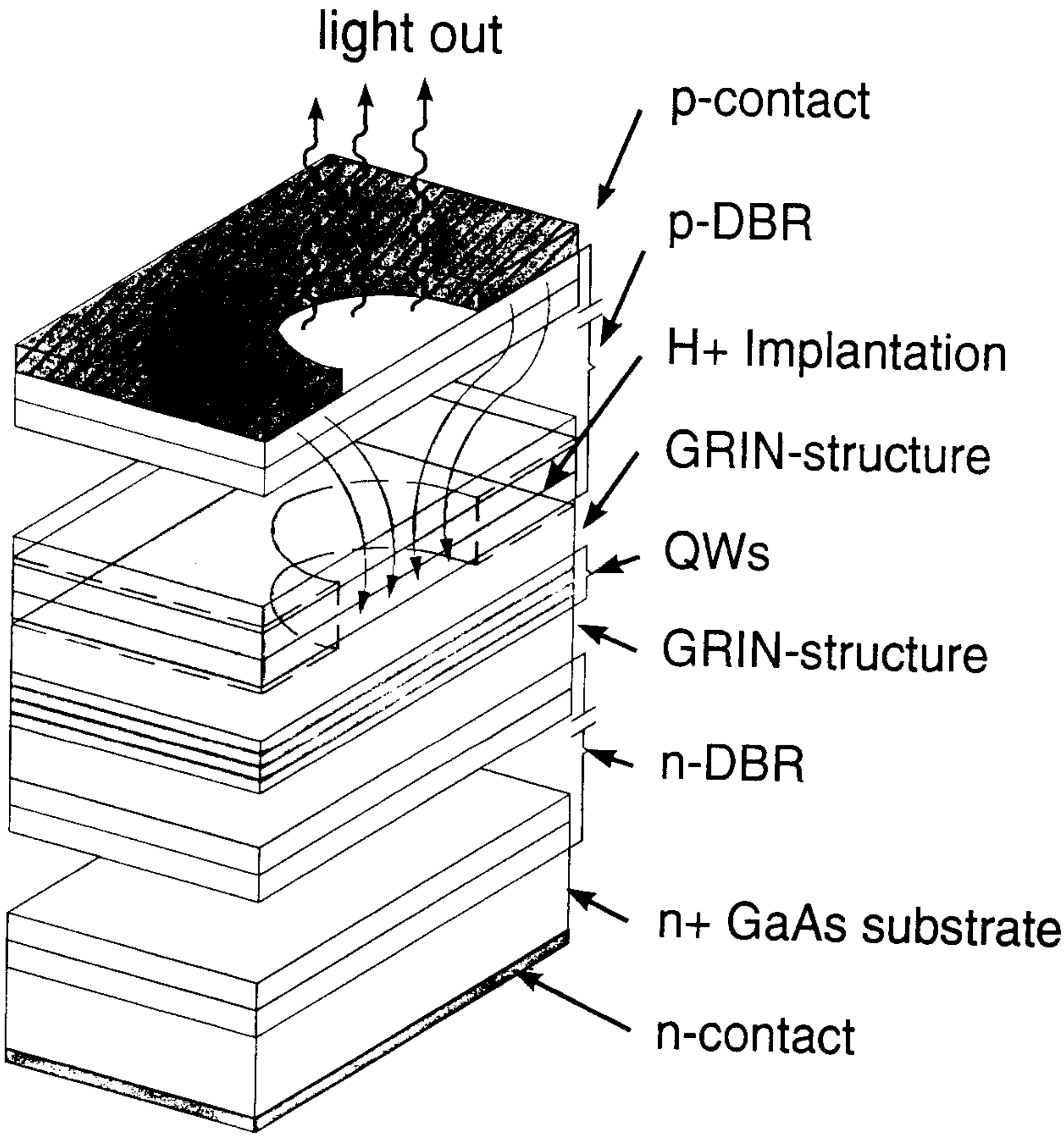


Tapfer et al., Appl. Phys. Lett. [illegible]
[illegible]



Schematic illustration of the strained-induced modification of the valence-band structure of direct-gap III-V semiconductors. (b) unstrained layer: heavy- and light-hole valence bands are degenerate. (a) biaxial compressive strain: valence band degeneracy is lifted and band gap is increased. (c) biaxial tensile strain: valence band splitting is reversed, i. e. the light-hole band becomes the highest one, and band gap is reduced.

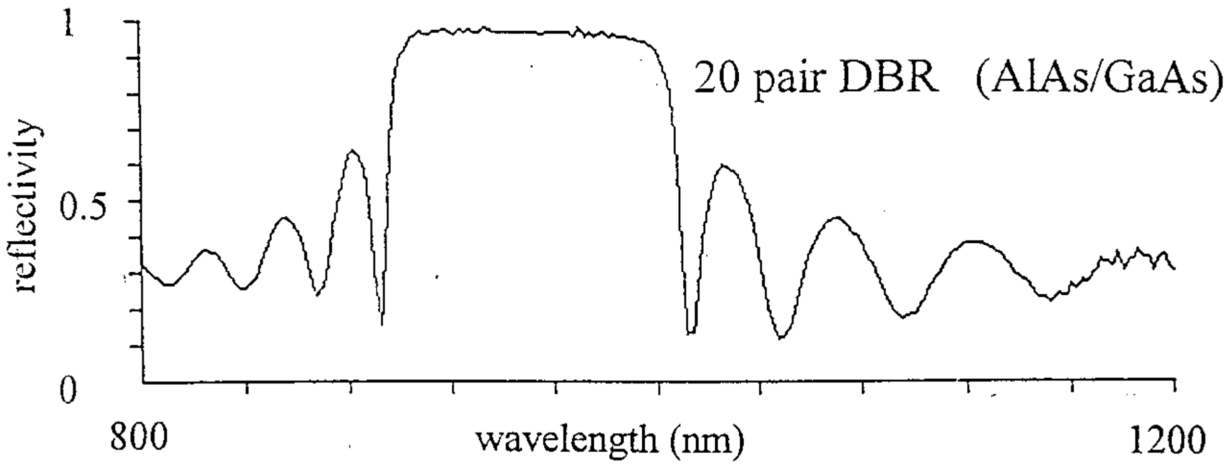
Planar, protonimplanted surface-emitting laser (sch. view)



Distributed Bragg Reflector (DBR)

Fabry-Perot-Resonator

Mirror : substituted by DBRs , composed of multiple double layer----- each layer $\lambda/4$ thick

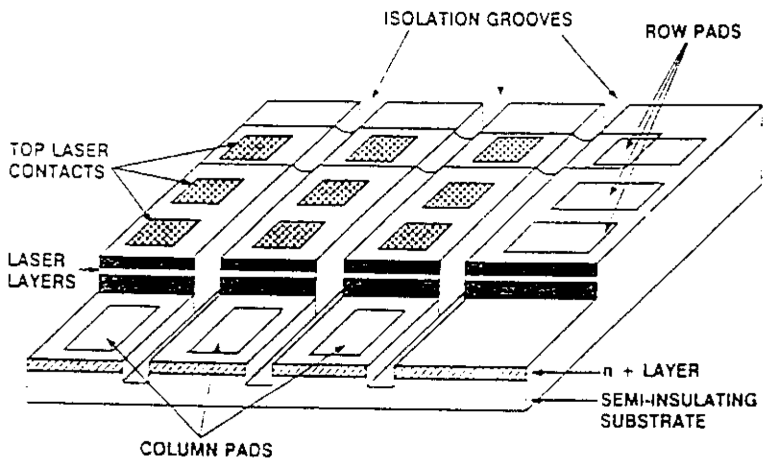


reflectivities: 10 pair DBR: $R \approx 95\%$

20 pair DBR $R \approx \geq 99\%$

VCSEL: Potentials

- high packaging into 2-dim. arrays
- low threshold currents
  ⇒extremely small radiation emitting volumen
- mono mode operation
- very efficient coupling into fibres



Scheme of a matrix-addressable VCSEL-array
J.L.Jewell et.al. IEEEE Journal of Quantum Electronics 27 (1991) 1332

applicable to: optical interconnections
optical parallel processing etc.

VCSEL: Demands

♦ matching: • location of the cavity mode
• max. reflectivity of DBRs
• gain spectrum of the QW

⇒ ≈ 0.5% accuracy of layer thicknesses
⇒ high flux stability
⇒accurate growth rates

♦ low resistivity in the vertical direction
for low heat production and
low voltage operation

⇒ gradual composition at heterointerfaces

♦ high crystalline perfection of the entire structure

⇒ avoid dislocations in the QW

Properties of DBRs composed of AlAs/GaAs

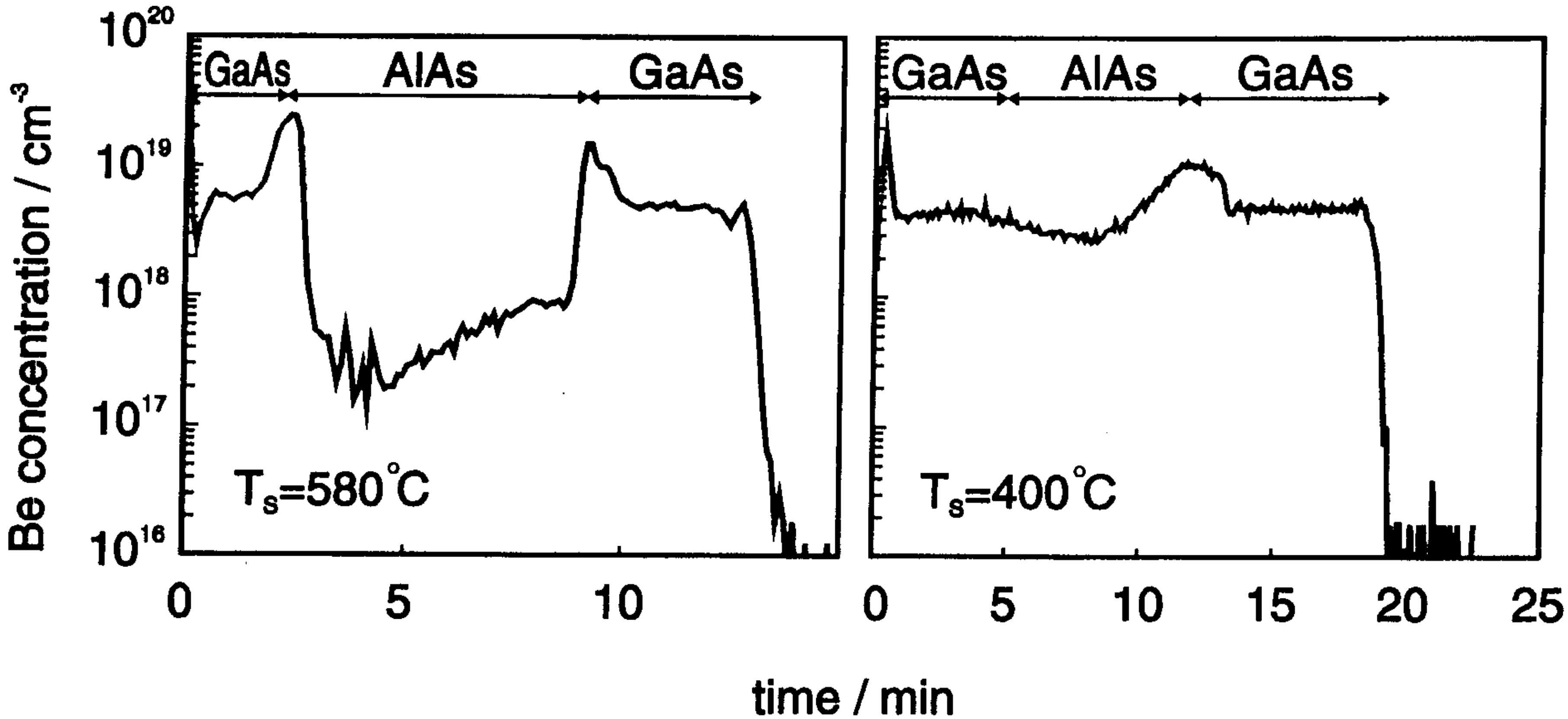
☺ • high reflectivity ($\Delta n \Rightarrow max$)
  $\Rightarrow$low number of $\lambda/4$-pairs

☺ • good thermal conductivity

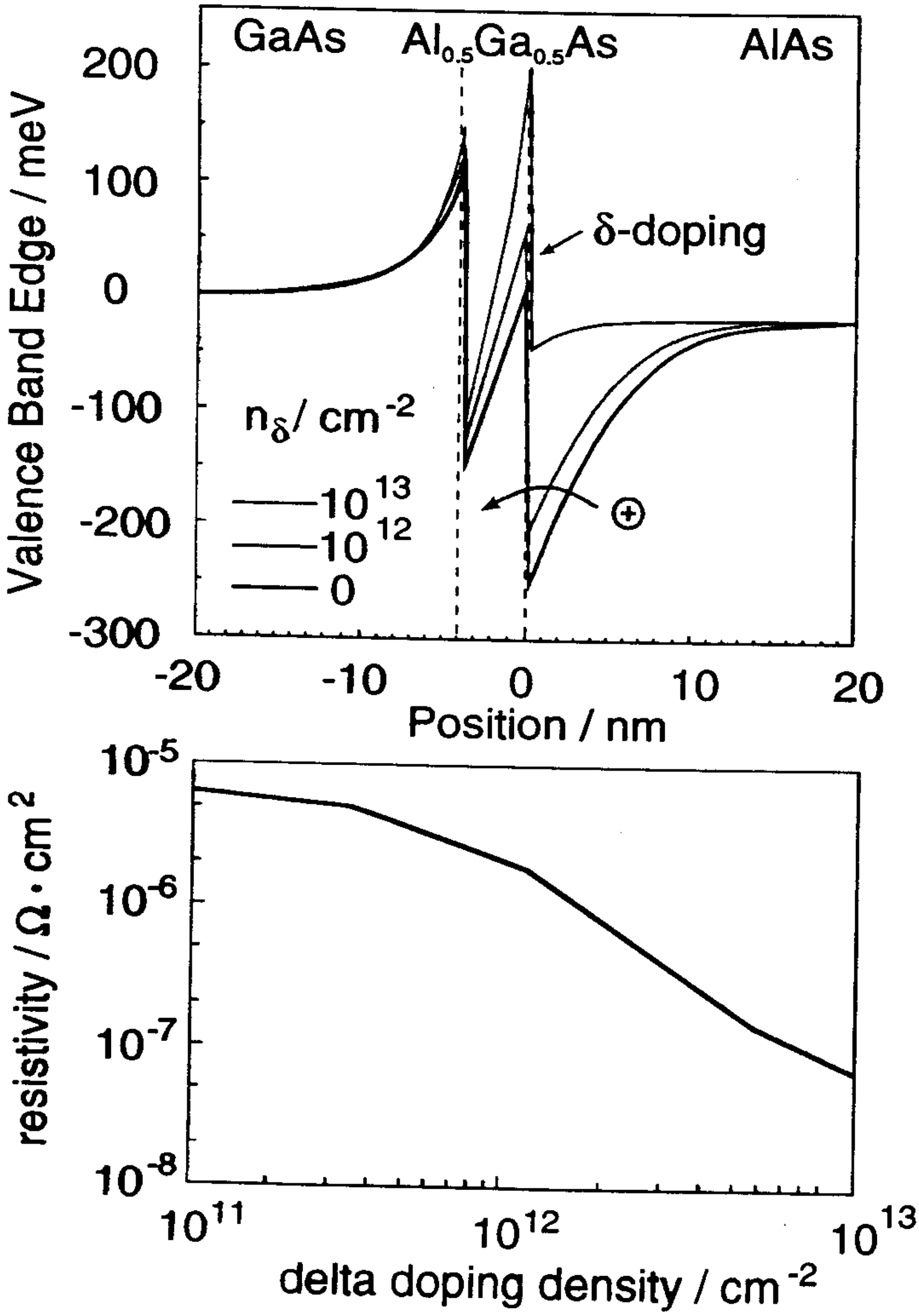
☹ • high series resistances
  $\Delta E_C \approx 0.2$ eV ; $\Delta E_V \approx 0.5$eV

Be Diffusion during MBE of AlAs/GaAs

* T_s dependence of Be incorporation



Influence of δ-doping on the GaAs/AlAs Heterobarrier



Calculated Temperature Distribution in a planar, protonimplanted VCSEL