UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

SMR/917 - 23

SECOND WORKSHOP ON SCIENCE AND TECHNOLOGY OF THIN FILMS

(11 - 29 March 1996)

" Selective MBE growth and deposition. "

presented by:

G.A.C. JONES
University of Cambridge
Cavendish Laboratory
Semiconductor Physics Research
Madingley Road
CB3 OHE Cambridge
United Kingdom

Selective MBE Growth and Deposition

G A C Jones

Cavendish Laboratory,

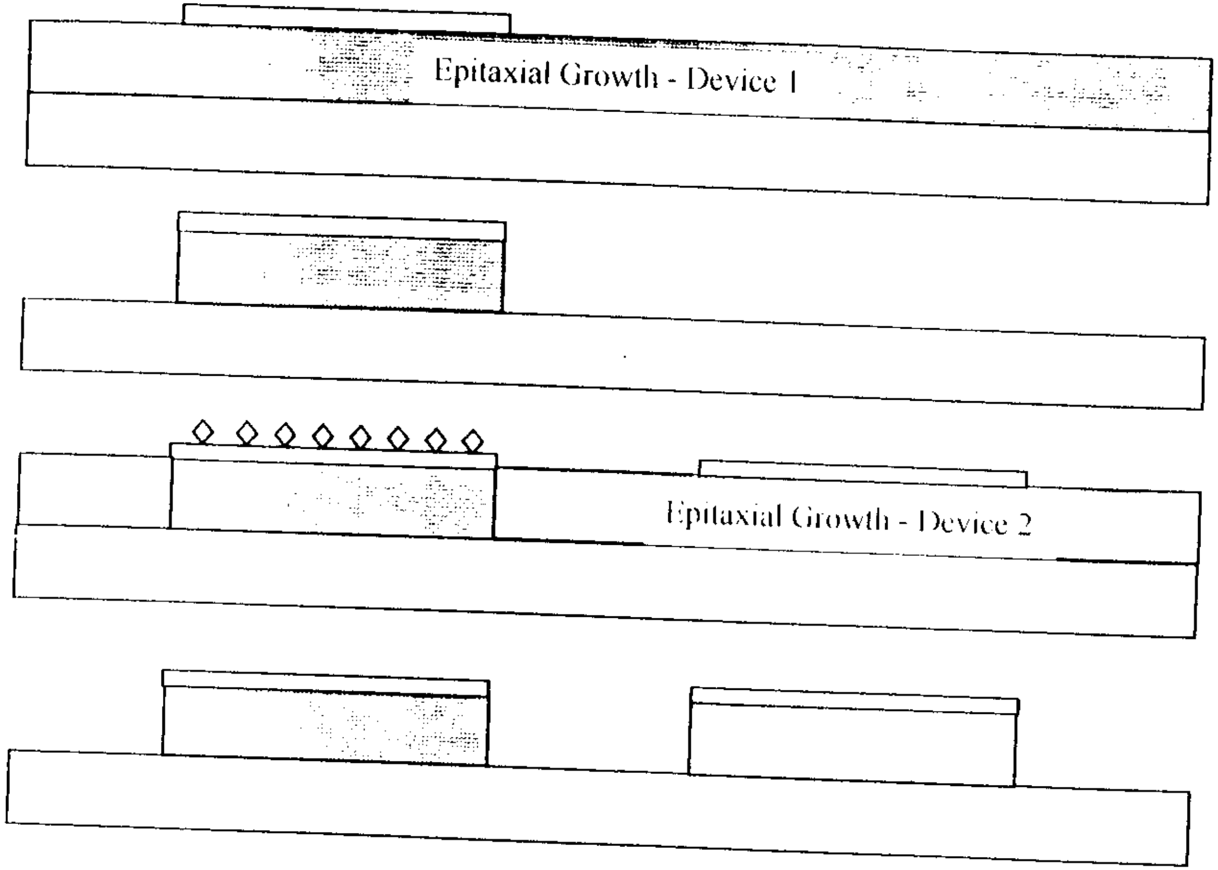
University of Cambridge, U.K.

Selective Growth

The flux of atoms is supplied *uniformly* to the surface, but the surface has been selectively modified.

- Growth through masking layers
- Growth on etched substrates
- Growth on vicinal planes

Device integration using sequential selective growth



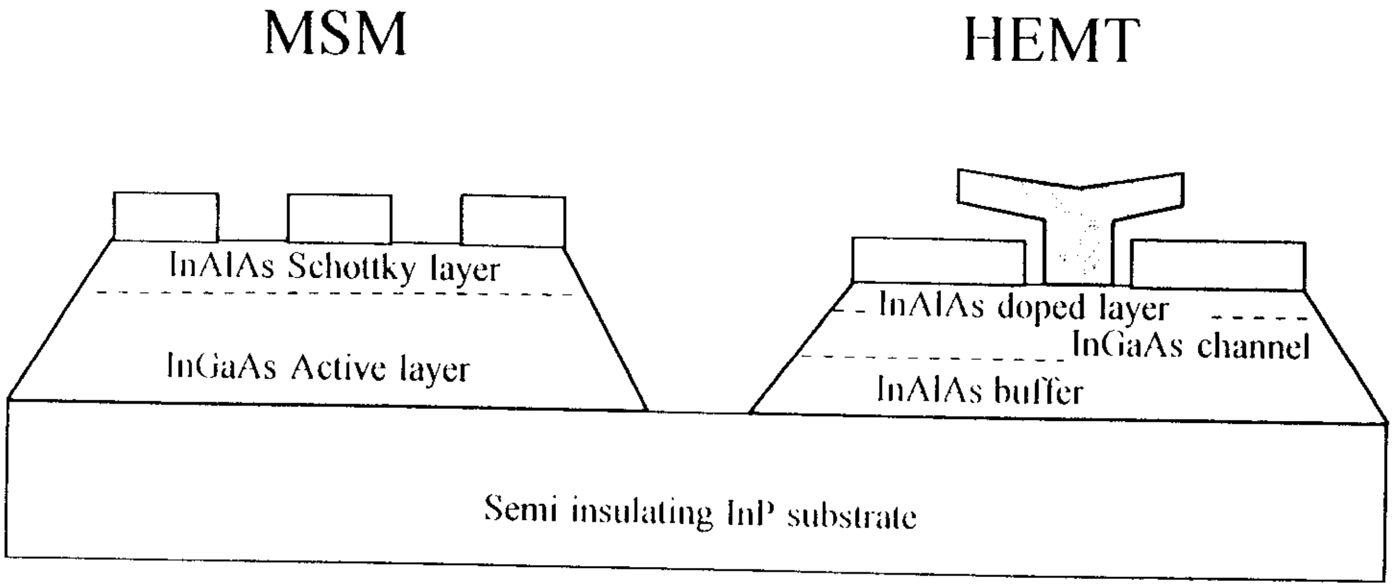
a) 1st growth and masking

b) etch 1st growth

c) 2nd growth and masking

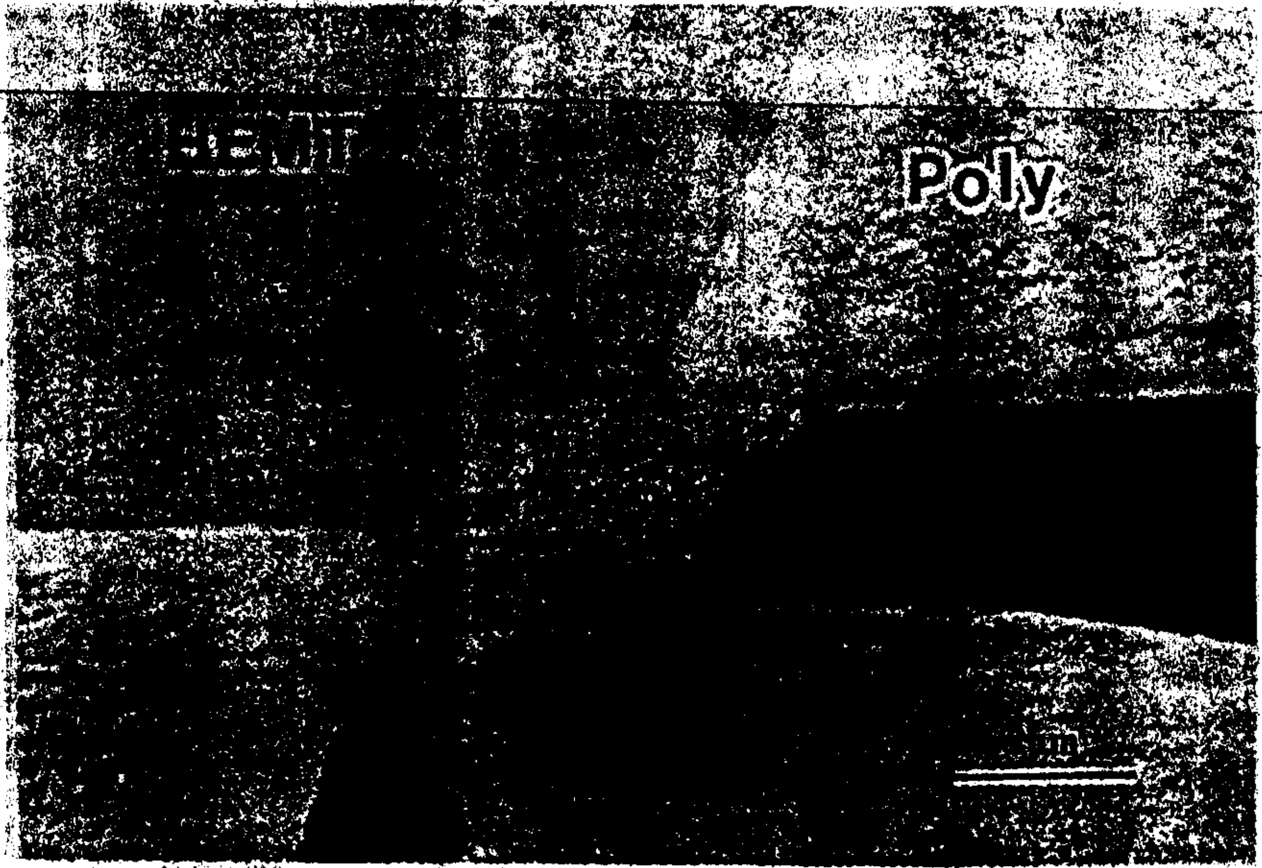
d) etch 2nd growth

etc.



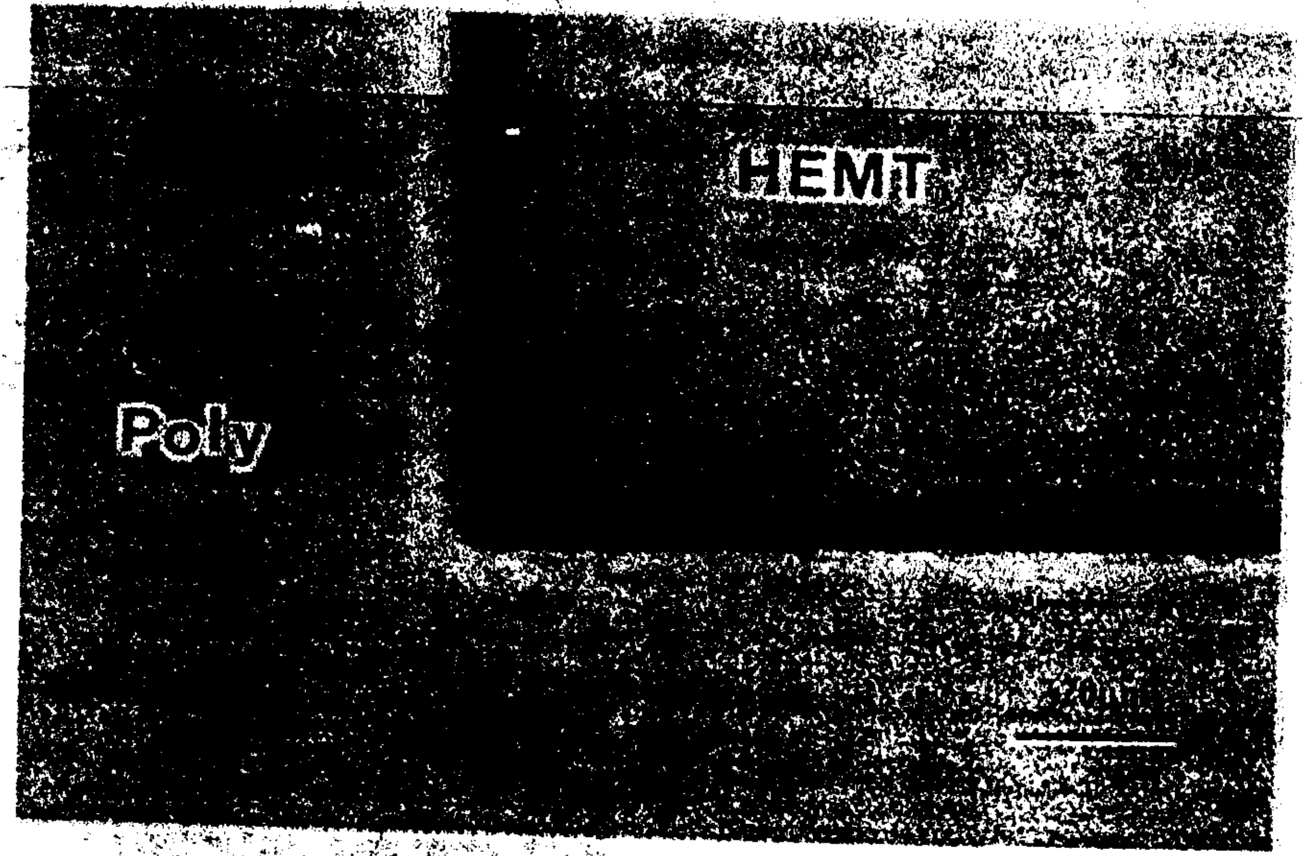
Cross-sectional view of MBE selective growth integration of MSM and HEMT devices

Reference: Y C Pao et al, J. Crystal Growth 127, (1993) 892-5.



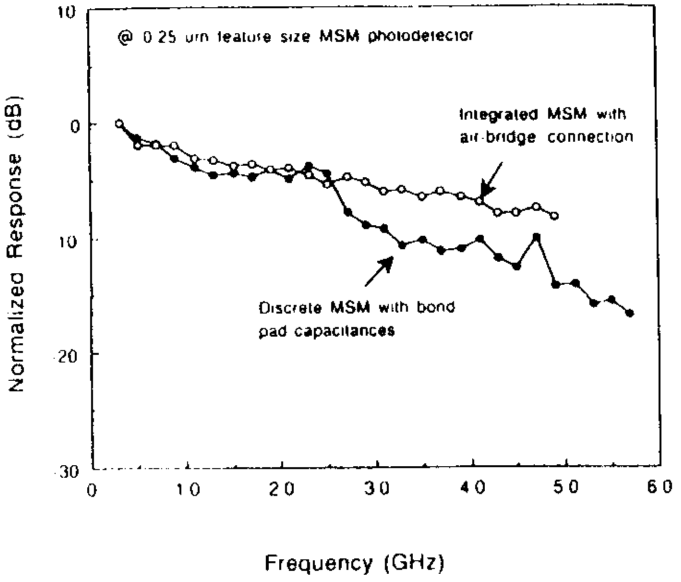
SEM micrograph of MBE selective growth of HEMT epitaxial layer. Overhang SiO_2 mask is not removed.

Reference Y C Pao et al. J. Crystal Growth 127,(1993),892-895

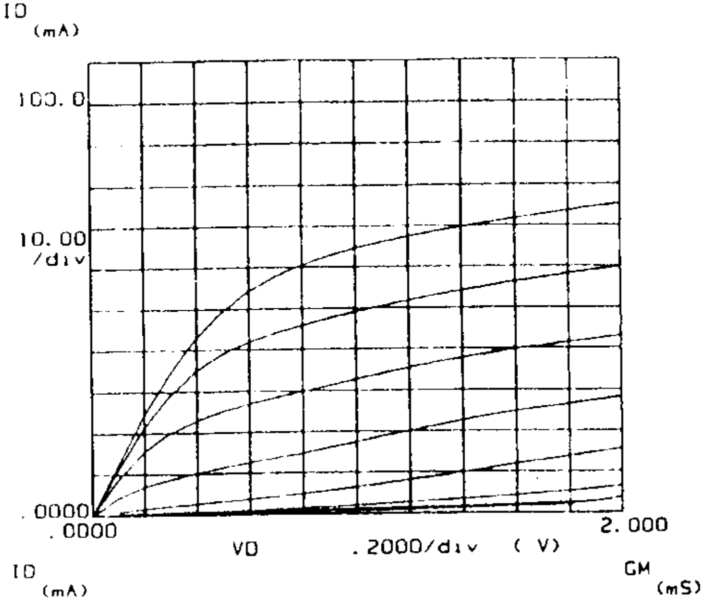


Selective MBE growth morphology of InAlAs/InGaAs HEMT on InP with dielectric mask patterning.

Reference Y C Pao et al. J. Crystal Growth 127,(1993),892-895



Photosensitivity of quarter micron feature size MSM fabricated on selectively grown MBE wafer.

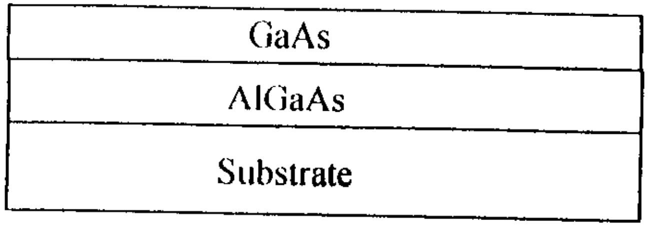


Typical I-V characteristic of 0.15um HEMT with gm of 900mS/mm fabricated on selectively grown MBE wafer.

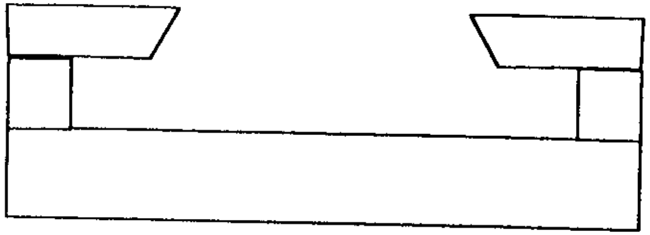
Reference Y C Pao et al. J. Crystal Growth 127,(1993),892-895

Selectively Masked MBE Growth

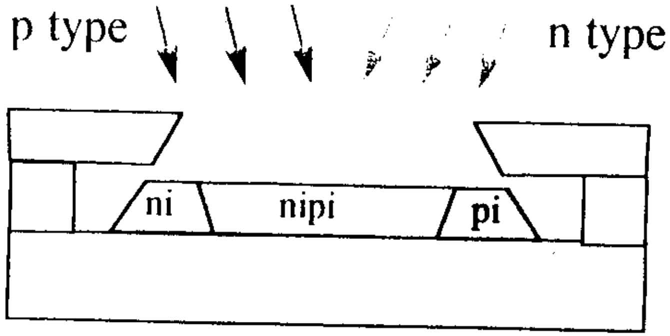
a) Grow GaAs/AlGaAs layers



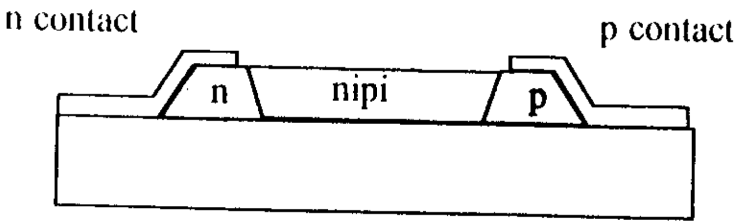
b) shadow mask formed by selective etch



c) MBE regrowth on patterned wafer



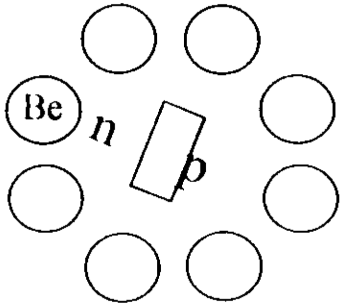
d) Mask removed and contacts applied



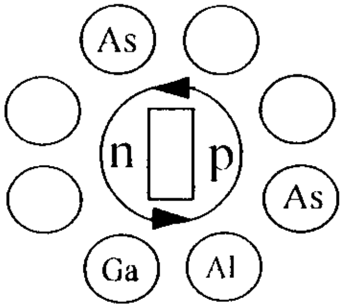
From:: X Wu et al., Journal of Crystal Growth 127, (1993) 896-899

Growth of a hetero-nipi modulator

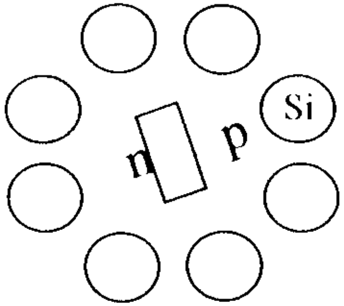
p δ-doping



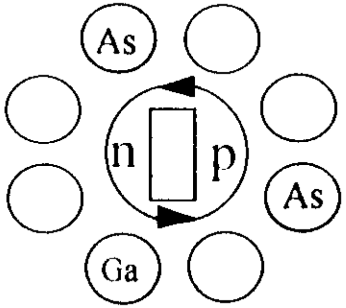
AlGaAs



n δ-doping

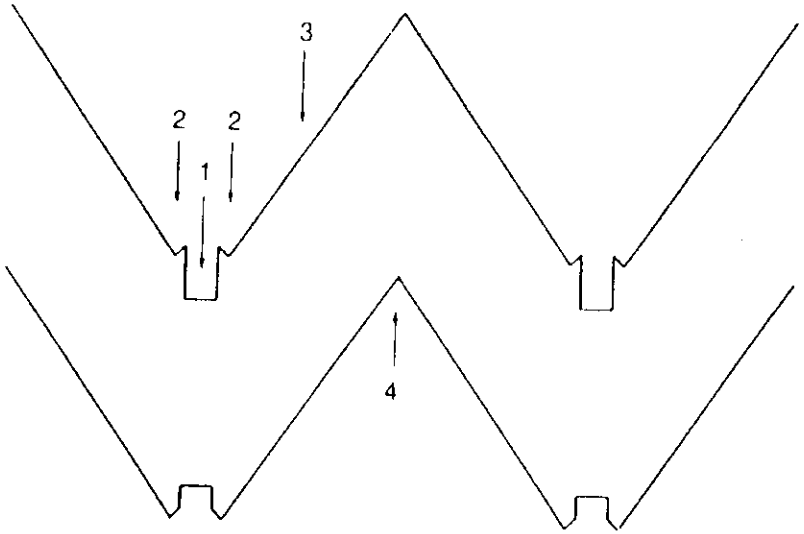


GaAs quantum wells



Reference: X Wu et al. Journal of Crystal Growth 127, (1993) 896-9

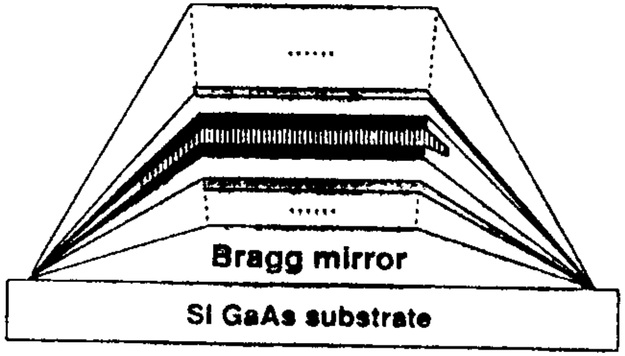
Bandstructure of interdigitally contacted hetero-nipi bandfilling modulator



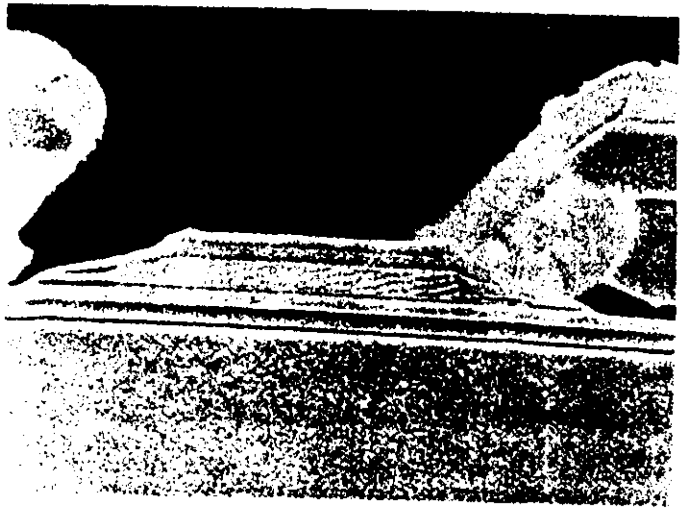
1) GaAs quantum well, 10nm
2) Si delta doping, 3.5 x 10^{12}
3) AlGaAs, x=0.3, 62nm
4) Be delta doping, 1.2 x 10^{13}

Reference: X Wu et al. Journal of Crystal Growth 127, (1993) 896-9

Selectively Masked MBE Growth



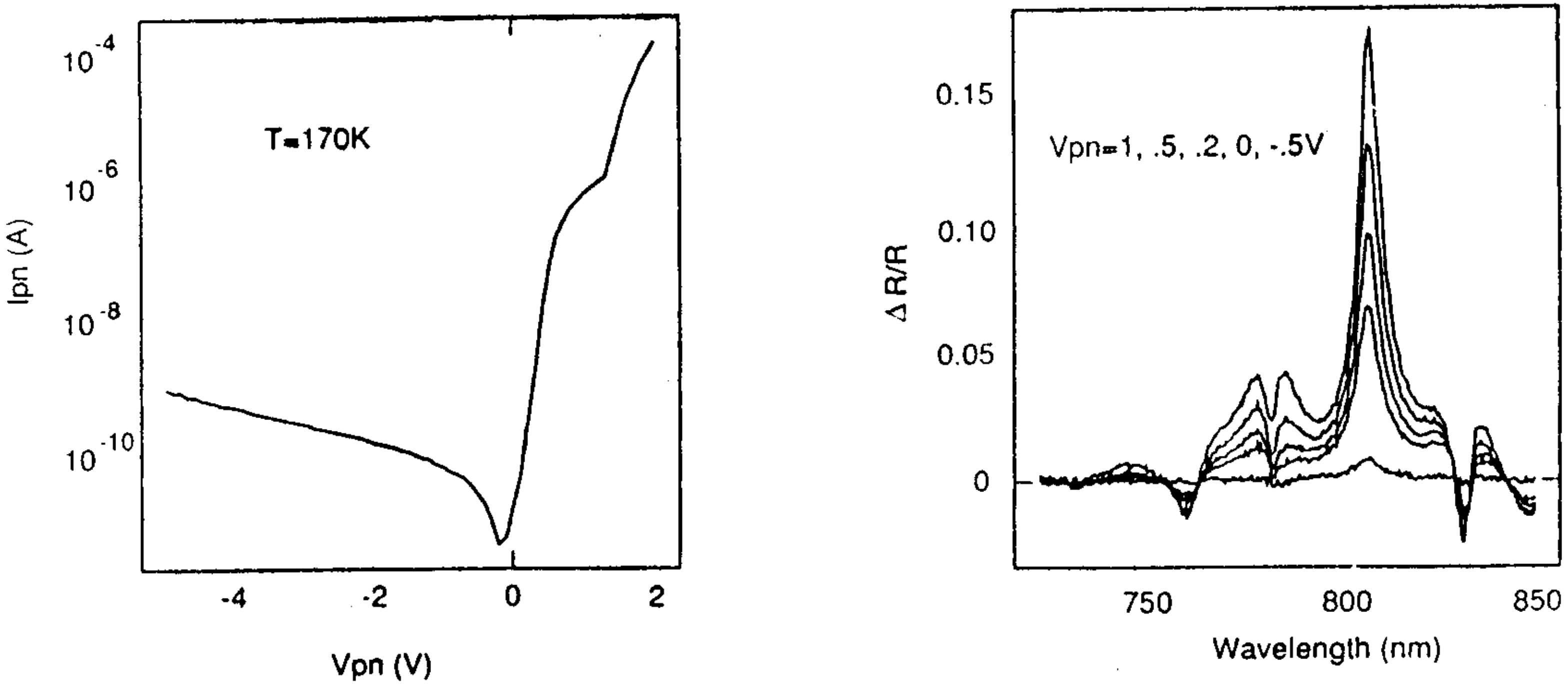
a) structure of the hetero-nipi modulator, a 3D structured crystal.



b) SEM cross section photograph of the hetero-nipi modulator

From:: X Wu et al., Journal of Crystal Growth 127, (1993) 896-899

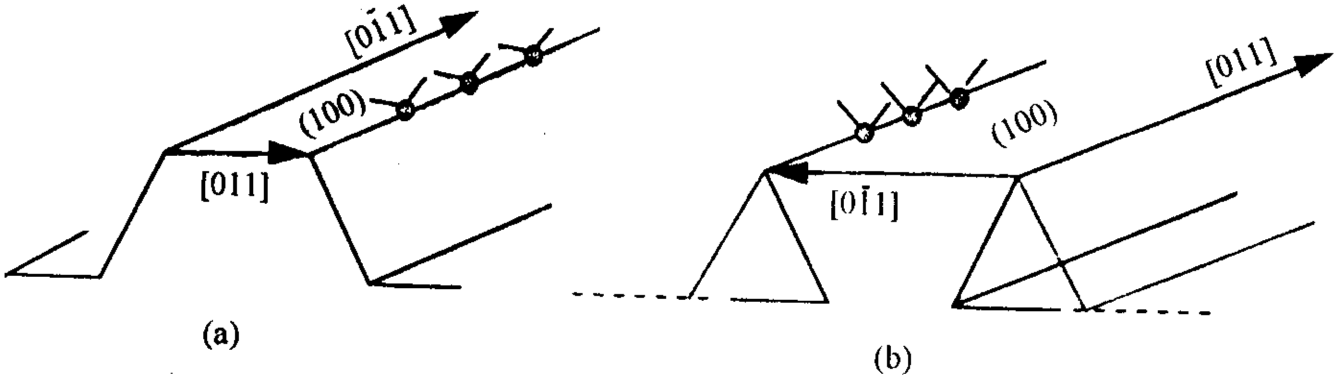
Characteristics of hetero-nipi modulator



I-V characteristics and Relative Reflectance of interdigital hetero-nipi modulator

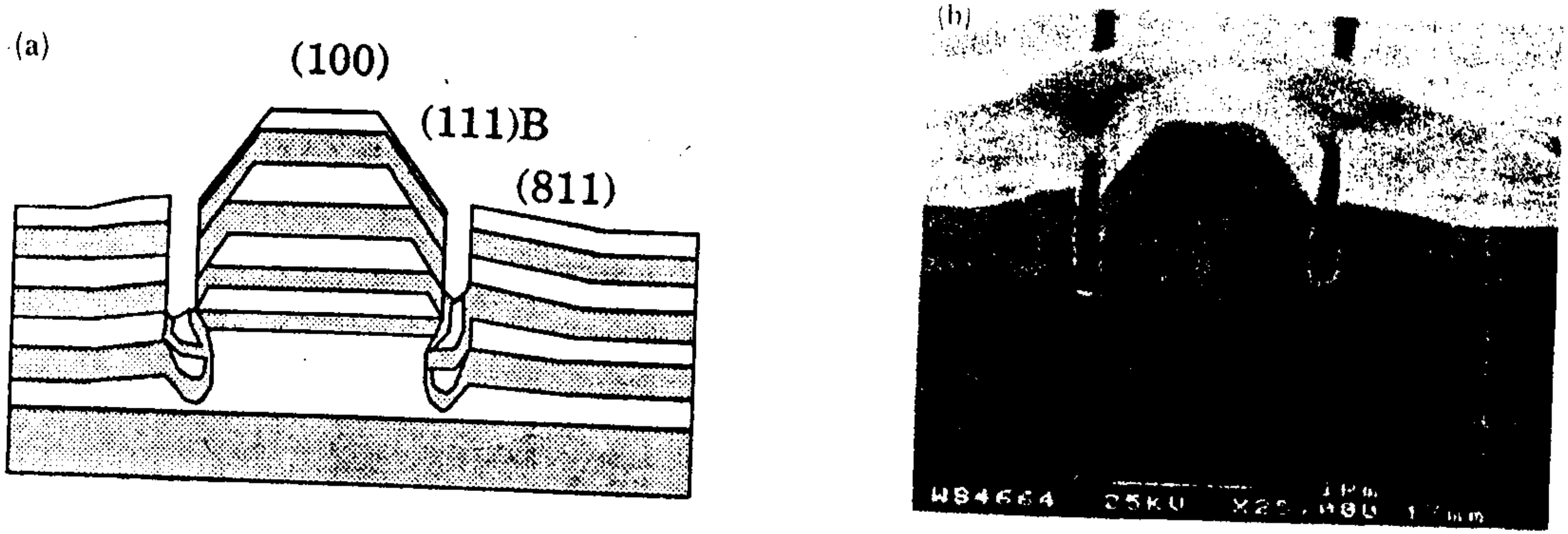
Reference: X Wu et al. Journal of Crystal Growth 127, (1993) 896-9

Selective chemical etching



Schematic drawing of the two most common mesa shapes (———) formed by patterned chemical etching of GaAs (100) using rectangular patterns with pattern edges along [0$\bar{1}$1] and [011]. The relative orientation of the As dangling orbitals and the mesa length direction are also shown. Another possibility is indicated in (b) (———)

MBE regrowth on RIE patterned substrate



Facet formation by MBE growth of 150nm GaAs (bright0 and AlGaAs (dark) layers on a 1.3 μm wide ridge mesa. The ridge was etched in the [011] direction by $SiCl_4$ RIE. Enhanced migration of Ga atoms from (111) planes to (100) planes lead to thicker layers growing on top of the ridge.

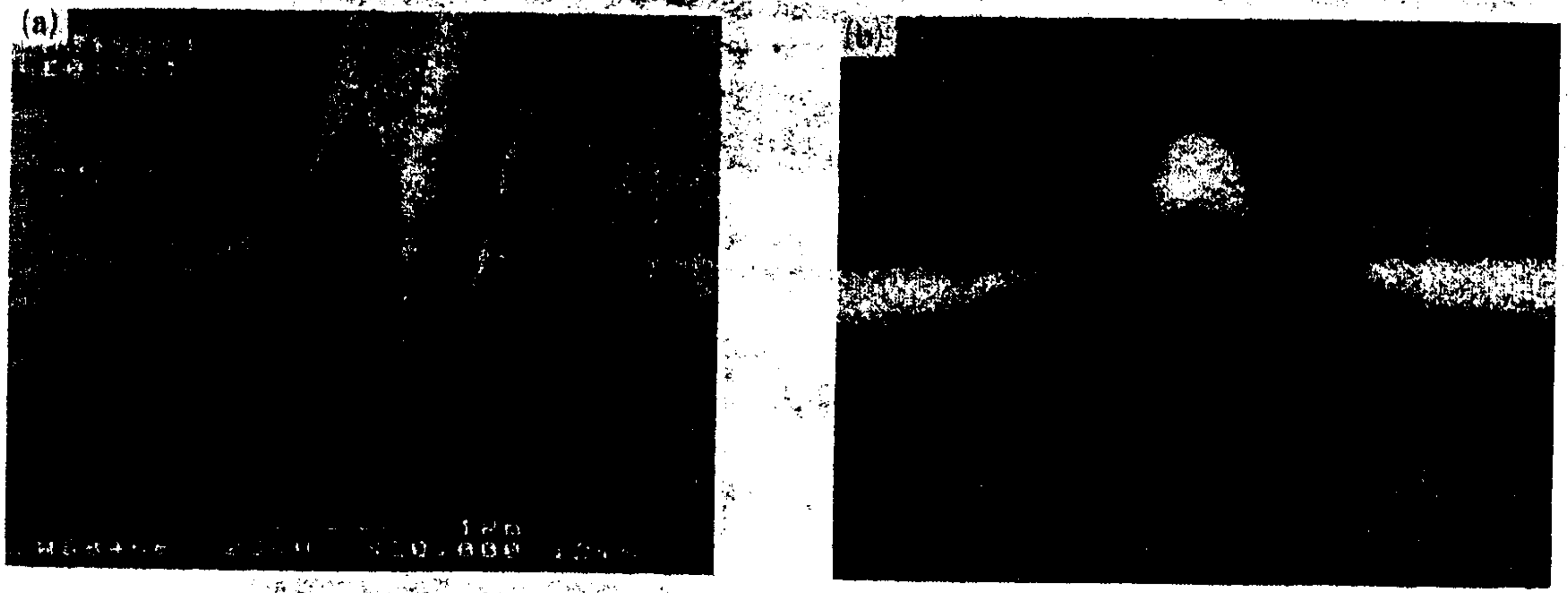
Reference: T Rohr et al Material Science and Engineering, B21 (1993) 153-6

MBE regrowth on RIE patterned substrate

Facet formation by MBE growth of 150nm GaAs (bright0 and AlGaAs (dark) layers on a 0.5μm wide ridge mesa. The ridge was etched in the [011] direction by $SiCl_4$ RIE. Enhanced migration of Ga atoms from (111) planes to (100) planes lead to thicker layers growing on top of the ridge. With decreasing ridge size, the (111) planes restrict the formation of the (100) facets leading to triangular shaped structures.

Reference: T Rohr et al Material Science and Engineering, B21 (1993) 153-6

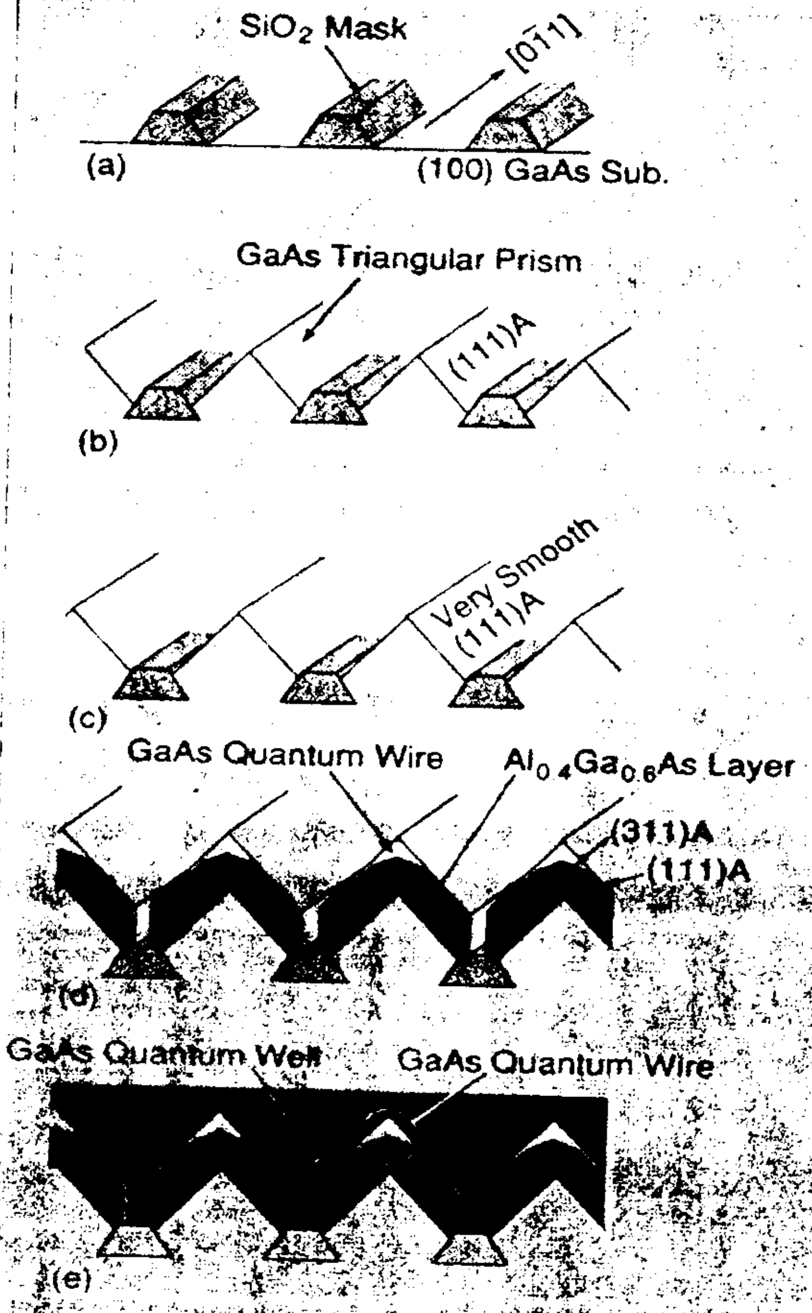
CL image of selectively grown quantum wire



SEM and panchromatic CL image of a 3nm GaAs SQW embedded in 30nm thick $Al_{0.3}Ga_{0.7}As$ barriers and 1.5μm of GaAs. The structure was grown by MBE on a 1 μm wide RIE etched ridge. The CL image was taken at T=85K.

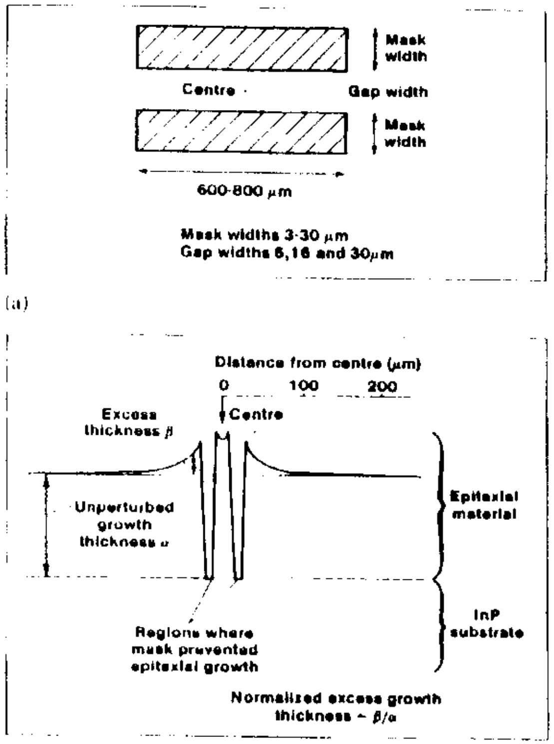
Reference: T Rohr et al Material Science and Engineering, B21 (1993) 153-6

Arrowhead shaped quantum wires

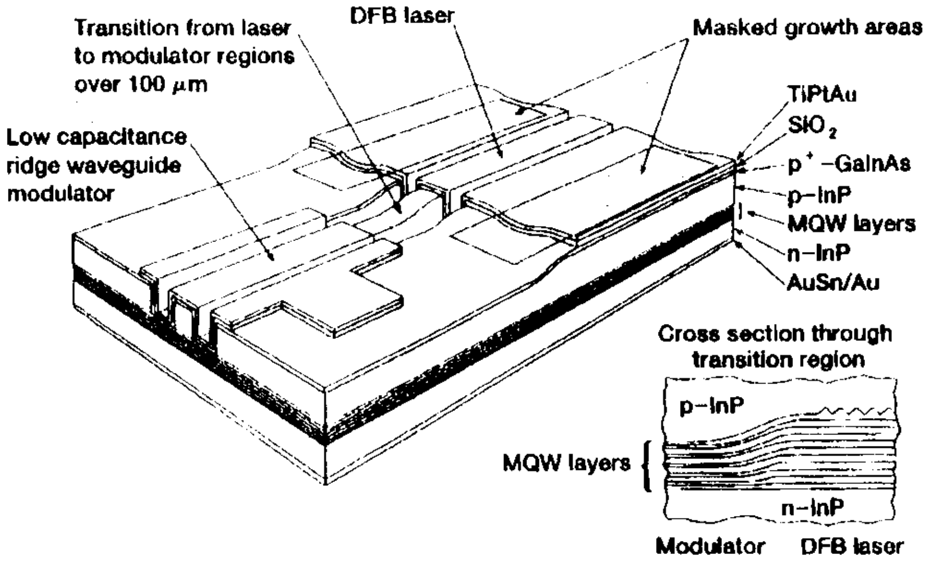


Reference: Tsukamoto et al. Appl. Phys. Lett. 62 (1) 1993, 49-51

Selective non-planar epitaxy of InP/GaInAs(P)



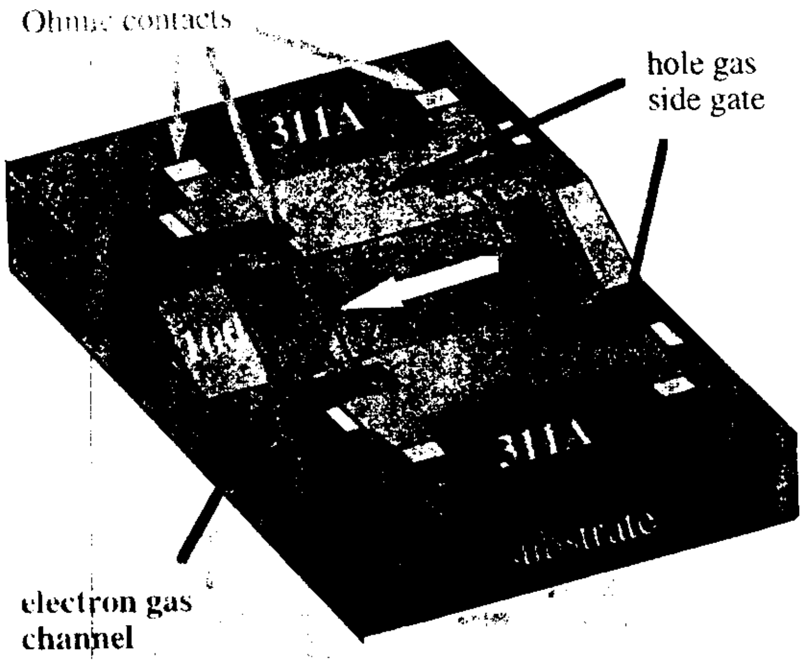
Thickness profile of MOCVD grown selective area epitaxial film.



Integration of laser and modulator utilising variable thickness quantum wells.

Reference: E J Thrush et al. Materials Science and Engineering, B21 (1993) 130-46

Hole-gated 1D electron channel



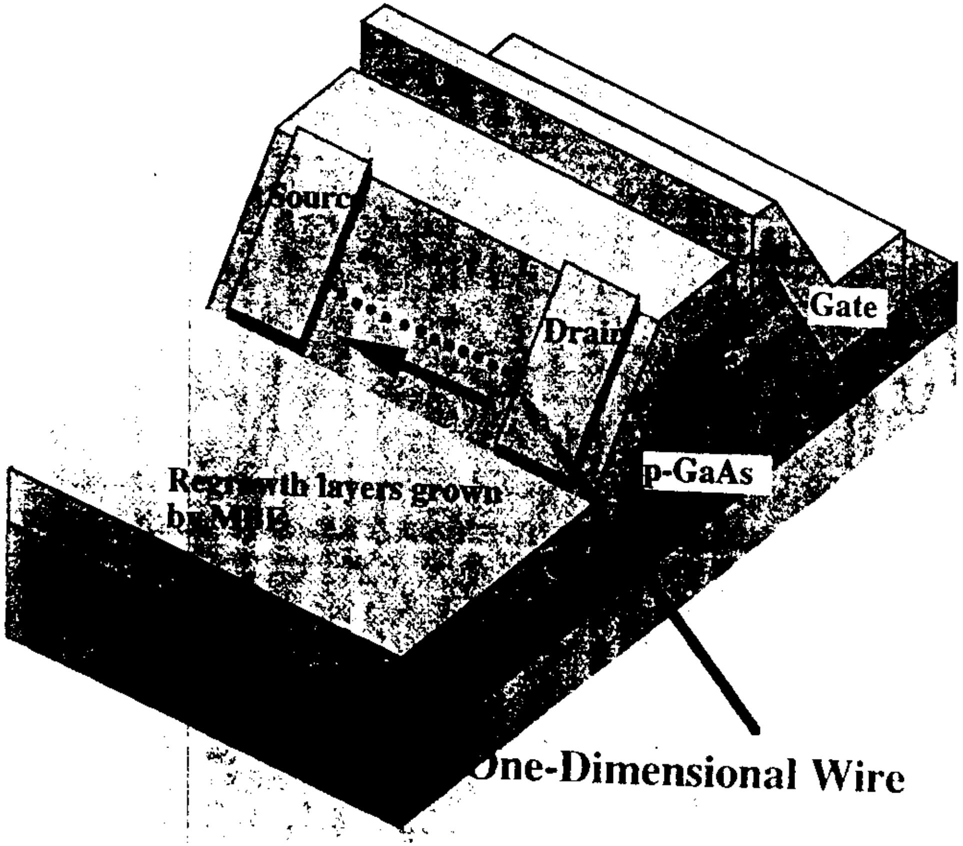
Silicon dopes n type on the 100 facet and p type on the 311A planes.

The hole gases on the 311A planes act as side gate to squeeze the electron channel

Channel widths down to 100 nm have been obtained

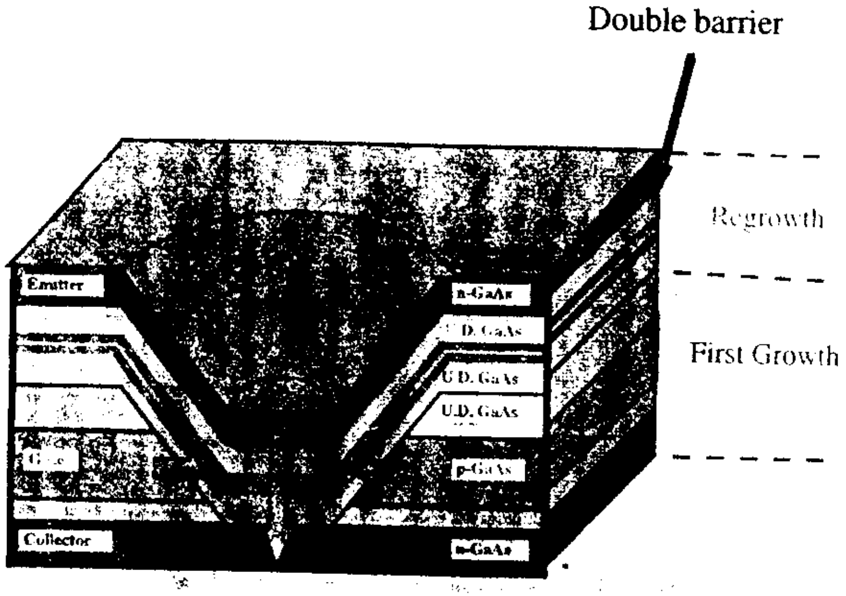
By growing on a (100) wafer patterned with (311)A facets the structure can be inverted to produce a one dimensioanl hole channel

One-Dimensional Wire Transistor



High Mobility 1-Dimensional Wire Transistors have been fabricated using the above technique. The Regrowth technique potentially allows 3-D circuits to be fabricated at wafer level.

Three Terminal Resonant Tunnelling Device



Many applications require three terminal devices. We have achieved this for a resonant tunnelling structure by introducing a side gate using regrowth technology. The collector contact and gate layers are grown first, then a hole is etched down through the gate and finally the double barrier and emitter contact layers are grown on top.

Removal of Surface Contamination

Thermal desorption

Around 400°C : Decomposition of As oxides + desorption of elemental As.

This is followed by desorption of Ga_2O peaking at ~480°C.

Above 500°C: Reaction of Ga_2O_3 like oxides with the GaAs substrate resulting in the formation of Ga_2O + elemental As.

$$Ga_2O_3 + 4GaAs \text{-------->} 3Ga_2O + As_4(2As_2)$$

Diffuse optical reflectivity measurements+ indicate that final stage is accompanied by a roughening of the sample surface.

Hydrogen Radical Cleaning

Hydrogen radicals reduce Ga_2O_3 by one of two possible mechanisms:

$$1)\quad Ga_2O_3 + 4H^* \text{-------->} Ga_2O + 2H_2O$$

or

$$2)\quad 4GaAs + 12H^* \text{-------->} 4Ga + 4AsH_3$$

$$Ga_2O_3 + 4Ga \text{-------->} 3Ga_2O$$

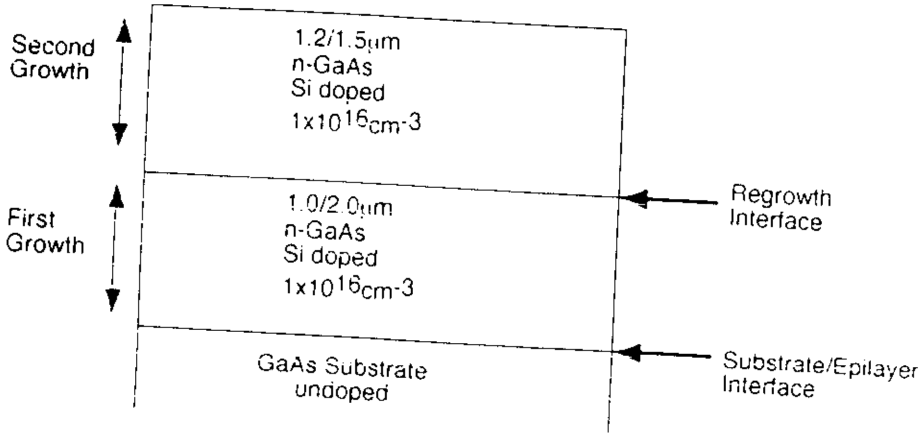
Observation by Asakawa* of increased H_2O pressure during cleaning indicates that 1) is most likely mechanism.

AFM images of ECR plasma hydrogen radical cleaned GaAs surfaces indicate reduction in surface roughening by a factor of 7 relative to thermally cleaned samples.

\+ C. M. Rouleau and R. M. Park, J. Vac. Sci and Tech. A11 (4) 1993 p1792.

* K. Asakawa and H. Iwata, American Vac. Soc. Series 10, Advanced Processing and Characterization Technologies.

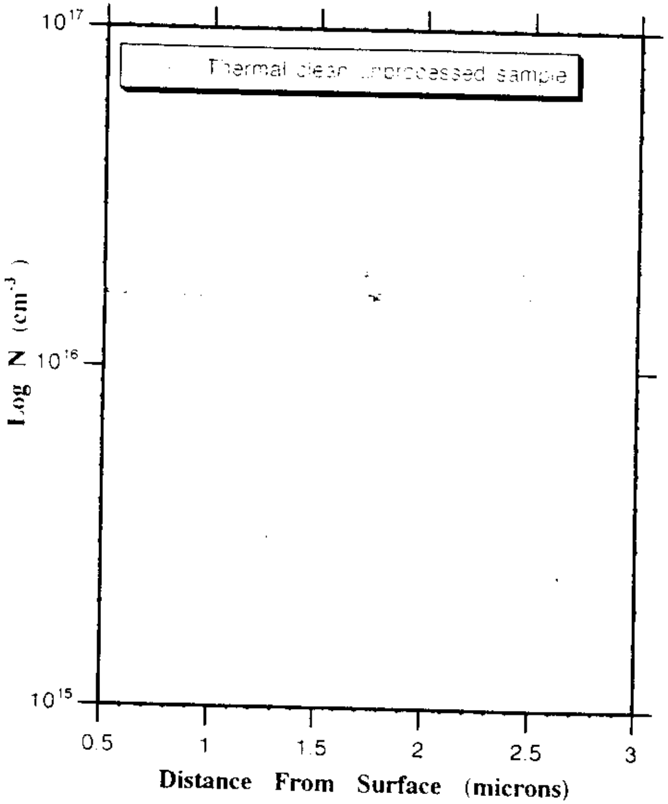
Sample Structure For Regrowth Interface Depletion Mesurements



Wafer removed from MBE system after first growth

One half of wafer patterned, one half air exposed only

Interface Depletion Measurement for Si Doped GaAs After Thermal Clean Of The Regrowth Interface.

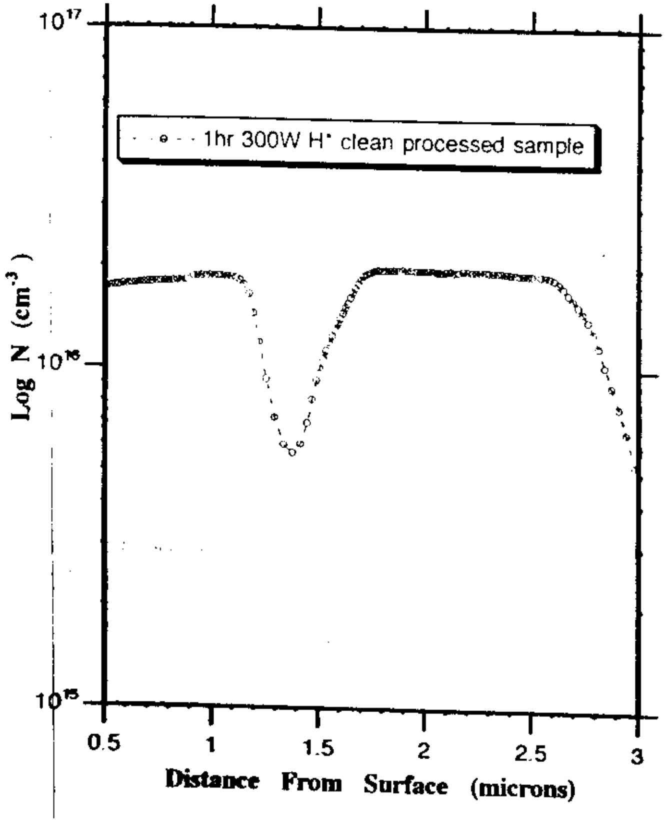


First growth: 2.0um
Second growth:1.5um

Doping: Nominally 1e16cm^{-3}

Interface state density:
5.34e12 cm

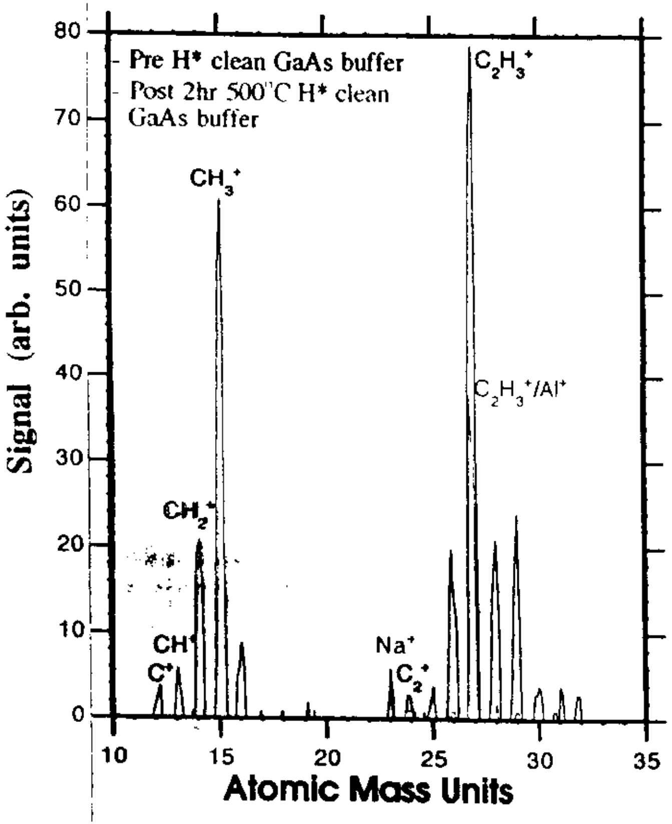
Interface Depletion Measurement for Si Doped GaAs After Hydrogen Radical Cleaning Of The Regrowth Interface.



First growth: 2.0um
Second growth:1.5um
Doping: Nominally 1e16cm^{-3}

Interface state density:
$4.34 \times 10^{11} cm^{-2}$

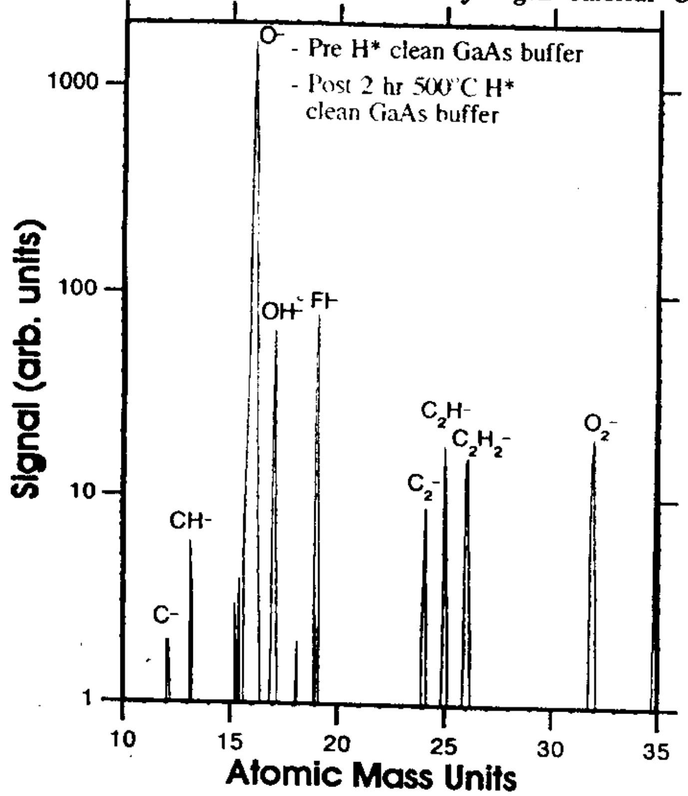
Surface SIMS Scans For GaAs Buffer C1023 Showing Significant Reduction In Hydrocarbon Contamination After Hydrogen Radical Cleaning.



Cleaning parameters:

Temp: 500°C
Time: 2 hrs
R.f. power: 300W

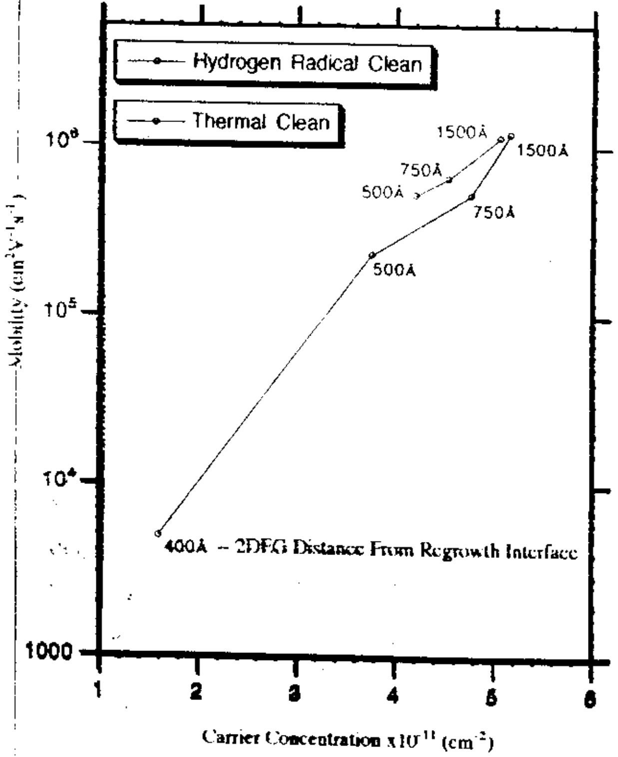
SIMS Scans For GaAs Buffer C1023 Showing Fall in Surface Oxide Levels After Hydrogen Radical Cleaning.



Sample Parameters:
Distance from regrowth interface to 2DEG: 500Å

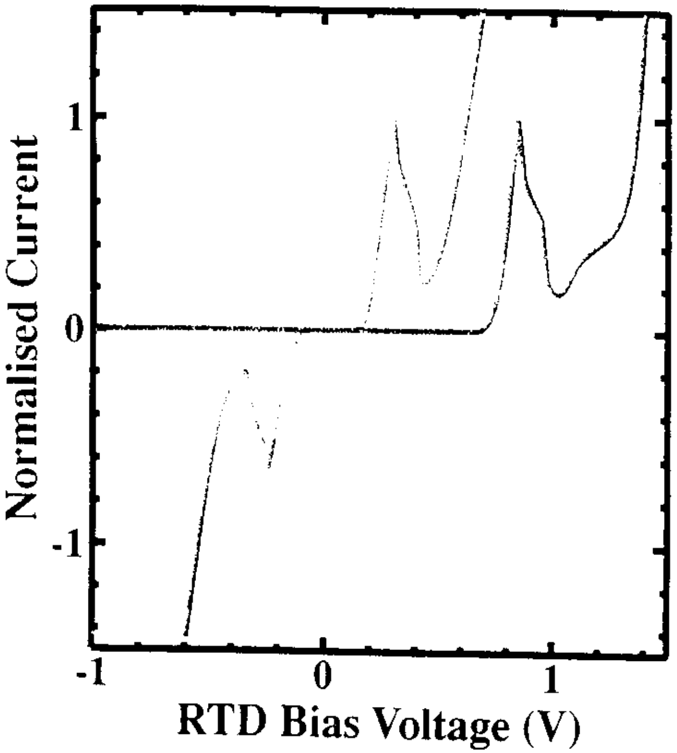
	Dark	Light
Carrier conc. (cm^{-2})	1.18e11	4.2e11
Mobility ($cm^2V^{-1}s^{-1}$)	1.6e4	5.2e5

Variation In 2DEG Mobility and Carrier Concentration With Distance From Regrowth Interface For Thermally and Hydrogen Cleaned Samples After Illumination.



- Fall in measured carrier concentration and mobility after illumination occurs for 2DEG/regrowth interface separations less than 1500Å.
- Thermally cleaned samples do not work in the dark even at 1500Å separation. Hydrogen cleaned sample with 2DEG/regrowth interface separation of 500Å found to work in the dark.

Current-Voltage Characteristics For 2 µm Diameter Regrown Resonant Tunnelling Diode With (Green) and Without (Red) Hydrogen Radical Cleaning of The Regrowth Interface.



Forward bias peak position for diode exposed to hydrogen is identical to that measured for control diodes with no regrowth interface (0.3V). A peak is also observed in reverse bias for this diode.

Summary

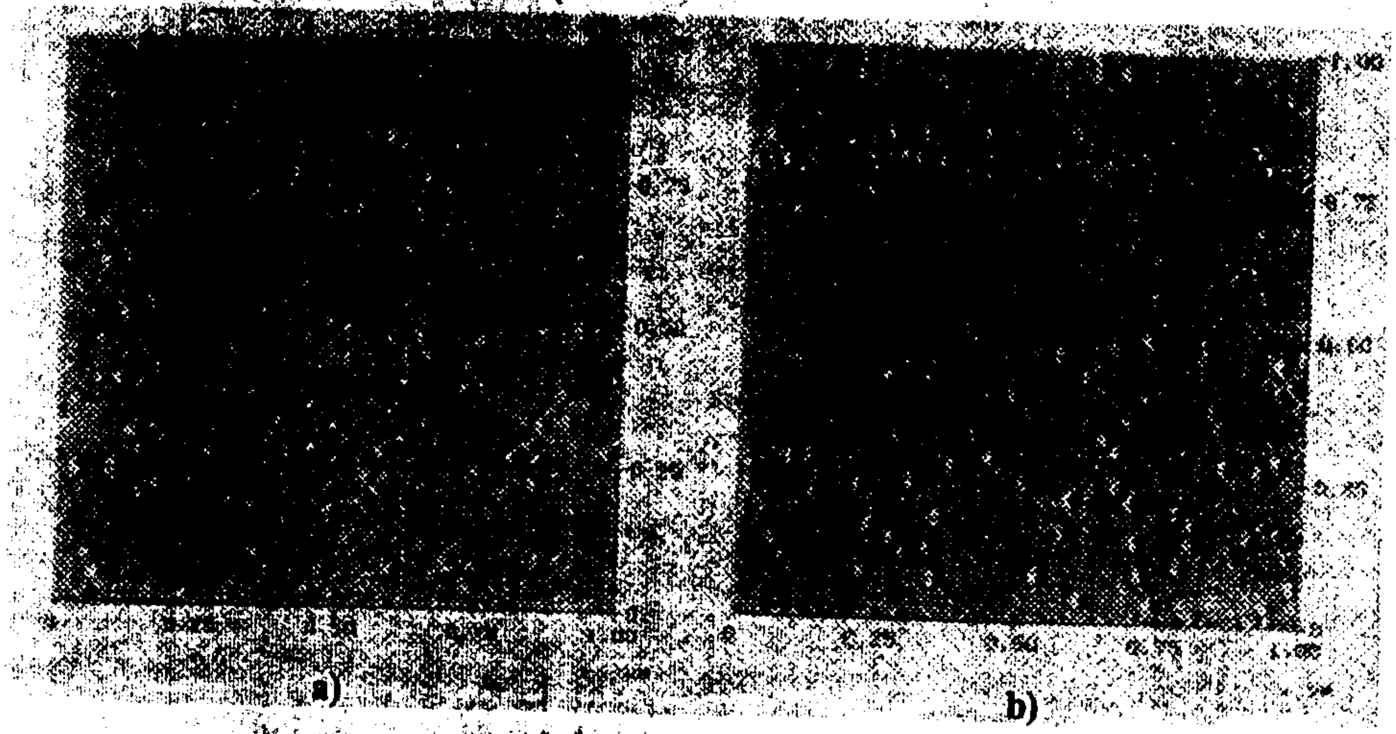
Hydrogen radical cleaning at 500°C has been used to reduce the surface oxide levels on GaAs by more than 3 orders of magnitude and significantly reduce hydrocarbon contamination levels prior to regrowth.

Variation in 2DEG mobility and carrier concentration as a function of distance from the regrowth interface has been measured for both hydrogen radical and thermally cleaned samples.

Hydrogen surface cleaning of the regrowth interface has allowed for the growth of a 2DEG 500Å from the interface with a mobility after illumination of 5.26×10^5cm^{2}V^{-1}s^{-1} at a carrier concentration of 4.20×10^{11}cm^{-2}. This sample was also found to work in the dark.

Successful production of some novel device structures by MBE regrowth on patterned GaAs wafers following hydrogen radical cleaning of the regrowth interface.

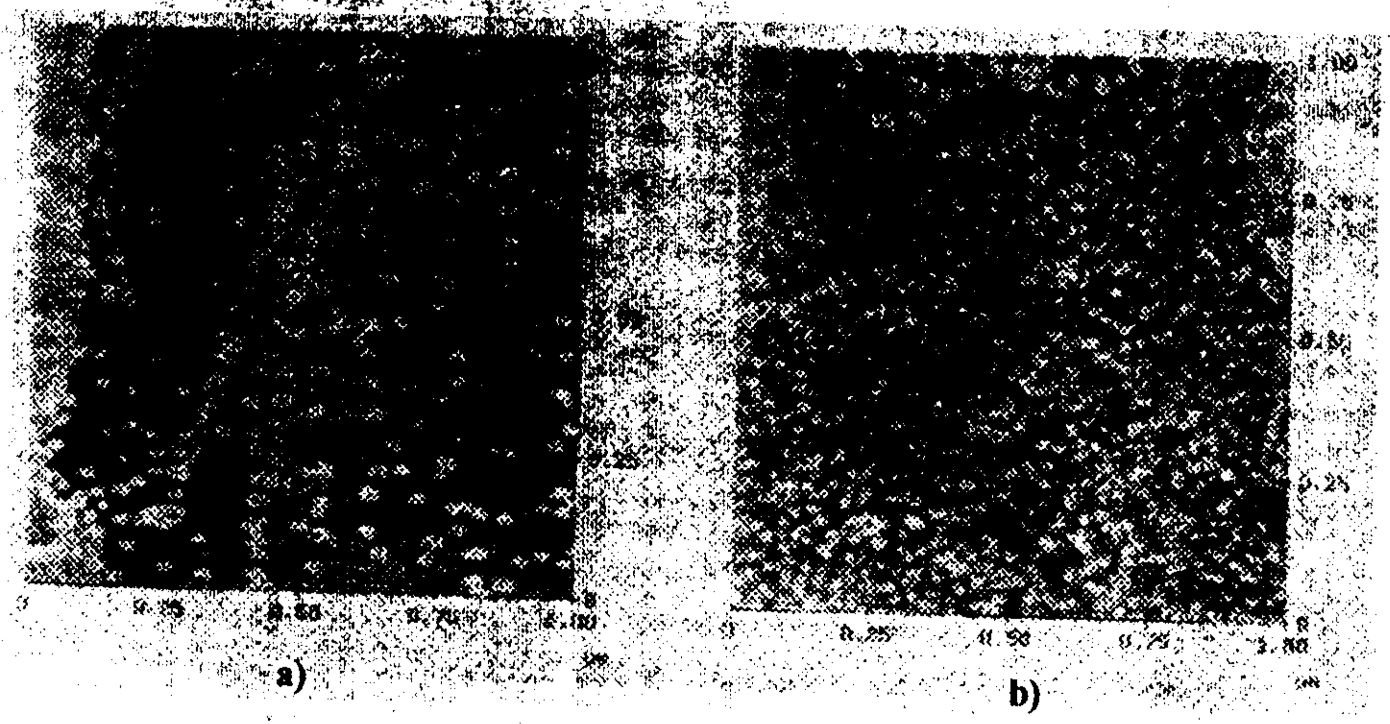
Self organised InAs quantum dots



The surface morphologies of 2.5ML of InAs grown at 500°C by MBE, a) without atomic-H irradiation and b) with atomic H irradiation. The scanned area is 1μm x 1μm.

Reference: Y J Chun et al. Proc. "New phenomena in Mesoscopic Structures" Hawaii, 1995

Self organised $In_{0.8}Ga_{0.2}As$ quantum dots

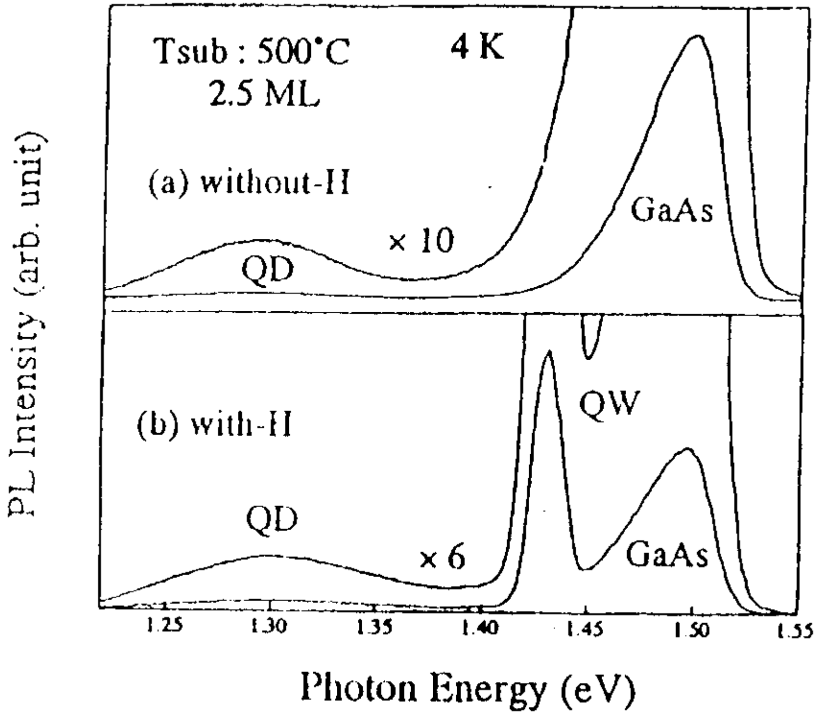


a) b)

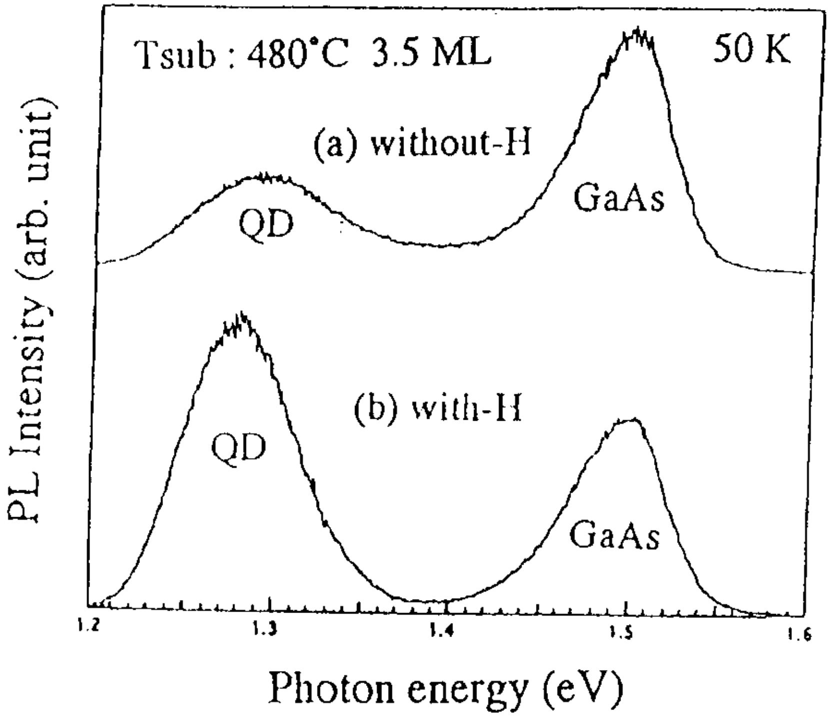
The surface morphologies of 3.5ML of $In_{0.8}Ga_{0.2}As$ grown at 480°C by MBE, a) without atomic-H irradiation and b) with atomic H irradiation. The dot sizes are 40nm and 20nm respectively.

Reference: Y J Chun et al. Proc. "New phenomena in Mesoscopic Structures" Hawaii, 1995

PL spectra of self organised InAs,InGaAs quantum dots



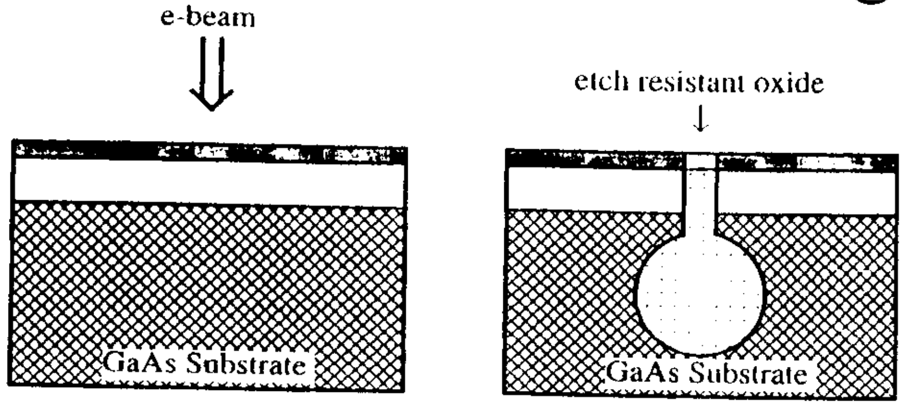
4K PL spectra of 2.5ML InAs film with and without atomic-H irradiation. Peak at 1.30eV



50K PL spectra of 3.5ML $In_{0.8}Ga_{0.2}As$ film with and without atomic-H irradiation.

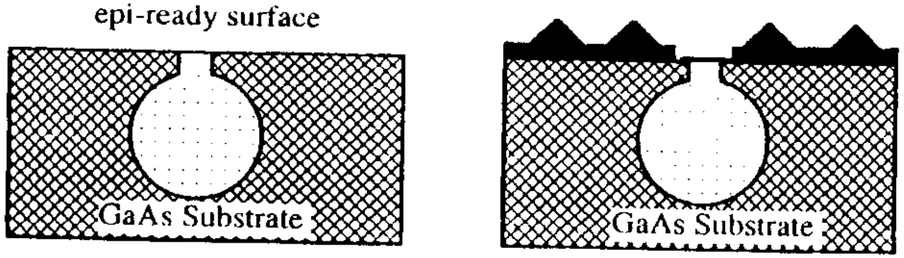
Reference: Y J Chun et al. Proc. "New phenomena in Mesoscopic Structures" Hawaii, 1995

Selective nucleation of InAs using e-beams



(a) e-beam exposure

(b) post-exposure



(c) pre-growth

(d) post-growth

▨ Native Oxide (≤10 nm)

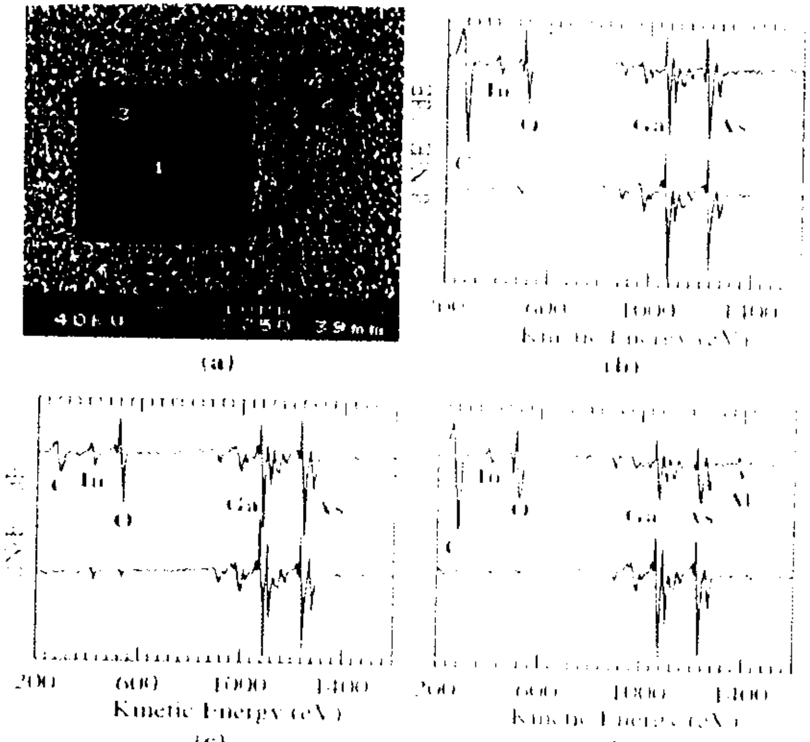
☐ E-Beam Irradiated Region (5 μm diameter)

☐ $Al_{0.6}Ga_{0.4}As$ (6-100 nm)

■ InAs (10-200 nm)

Reference: J W Sleight et al Appl. Phys. Lett. 66 (11), March 1995, 1343-5

Selective nucleation of InAs on GaAs



before

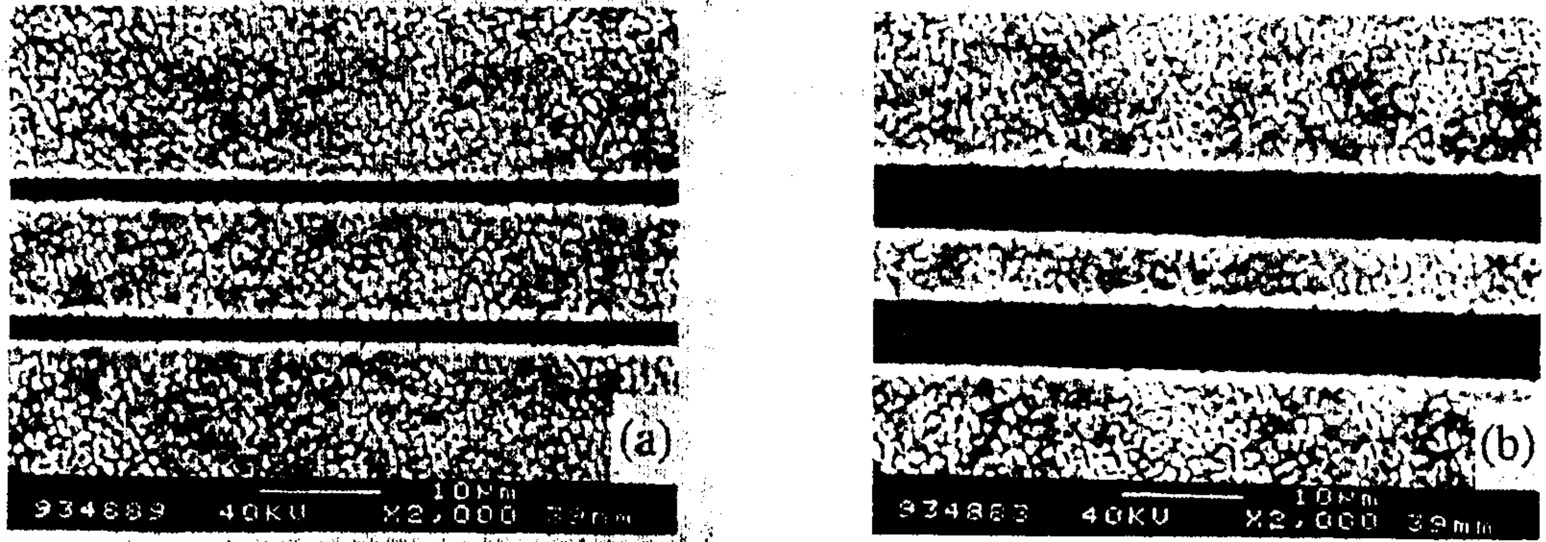
after

(a) (b) (c) (d)

SEM image of selective nucleation of 10nm of InAs on GaAs. Auger spectra a), b) and c) are taken from points 1,2 and 3, before and after argon ion sputtering to a depth of 2nm.

Reference: J W Sleight et al Appl. Phys. Lett. 66 (11), March 1995, 1343-5

Selective nucleation of InAs on GaAs



Scanning electron micrograph image of 200nm deep trenches defined by e-beam lithography and post InAs growth (T_s=600°C, R_d=0.15nm.s^{-1}). The e-beam patterns consist of 1µm wide lines on 10µm centres written with an integrated charge density of 20C.cm^{-2} and 30C.cm^{-2}.

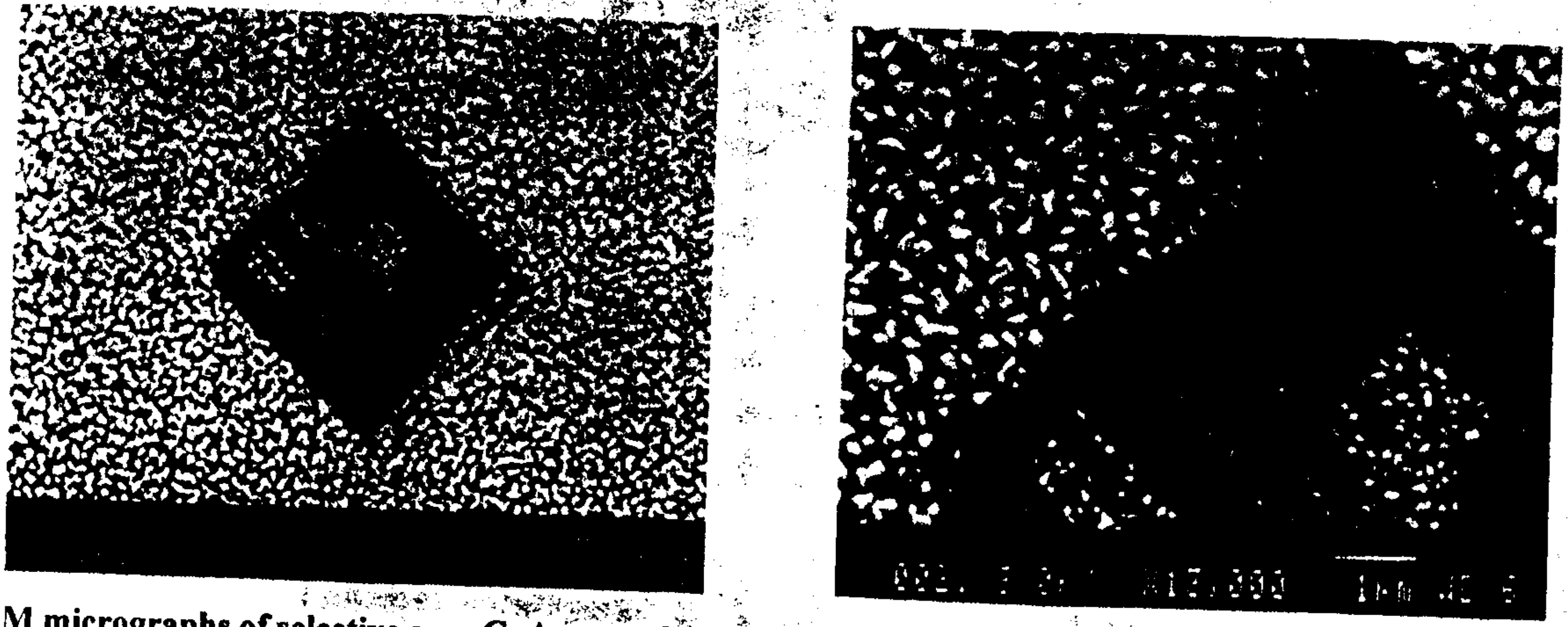
Reference: J W Sleight et al Appl. Phys. Lett. 66 (11), March 1995, 1343-5

Selective nucleation of InAs on GaAs

SEM images of 2D arrays of InAs clusters grown on GaAs. The clusters nucleate in the regions of the substrate not exposed to the e-beam. The substrate temperature was 650°C for a) and 550°C for b). The growth rate was 0.15nm.s^{-1} for both.

Reference: J W Sleight et al Appl. Phys. Lett. 66 (11), March 1995, 1343-5

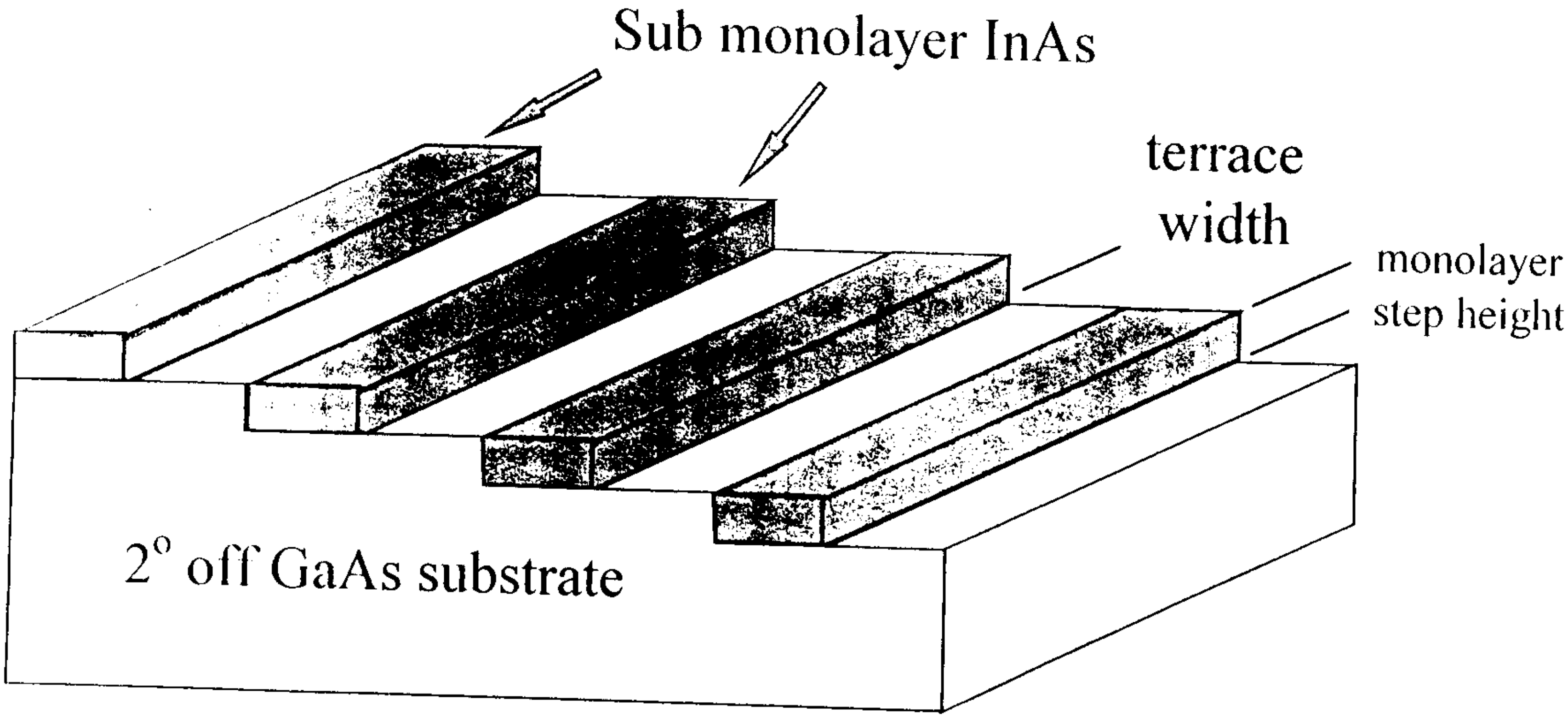
Selective area growth of GaAs on hydrogenated *n*-Si(100) using STM oxide patterning



SEM micrographs of selective area GaAs growth on an *n*-Si(100) substrate patterned using an STM operating in air. The patterned regions consist of four 2 μm squares patterned within a 7.3μm square previously exposed with a tip bias voltage of +1.7V. Three of the regions are written with a tip bias of +4V and the fourth at +2V.

Reference: Dagata et al. Appl. Phys. Lett. 57 (23) 1990 2437-9

Growth on mis-orientated substrates



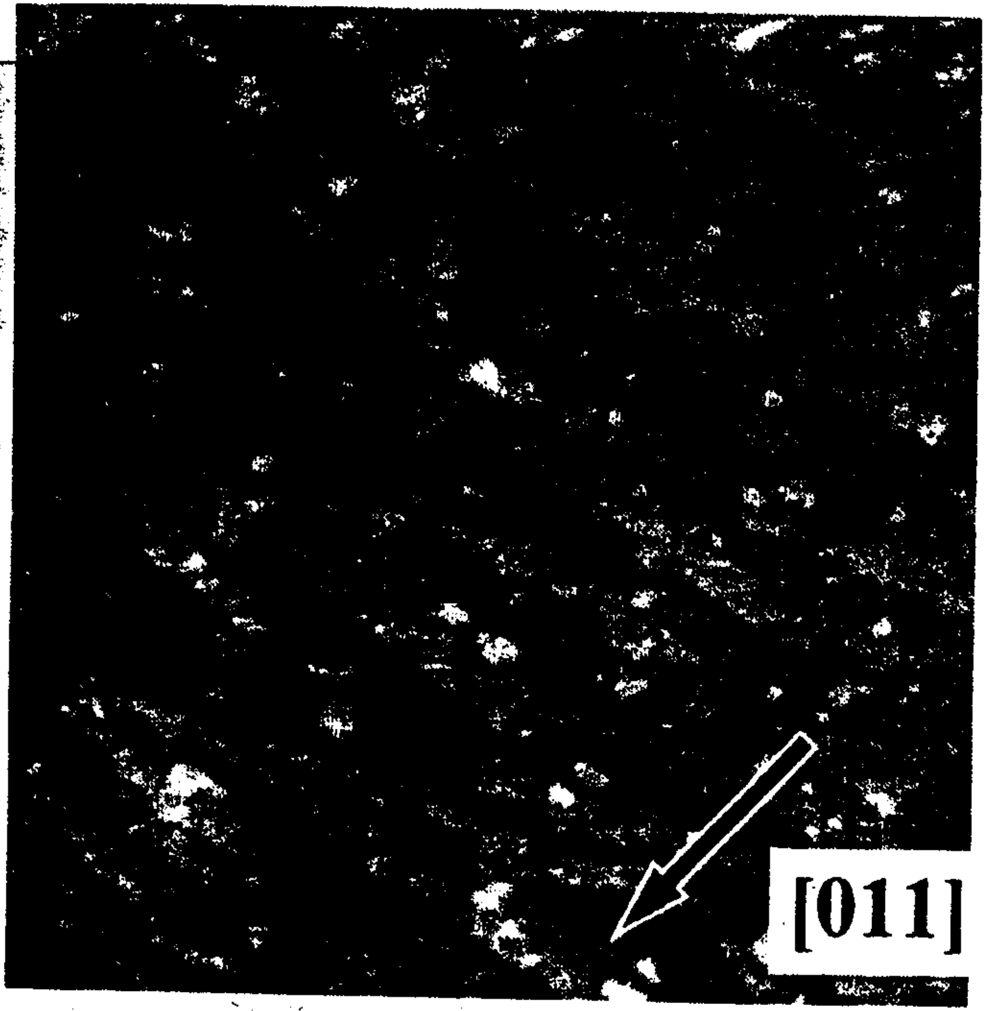
Sub monolayer InAs

terrace
width

monolayer
step height

2° off GaAs substrate

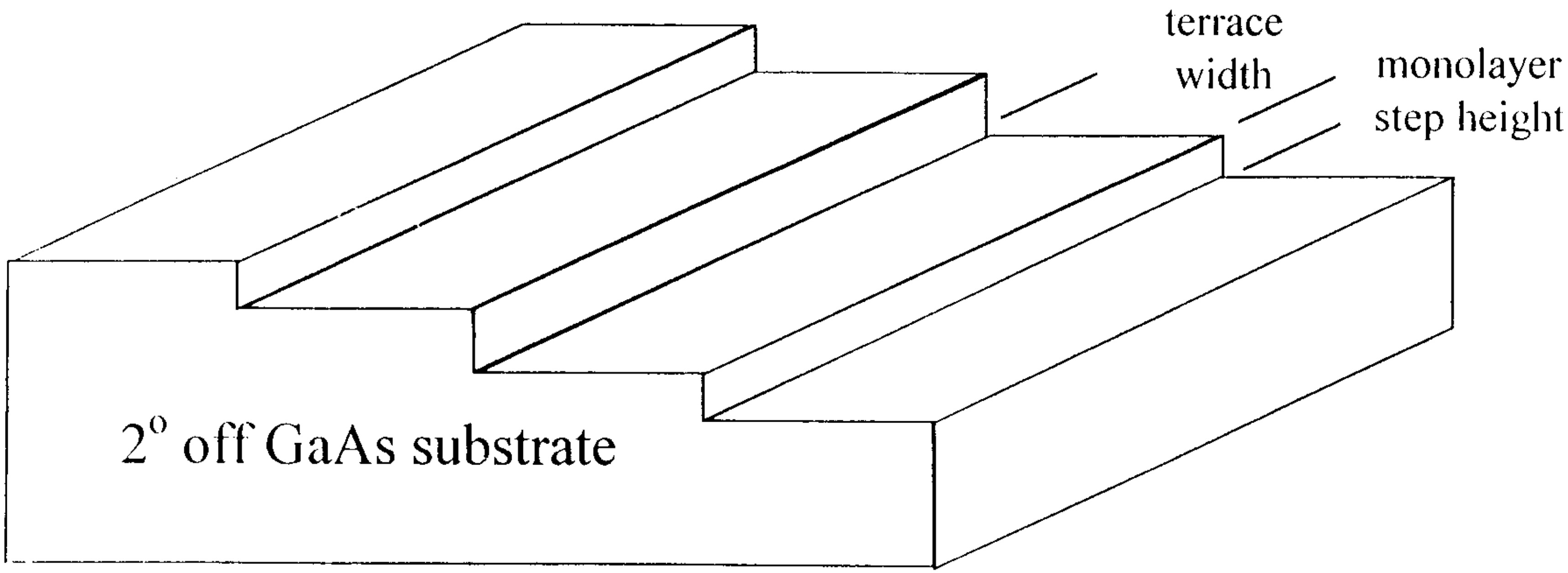
GaAs(100) 1°



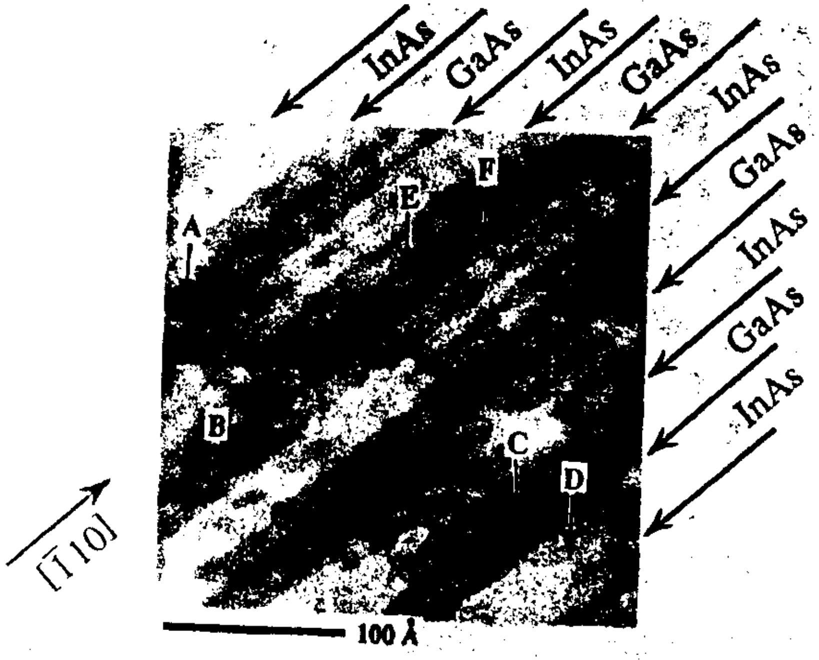
Mean terrace width: 8 nm

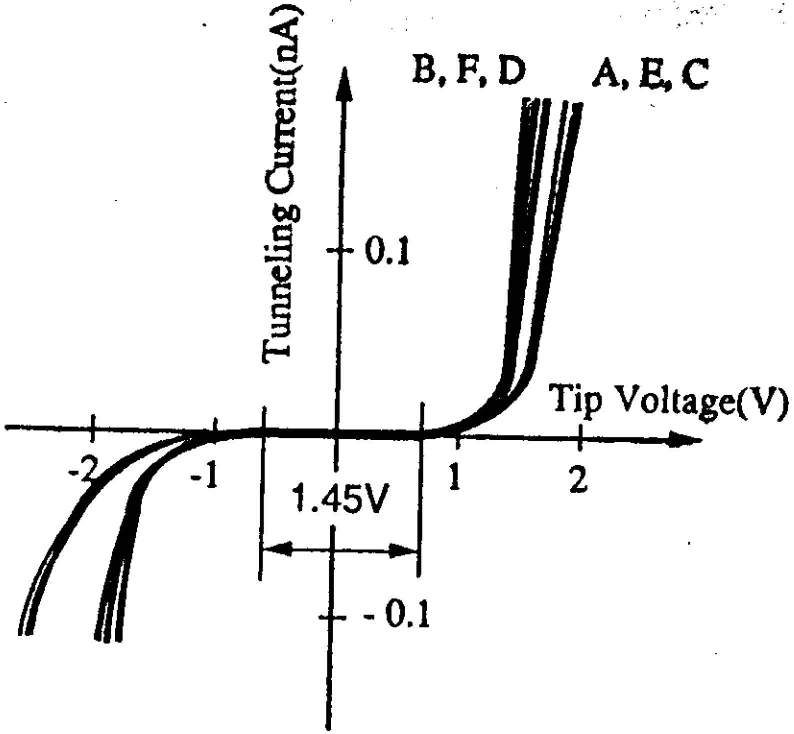
Scan Area: 100 nm x 100 nm

Growth on mis-orientated substrates



InAs wires grown by Gas Source MEE on a 2^0 misorientated GaAs(100) surface





From: J H Noh et al, JJAP Lett.