Molecular Beam Epitaxy

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Tutorial Session #1—Epitaxial Growth

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Molecular Beam Epitaxy (MBE)

Technique to grow crystalline thin films in ultrahigh vacuum (UHV) with precise control of thickness, composition and morphology

Why important for ICPS participants?

- 1984 — ICPS-17 San Francisco, CA (USA)
  350 papers, 1050 participants
  33% of the papers on MBE grown heterostructures and SL
- 1986 — ICPS-18 Stockholm (Sweden)
  420 papers, 850 participants
  35% of the papers on MBE grown heterostructures and SL
- 1988 — ICPS-19 Warsaw (Poland)
  440 papers, 870 participants
  40% of the papers on MBE grown Heterostructures and SL
- 1990 — ICPS-20 Thessaloniki (Greece)
  630 papers, 1000 participants
  45% of the papers on MBE grown heterostructures and SL
- 1992 — ICPS-21 Beijing (China)
  450 papers, ~ 800 participants
  50% of the papers on MBE grown heterostructures and SL

Why has MBE attracted so much attention?

MBE provides unique capability to study crystal growth in real-time and on a subnanometer scale

- Reflection high-energy electron diffraction (RHEED)
- In-situ X-ray diffraction (XRD)
- Reflectance difference spectroscopy (RDS)
- Scanning tunneling and atomic force microscopy (STM, AFM)

Growth of artificially layered crystals of various complexity with high degree of control and reproducibility

- In „low-dimensional structures“ the experimental physics based on quantum phenomena in brought to classroom
- Improved performance and new functionalities in heterojunction devices
- Materials engineering at the atomic level despite lattice mismatch, chemical incompatibility, structural dissimilarity and / or differences in thermal expansion

...IT ALL BEGAN WITH..

W. Shockley
"Transistor electronics"
Proc. IRE 40, 1289 (1952)

H. Kroemer
"Wide-gap emitter for transistors"
Proc. IRE 45, 1535 (1957)

H. Kroemer
"Heterojunction injection lasers"
Proc. IRE 51, 1782 (1963)

BAND-GAP ENGINEERING
(WAVE FUNCTION ENGINEERING)

K. G. Günther
"Three-temperature method"
Z. Naturforschg. 13a, 1081 (1958)

J. R. Arthur
"Interaction of Ga and As_2 molecular beams with GaAs surfaces"
J. Appl. Phys. 39, 4032 (1968)

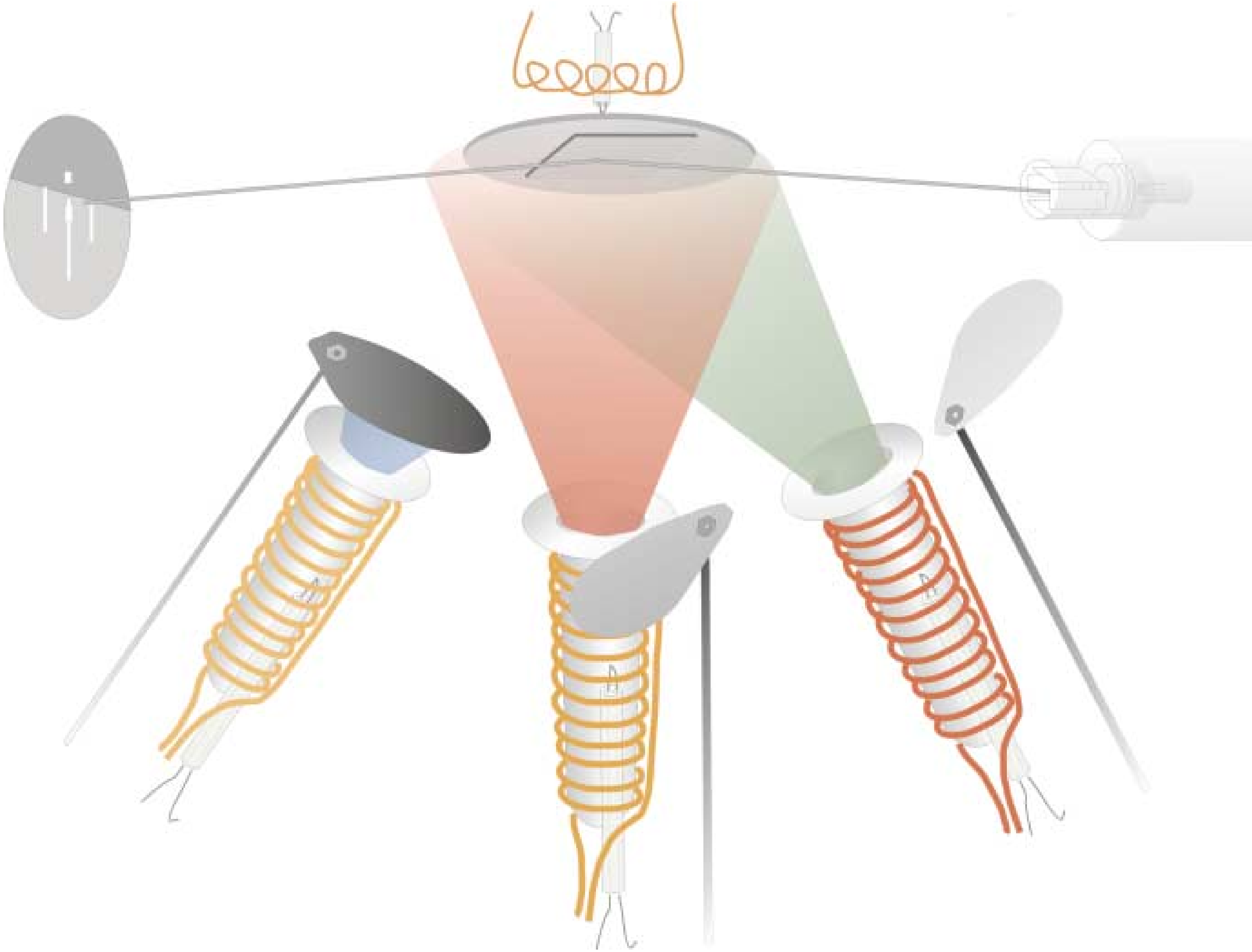
A. Y. Cho
"Epitaxial growth of GaAs by molecular beam epitaxy"
J. Appl. Phys. 41, 2780 (1970)

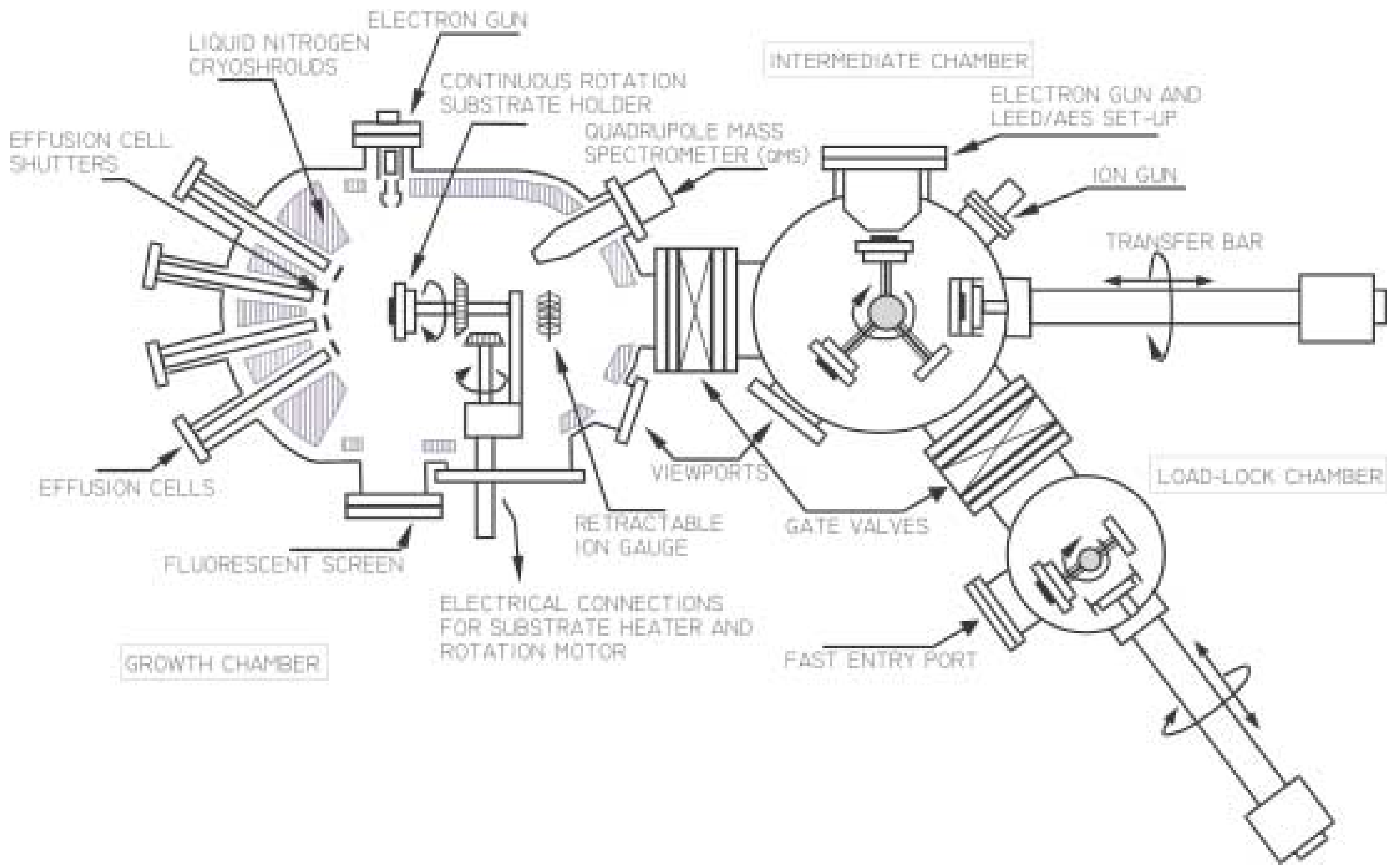
SUBNANOMETER (ATOMIC)
CONTROL OF CRYSTAL GROWTH

L. V. Keldish
"Artificial periodic potential through ultrasonic-wave deformation"
Fiz. Tverd. Tela 4, 2265 (1962)

L. Esaki and R. Tsu
"Artificial semiconductor superlattices"
IBM J. Res. Develop. 14, 61 (1970)

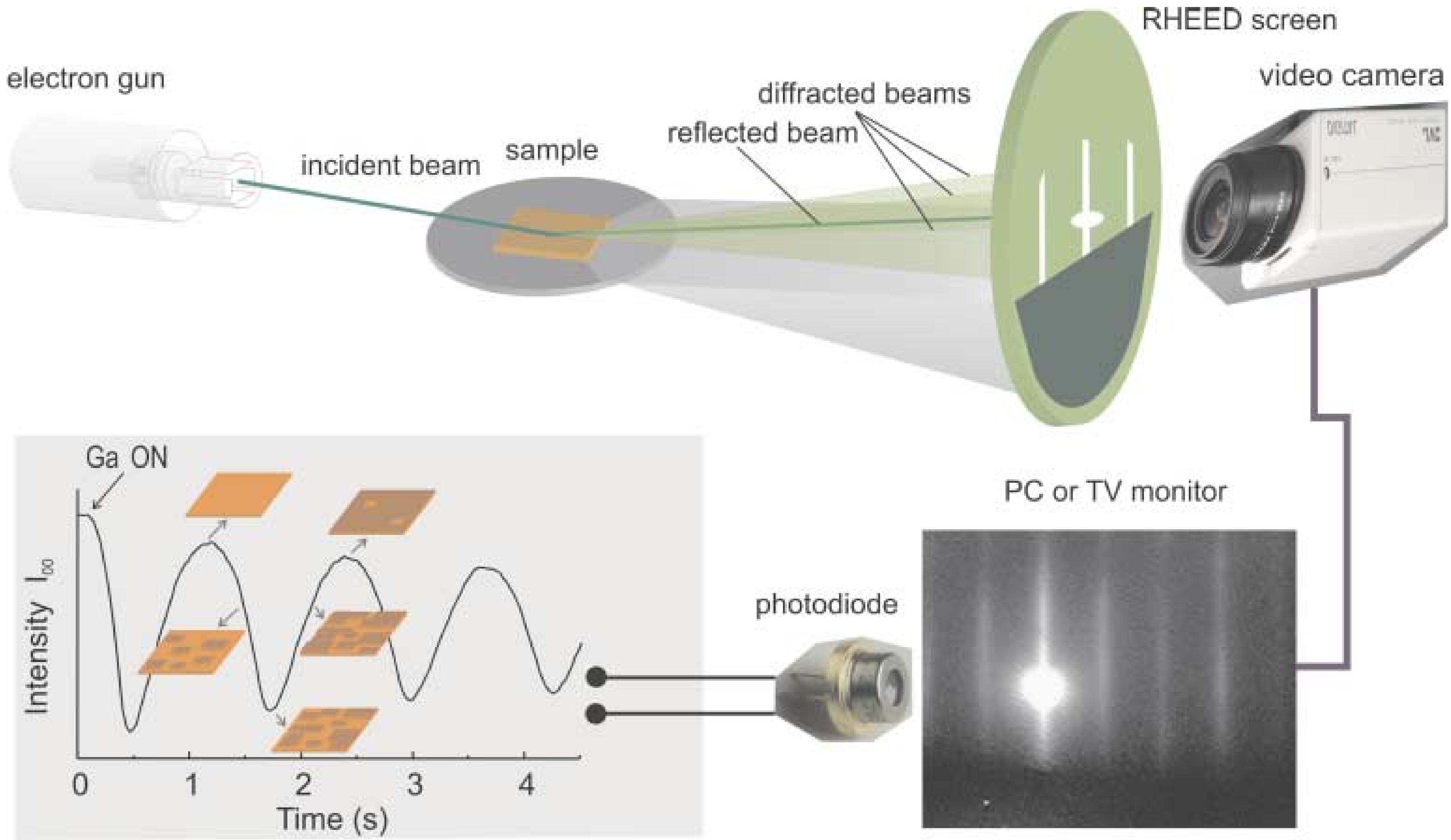
ARTIFICIAL (MAN-MADE) MATERIALS
VERTICAL TRANSPORT (TUNNELING)
-------> BLOCH OSCILLATOR
-------> QUANTUM CASCADE LASER




ELECTRON GUN
LIQUID NITROGEN CRYOSHROUDS
CONTINUOUS ROTATION SUBSTRATE HOLDER
INTERMEDIATE CHAMBER
ELECTRON GUN AND LEED/AES SET-UP
QUADRUPOLE MASS SPECTROMETER (QMS)
EFFUSION CELL SHUTTERS
ION GUN
TRANSFER BAR
EFFUSION CELLS
VIEWPORTS
LOAD-LOCK CHAMBER
RETRACTABLE ION GAUGE
GATE VALVES
FLUORESCENT SCREEN
ELECTRICAL CONNECTIONS FOR SUBSTRATE HEATER AND ROTATION MOTOR
FAST ENTRY PORT
GROWTH CHAMBER

Characteristics of Molecular Beam Epitaxy

- Low growth rate of ~ 1 monolayer (lattice plane) per sec
- Low growth temperature (~ 550°C for GaAs)
- Smooth growth surface with steps of atomic height and large flat terraces
- Precise control of surface composition and morphology
- Abrupt variation of chemical composition at interfaces
- In-situ control of crystal growth at the atomic level



electron gun
incident beam
sample
reflected beam
diffracted beams
RHEED screen
video camera
Ga ON
Intensity I_{00}
0
1
2
3
4
Time (s)
photodiode
PC or TV monitor

Early Model for MBE Growth of III-V Semiconductors

- Thermal-energy neutral beams of constituent elements (atoms or molecules) arrive at heated substrate surface and make up the single-crystal film

- Growth rate and alloy composition determined by flux of group III elements arriving at the growth surface

- Stoichiometry secured by excess group V flux impinging on the growth surface

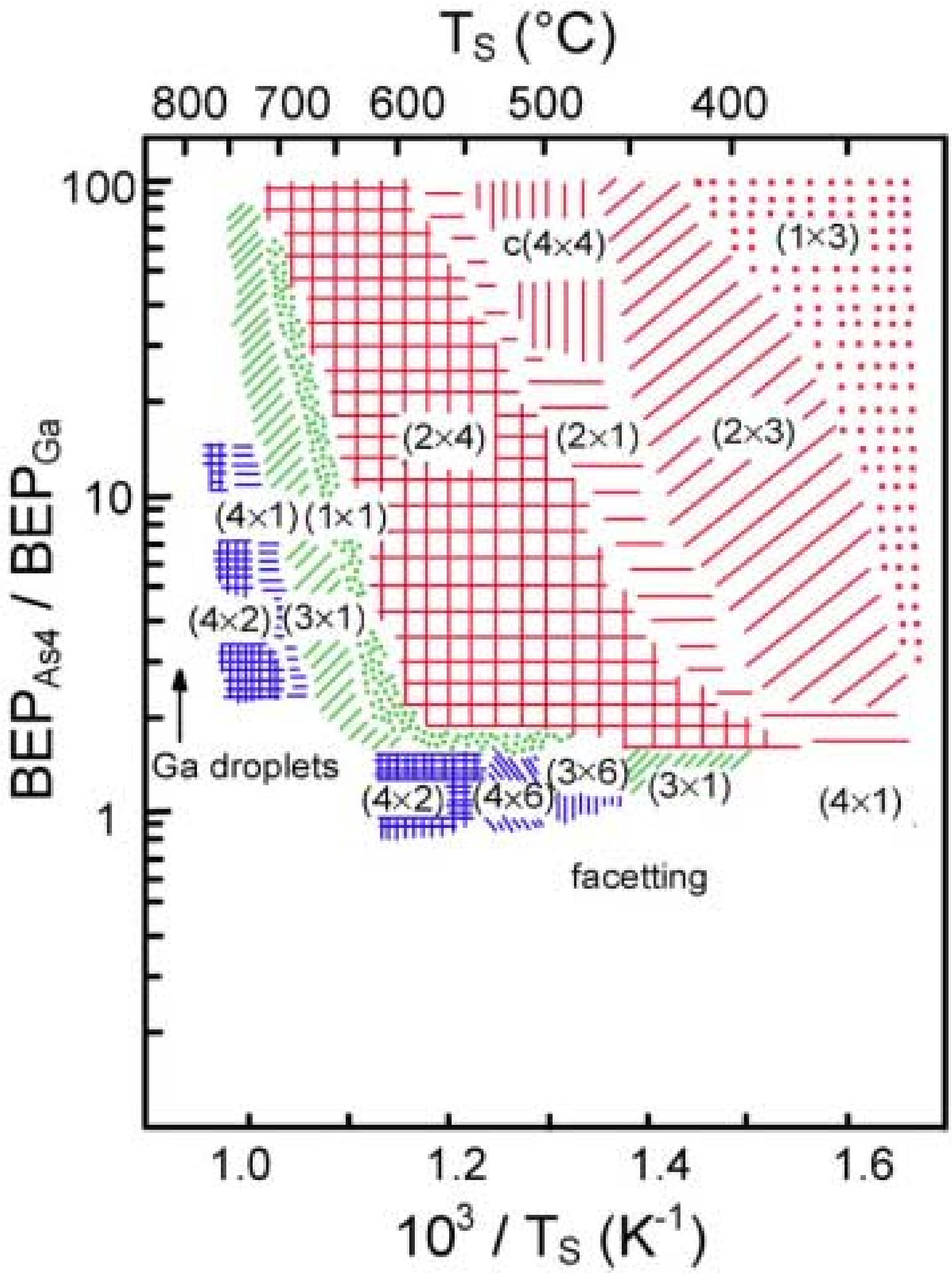
- Group V rich surfaces provide stable growth conditions

  ⇨ Layer-by-layer growth

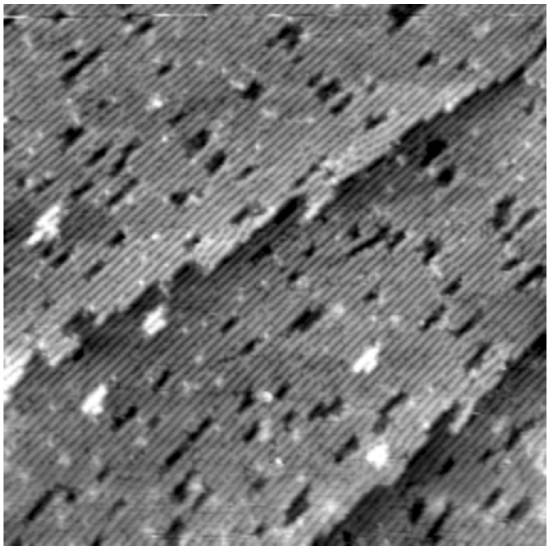
- Incorporation of n- and p-type dopants depends on flux of respective impurity species

  ⇨ Unity sticking coefficient

Surface phase diagram for GaAs(001) growth from Ga and As_4

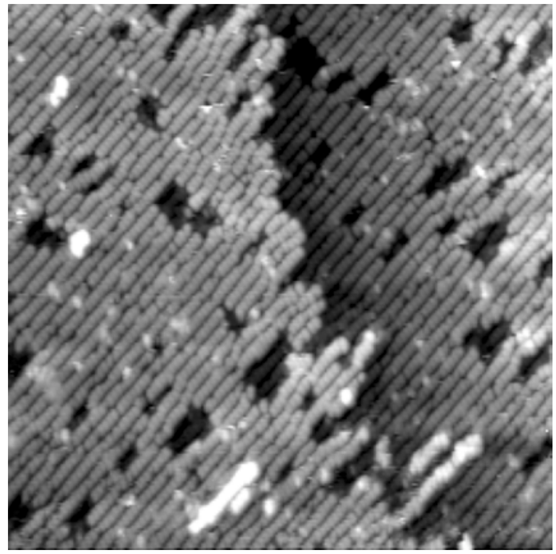


L. Däweritz, R. Hey
Surf. Sci. 236, 15(1990)



10 nm

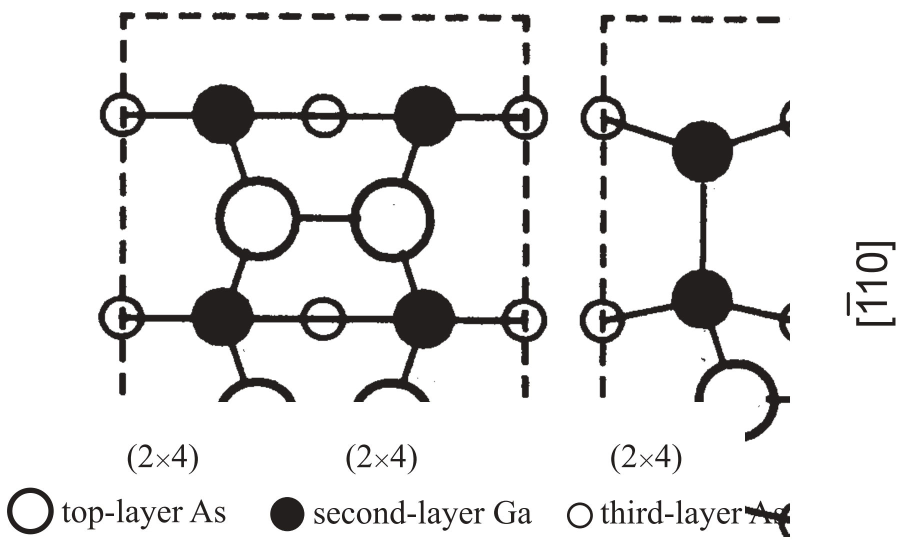
0.5° toward (111)Ga (A)

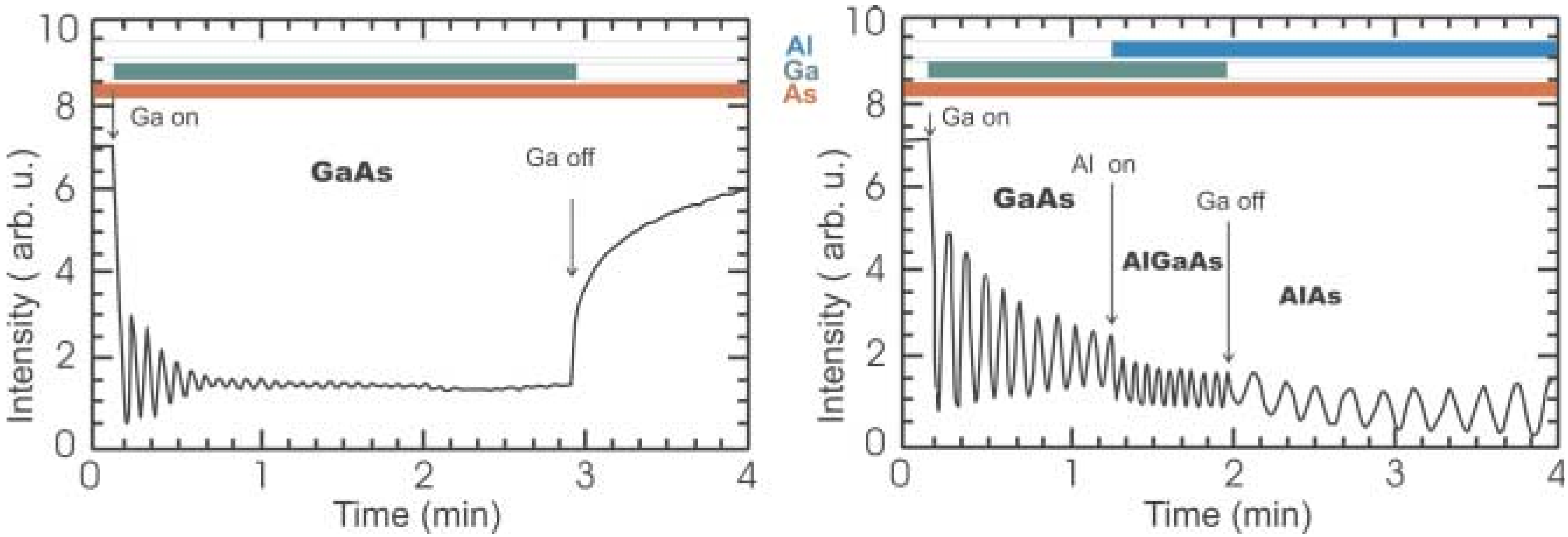


10 nm

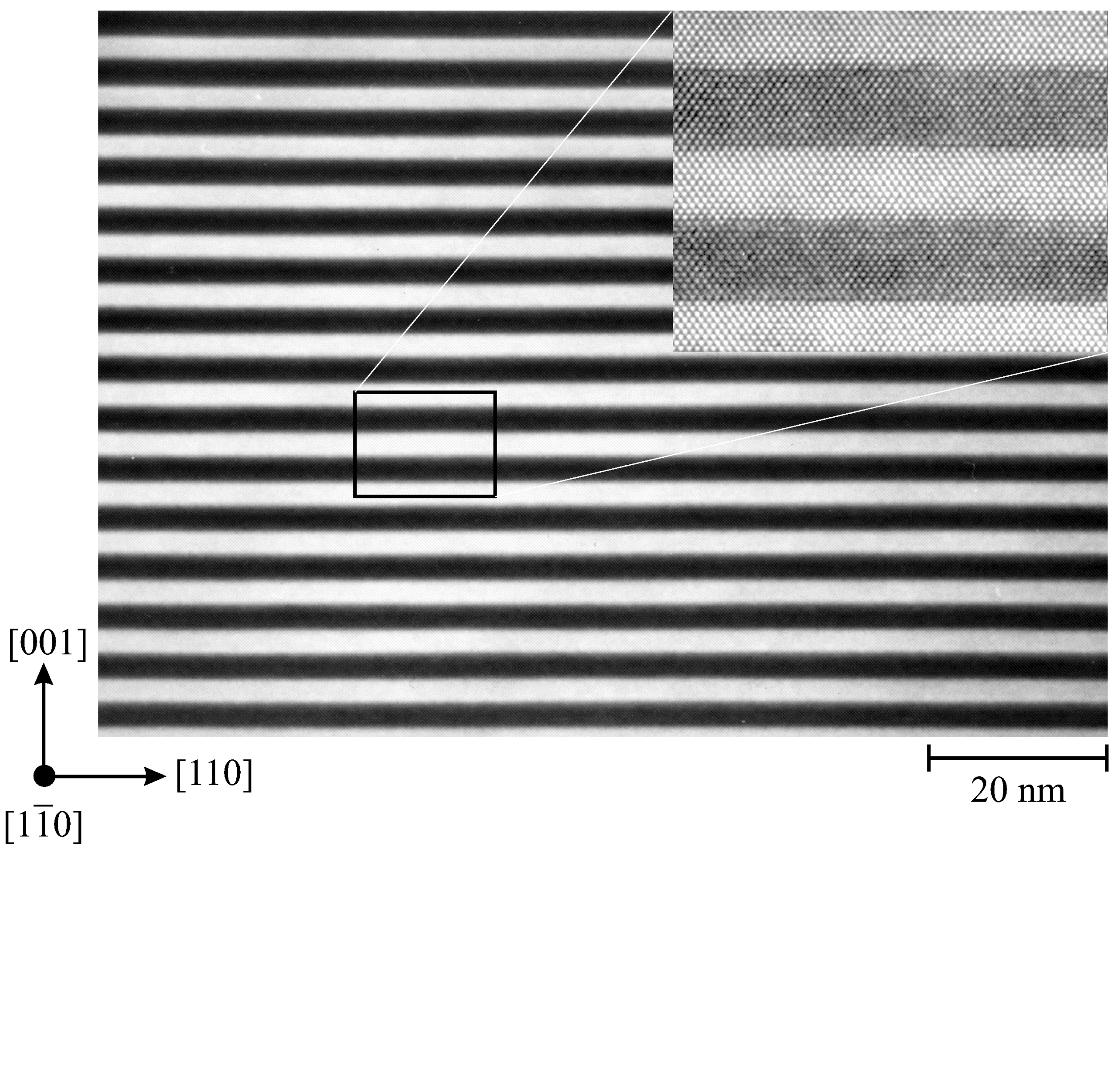
0.5° toward $(1\bar{1}1)$As (B)

(2 x 4) reconstructed terraces on vicinal GaAs(001) with straight As dimer and missing dimer rows, holes and islands. B-type steps are more ragged than A-type steps.





Al
Ga
As
Ga on
GaAs
Ga off
Intensity (arb. u.)
Time (min)
Ga on
Al on
GaAs
Ga off
AlGaAs
AlAs
Intensity (arb. u.)
Time (min)


[001]
[110]
[1$\bar{1}$0]
20 nm

Layer-by-Layer Growth Mode in MBE

Ideal Picture

- Atoms impinging on the surface diffuse and nucleate 2D island
- Islands grow by attaching further atoms until the layer is completed
- Process repeats for subsequent layer

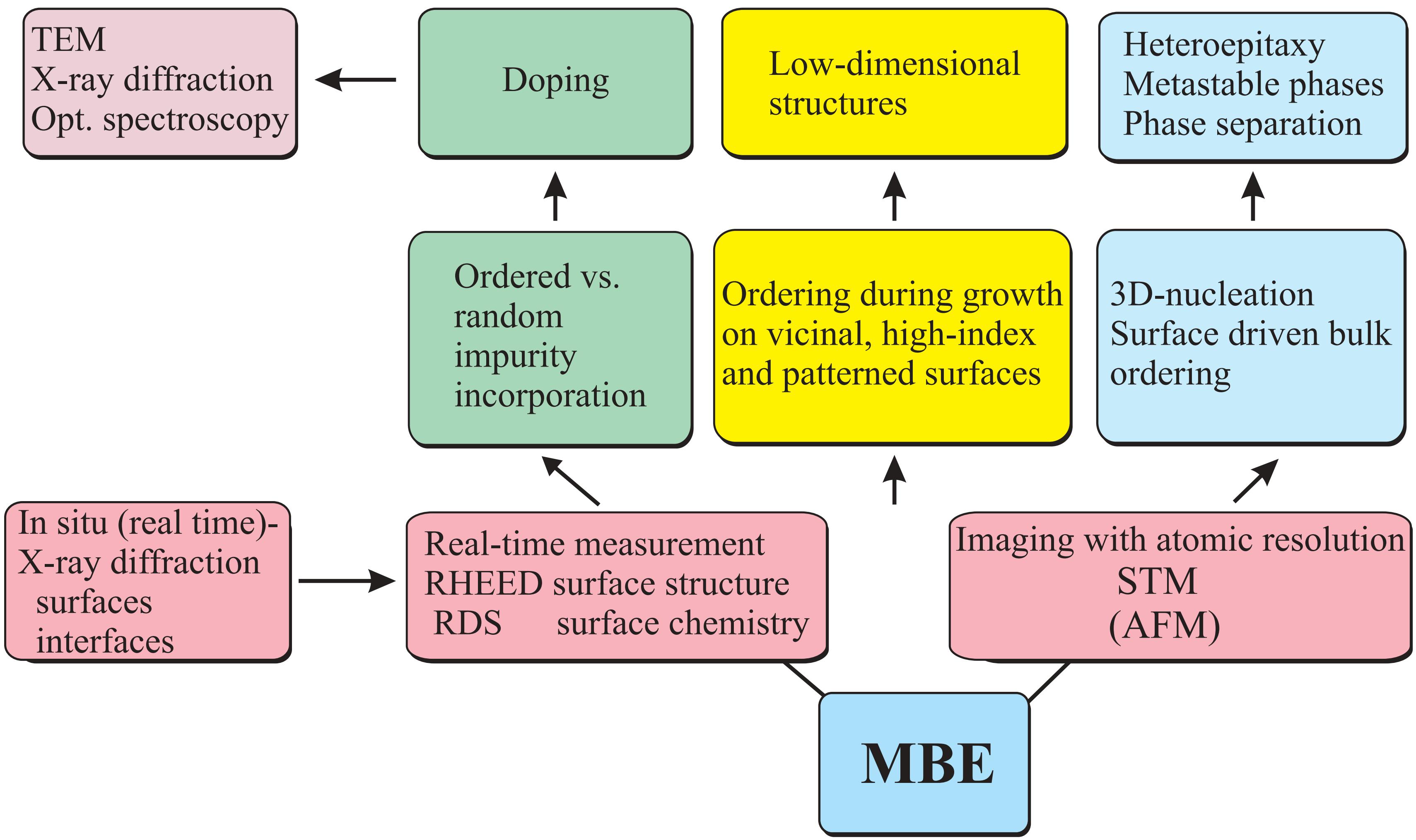
Real Picture

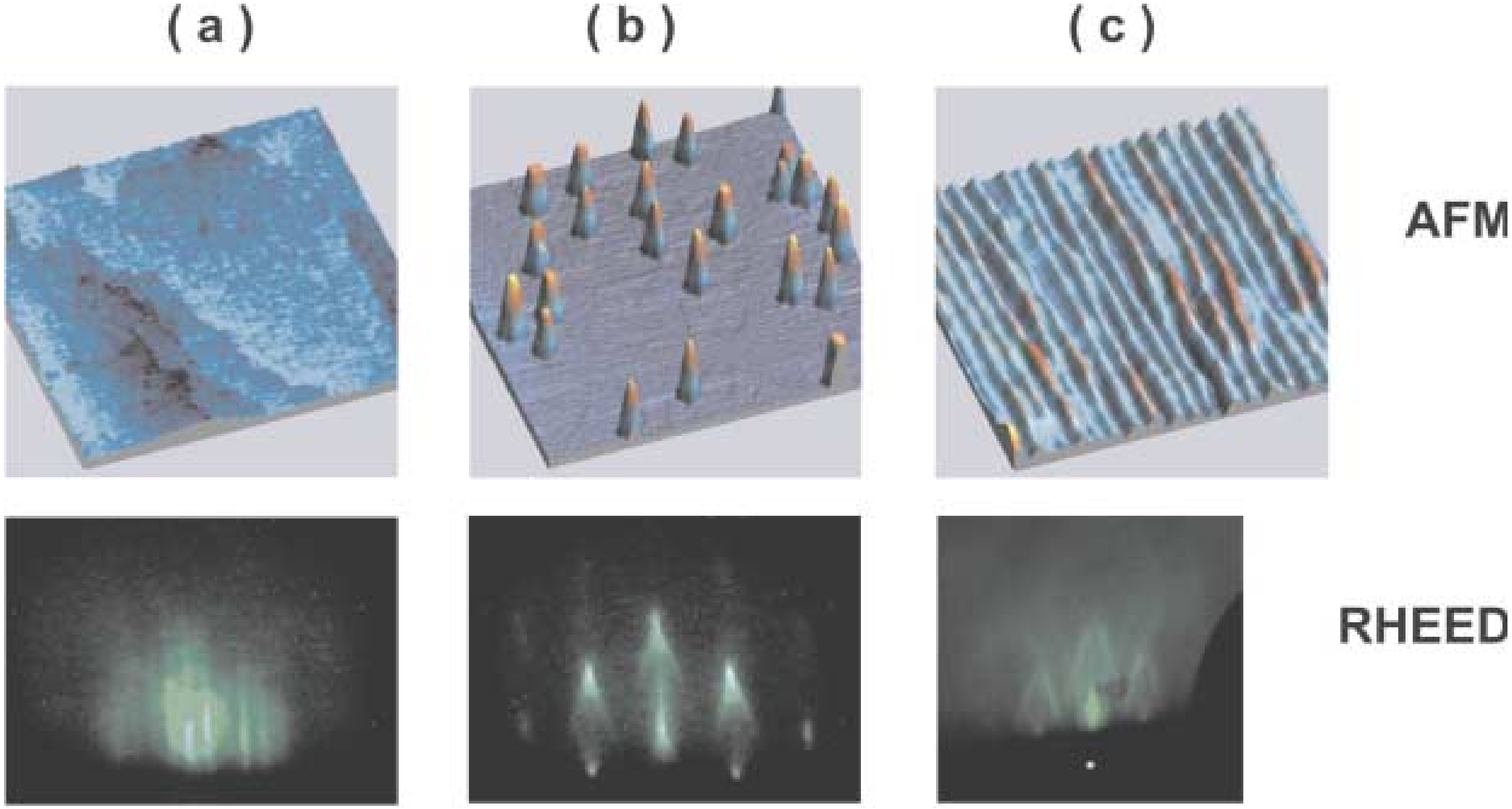
- Subsequent layer is nucleated before previous one is completed
- Number of incomplete layers, i.e. surface roughness, increases with growth time

⇓ Upon interruption of growth the surface starts to recover

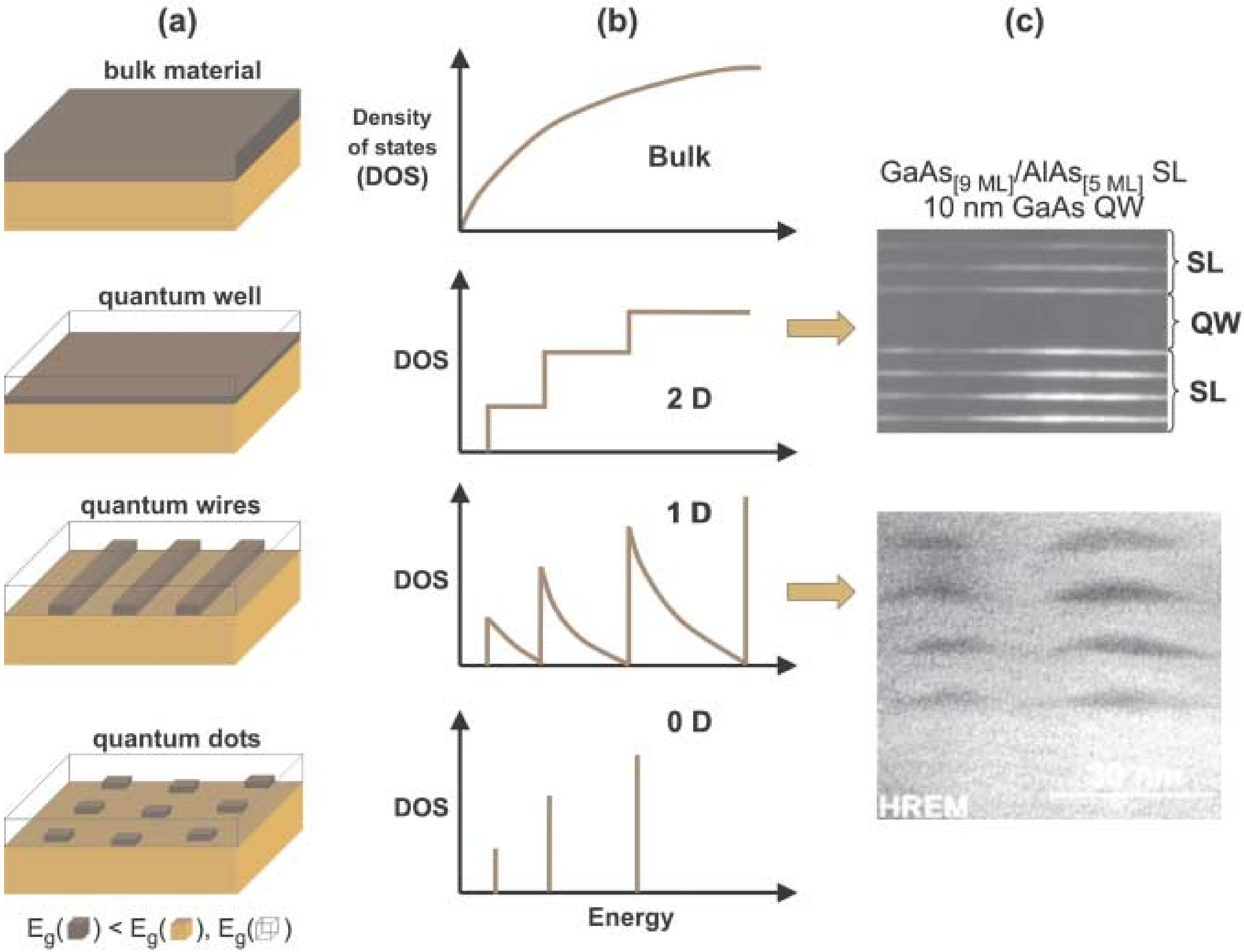
Its roughness decreases and it returns to the initial flat state.

Atomic-level growth control

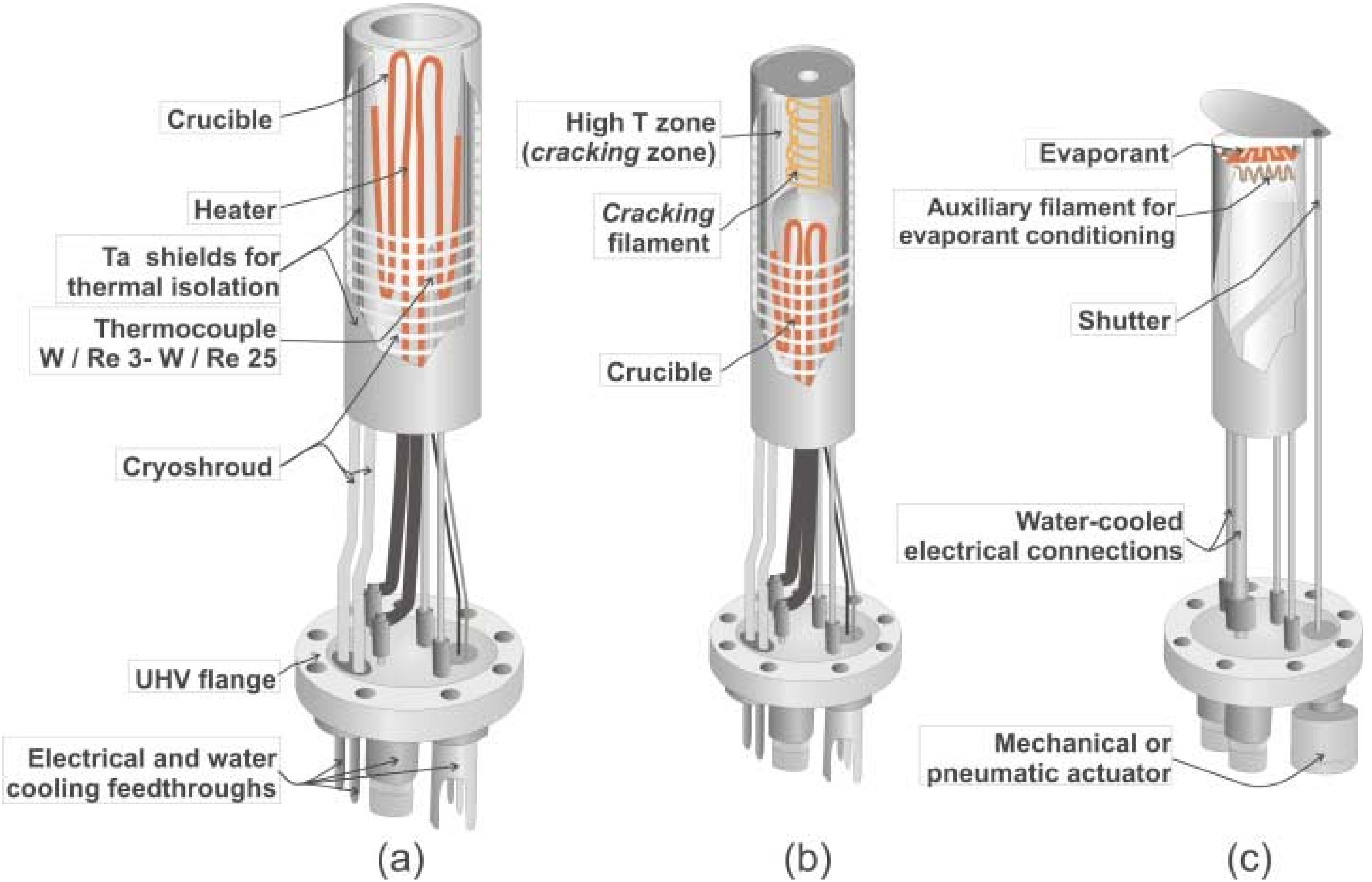




(a)
(b)
(c)
AFM
RHEED



(a)
(b)
(c)
bulk material
quantum well
quantum wires
quantum dots
E_g( ) < E_g( ), E_g( )
Density of states (DOS)
Bulk
DOS
2 D
DOS
1 D
DOS
0 D
Energy
GaAs[9 ML]/AlAs[5 ML] SL
10 nm GaAs QW
SL
QW
SL
HREM



Crucible
Heater
Ta shields for thermal isolation
Thermocouple W / Re 3- W / Re 25
Cryoshroud
UHV flange
Electrical and water cooling feedthroughs
(a)
High T zone (*cracking* zone)
Cracking filament
Crucible
(b)
Evaporant
Auxiliary filament for evaporant conditioning
Shutter
Water-cooled electrical connections
Mechanical or pneumatic actuator
(c)

Examples

MBE of sophisticated lattice-matched heterostructures

- Extremely high electron mobility in modulation-doped (Al,Ga)As/GaAs heterostructures
- Layer sequence in quantum/cascade lasers (QCL)

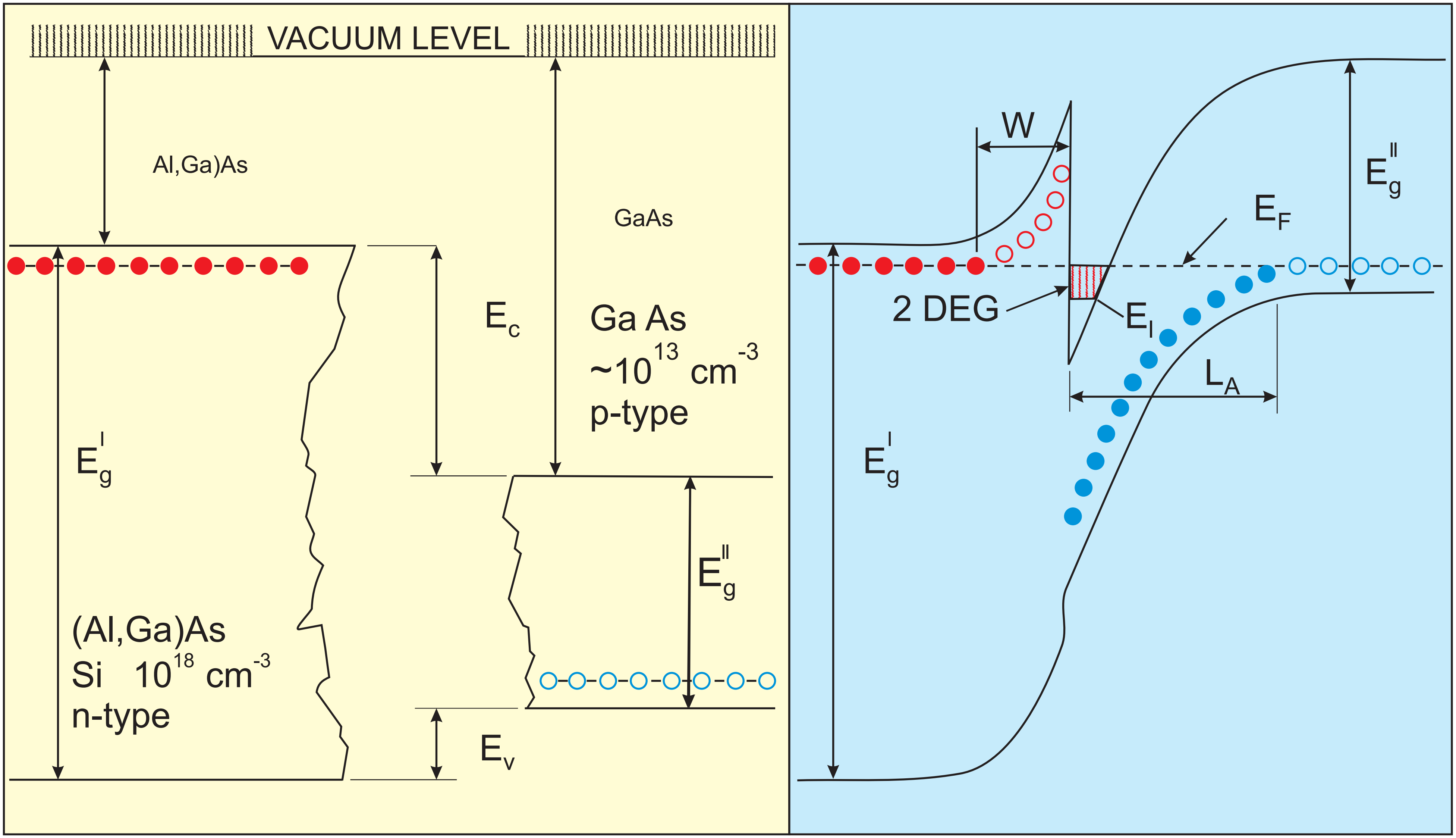
Heteroepitaxy of materials dissimilar in

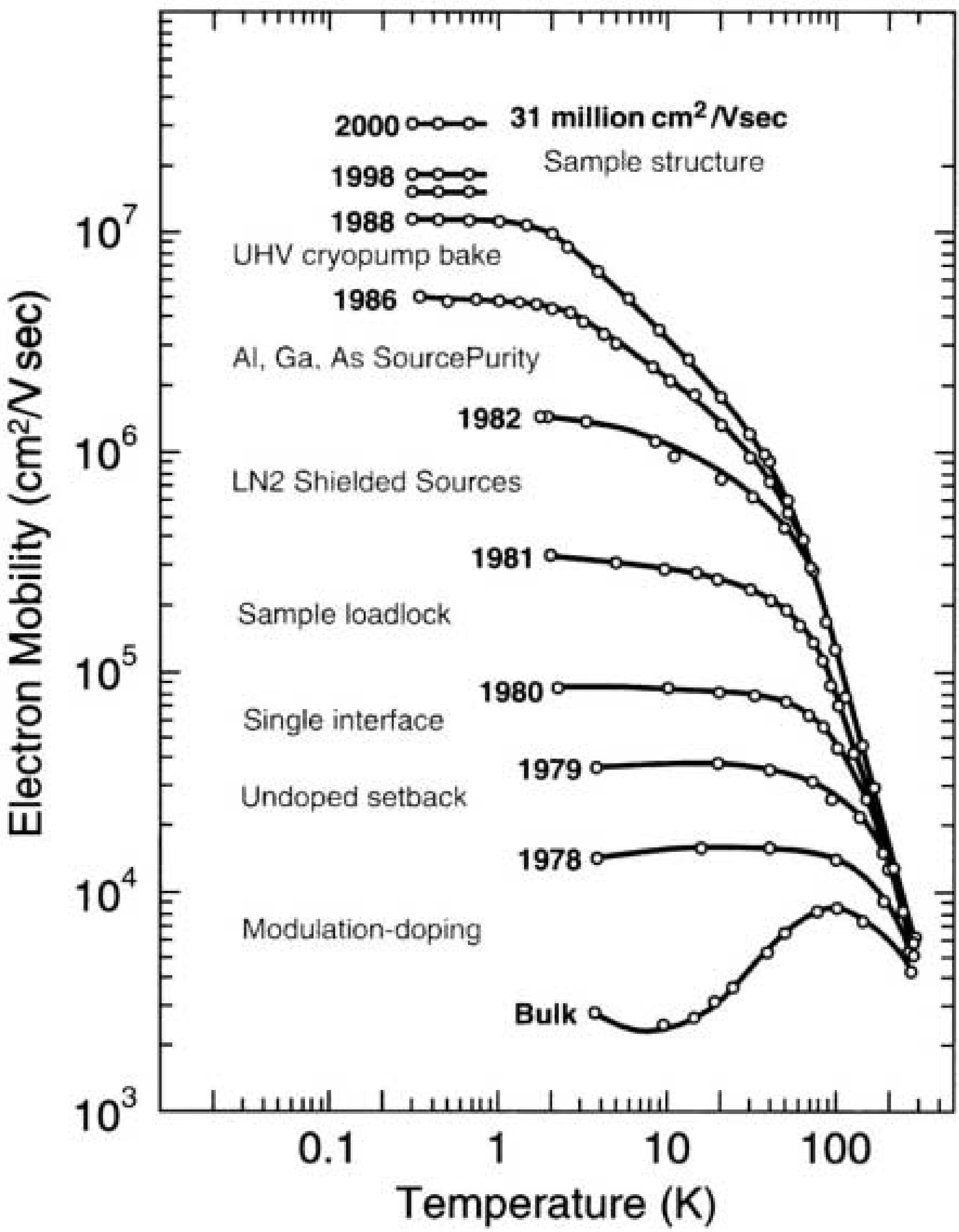
- Lattice parameter
- Crystal structure
- Bonding character
- Properties

- MnAs on GaAS
- GaN on Li AO2

Characterization of Interfaces

- High-resolution transmission electron microscopy
- High-resolution x-ray diffraction
- Ion beam channelling and scattering techniques
- Raman scattering
  - Folded phonons
  - Interface phonons
- Optical emission and absorption spectroscopy
- Magnetotransparent measurements
- Cross-sectional scanning tunneling microscopy


VACUUM LEVEL
Al,Ga)As
GaAs
E_c
Ga As
~10^13 cm^-3
p-type
E_g^I
(Al,Ga)As
Si 10^18 cm^-3
n-type
E_g^II
E_v
W
E_F
2 DEG
E_I
L_A
E_g^I
E_g^II



L. Pfeiffer, K.W. West / Physica E 20 (2003) 57 –64

From Interband to Intersubband Emitter

bipolar **unipolar**