Zhores I. Alferov

Semiconductor Heterostructures: State-of-Art and Future Trends

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- **Introduction**
- **Classical heterostructures**
- **Quantum well and superlattice heterostructures**
- **Quantum wire and quantum dot heterostructures**

  For each above topics it will be considered:

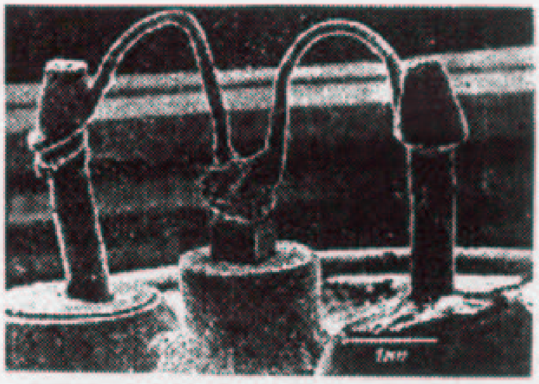
  (i) Fundamental physical phenomena

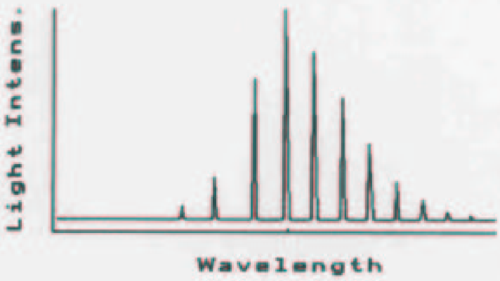
  (ii) Important consequences for applications

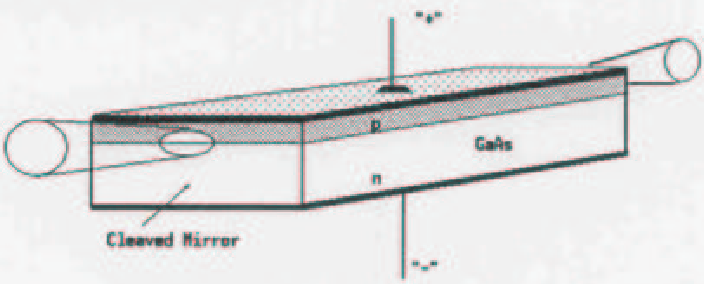
  (iii) Important technological consideration
- **Future trends in heterostructure technology**
- **Summary**

p-n Junction Lasers and LED..

* **Jan.. 1962 :** the superluminiscent narrowing of optical emission from GaAs diodes was observed (Physico-Technical institute, USSR).
* **July 1962 :** Lincoln Lab., MIT (USA)- the same result was observed.
* **Sep.-Dec. 1962:** Coherent light emission from GaAs Junction - General Electric , IBM, (USA); FIAN (USSR).



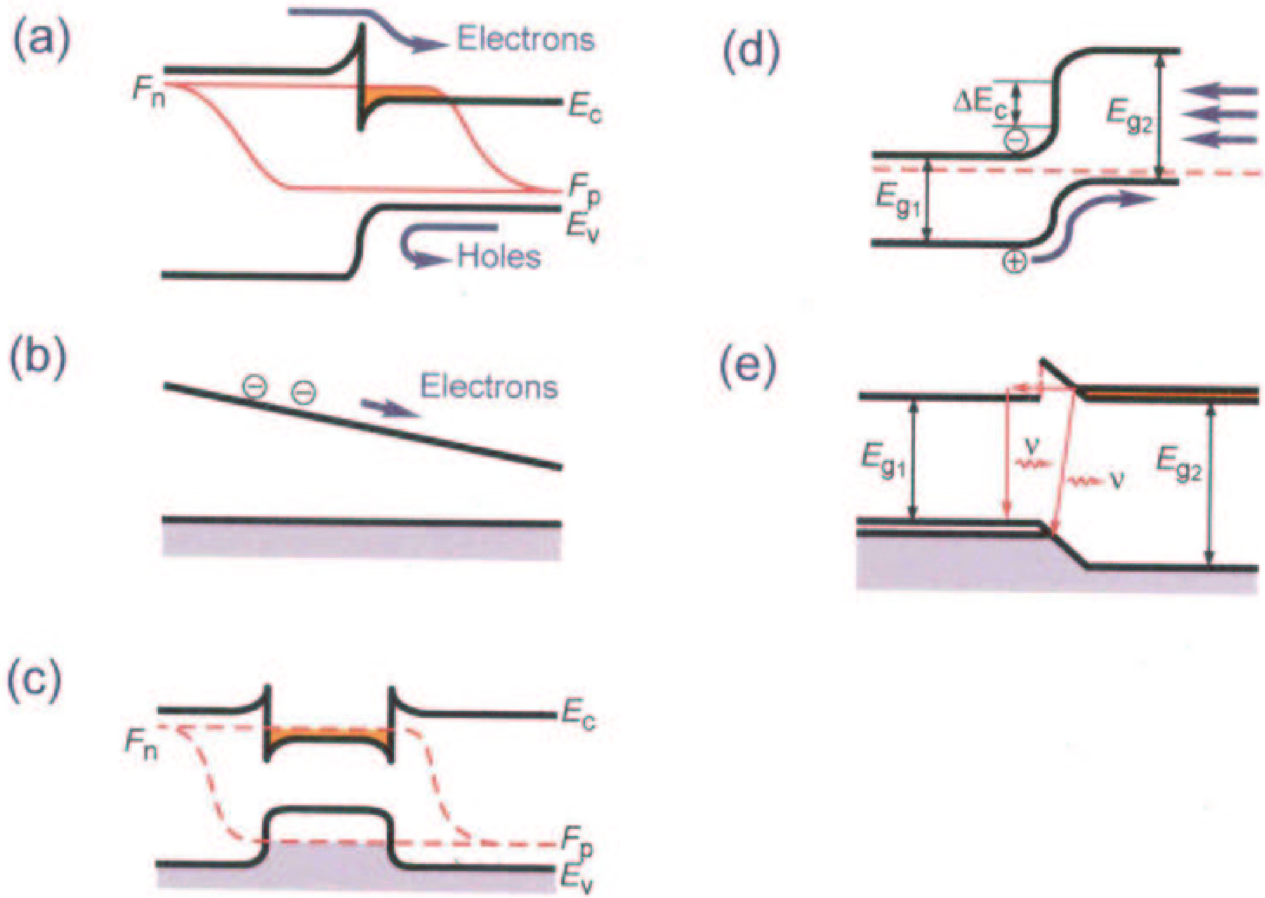




Optical Gain condition:

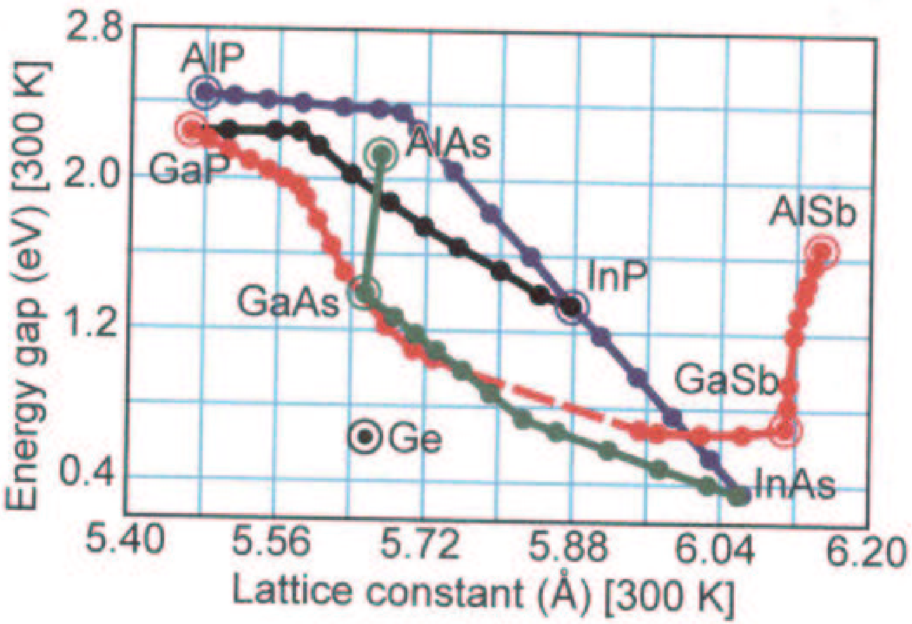
$$E_F^n - E_F^p > E_g$$

Fundamental physical phenomena in classical heterostructures



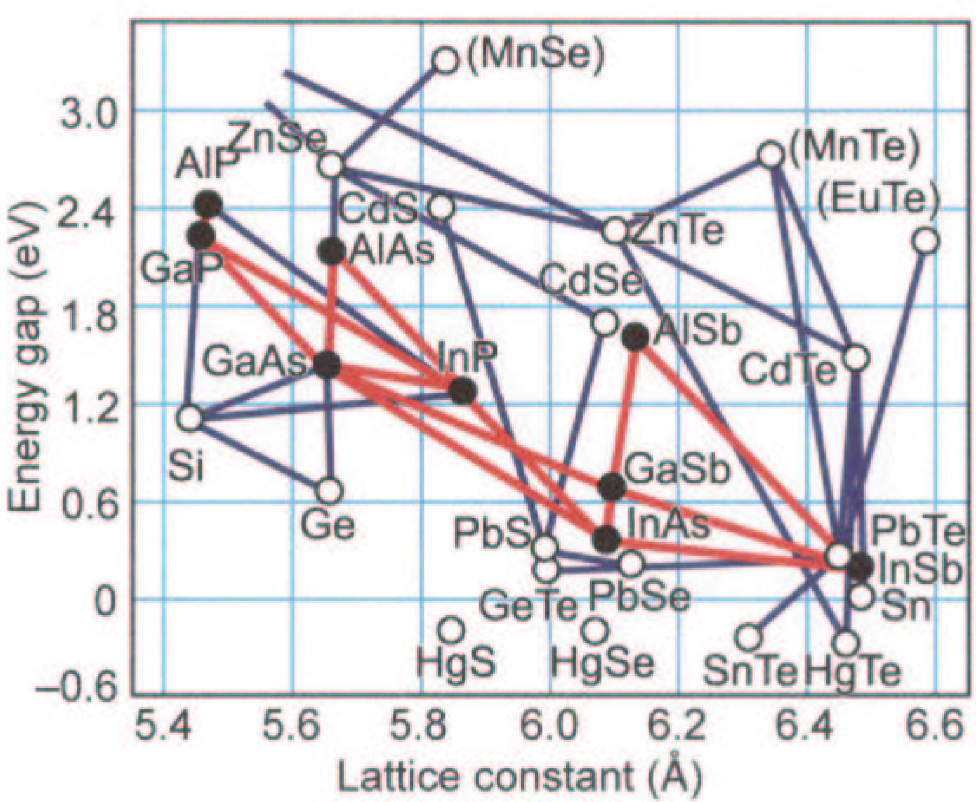
Heterojunctions—a new kind of semiconductor materials:

Long journey from infinite interface recombination to ideal heterojunction



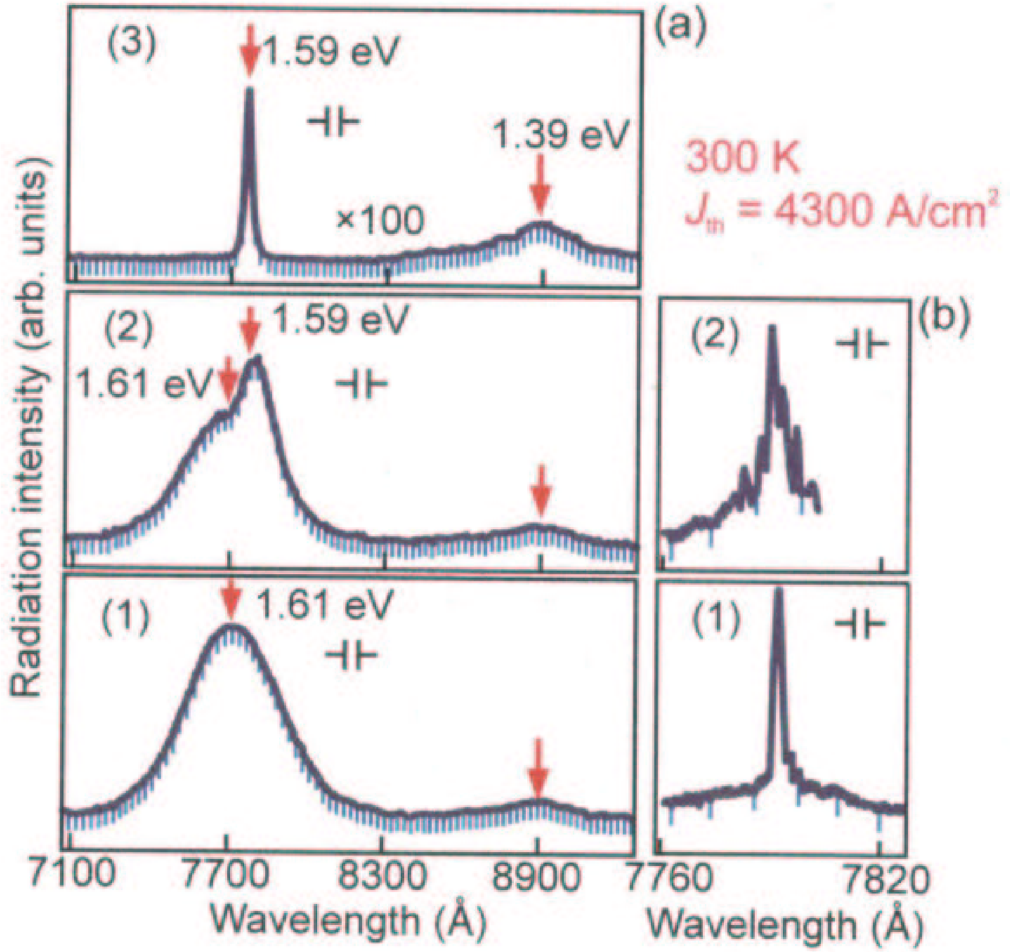
Lattice matched heterojunctions

- Ge–GaAs–1959 (R. L. Anderson)
- AlGaAs–1967 (Zh. Alferov *et al.*, J. M. Woodall & H. S. Rupprecht)
- Quaternary HS (InGaAsP & AlGaAsSb) Proposal–1970 (Zh. Alferov *et al.*) First experiment–1972 (Antipas *et al.*)

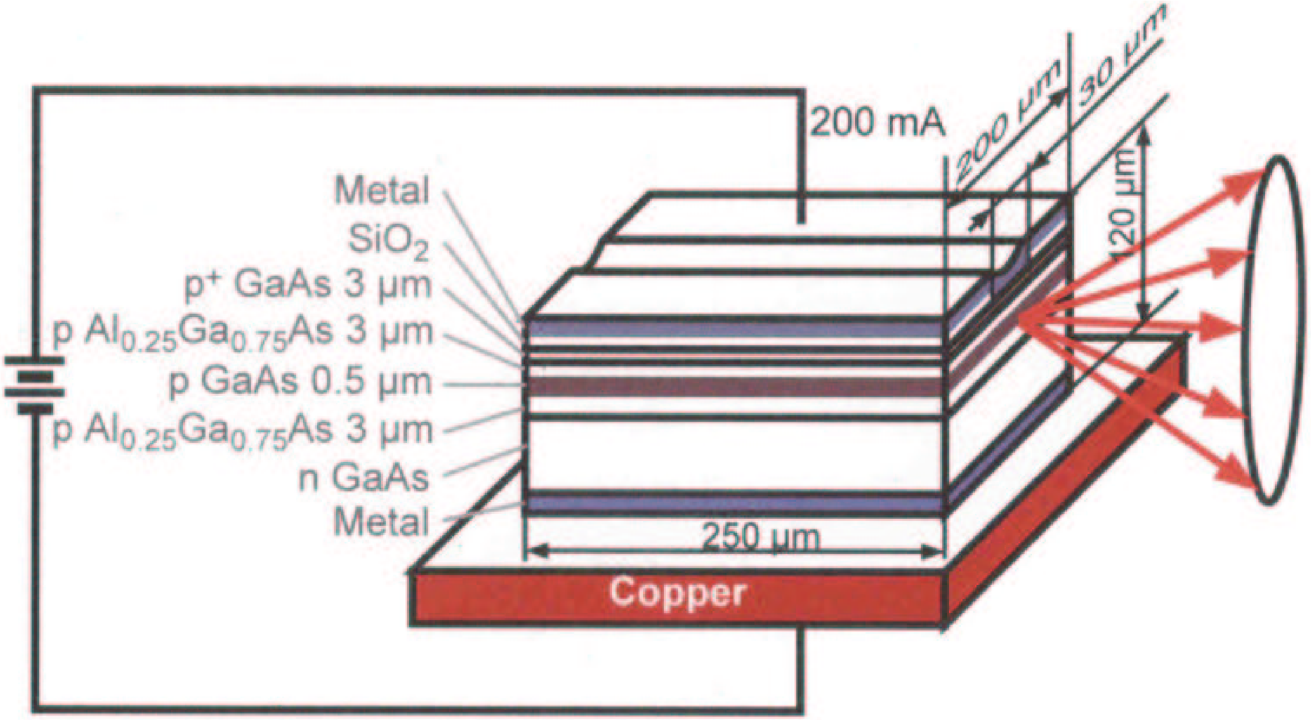


Energy gaps vs lattice constants for semiconductors IV elements, III–V and II(IV)–VI compounds and magnetic materials in parentheses. Lines connecting the semiconductors, red for III–V, and blue for others, indicate quantum heterostructures, that have been investigated. Nitrides have not been yet included.

Radiation spectrum for the first low threshold $Al_xGa_{1-x}As$ DHS laser at room temperature



Schematic representation of the DHS injection laser in the first CW-operation at room temperature



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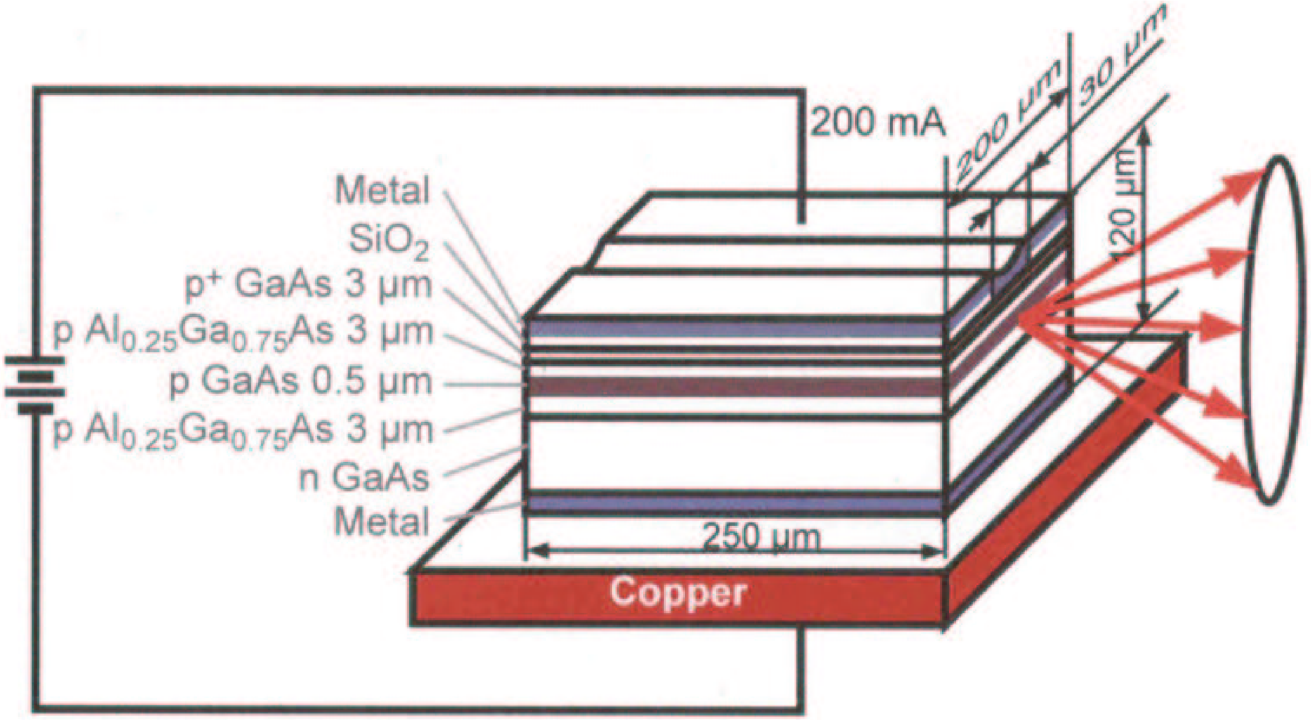
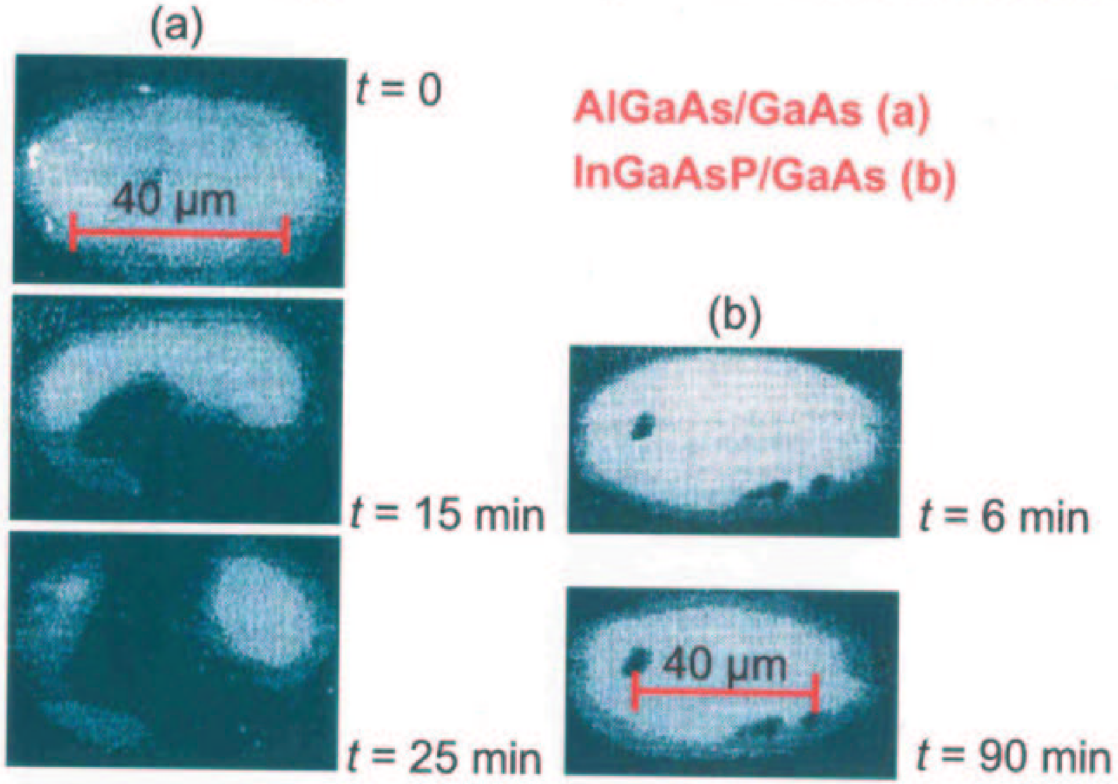


Time evolution of DHS active region under high level photoexcitation



Diameter of Kr^{+}-laser excitation beam — 40 µm

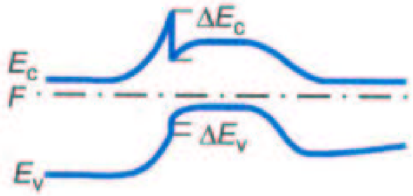
Excitation level (a) 10^4 W/cm^2, (b) 10^5 W/cm^2

Heterostructure solar cells

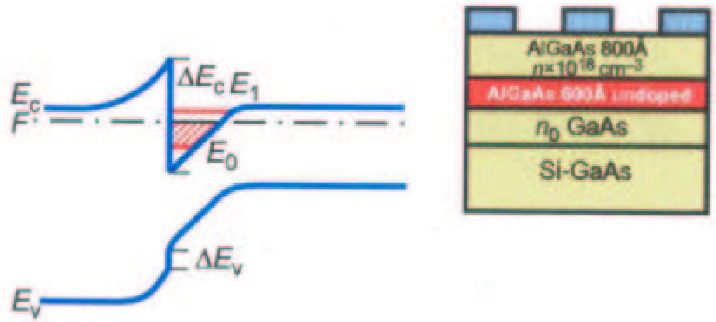
Space station "Mir" equipped with heterostructure solar cells

Heterostructure microelectronics

Heterojunction Bipolar Transistor

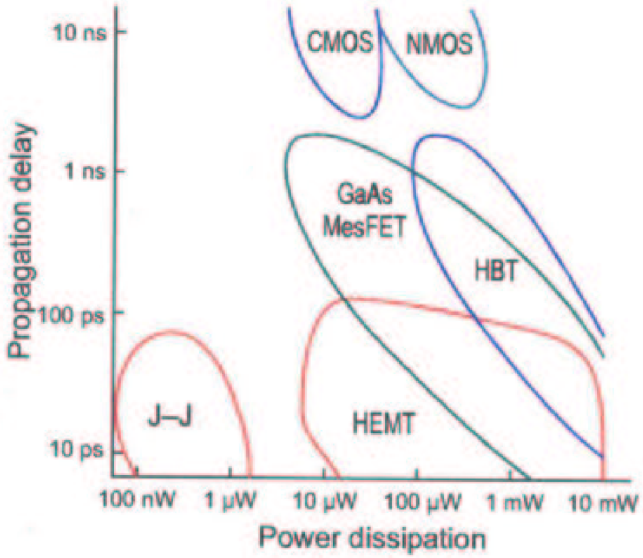


Suggestion—1948 (W.Shockley)
Theory—1957 (H.Kroemer)
Experiment—1972 (Zh.Alferov *et al.*)
AlGaAs HBT



***N*AlGaAs-*n* GaAs Heterojunction**

HEMT—1980 (T.Mimura et al.)



Speed-power performances

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Classical heterostructures

I. Fundamental physical phenomena

- One-side injection
- Superinjection
- Diffusion in built-in quasi-electric fields
- Electron confinement
- Optical confinement
- Wide-gap window effect
- Diagonal tunneling through heterostructure interface

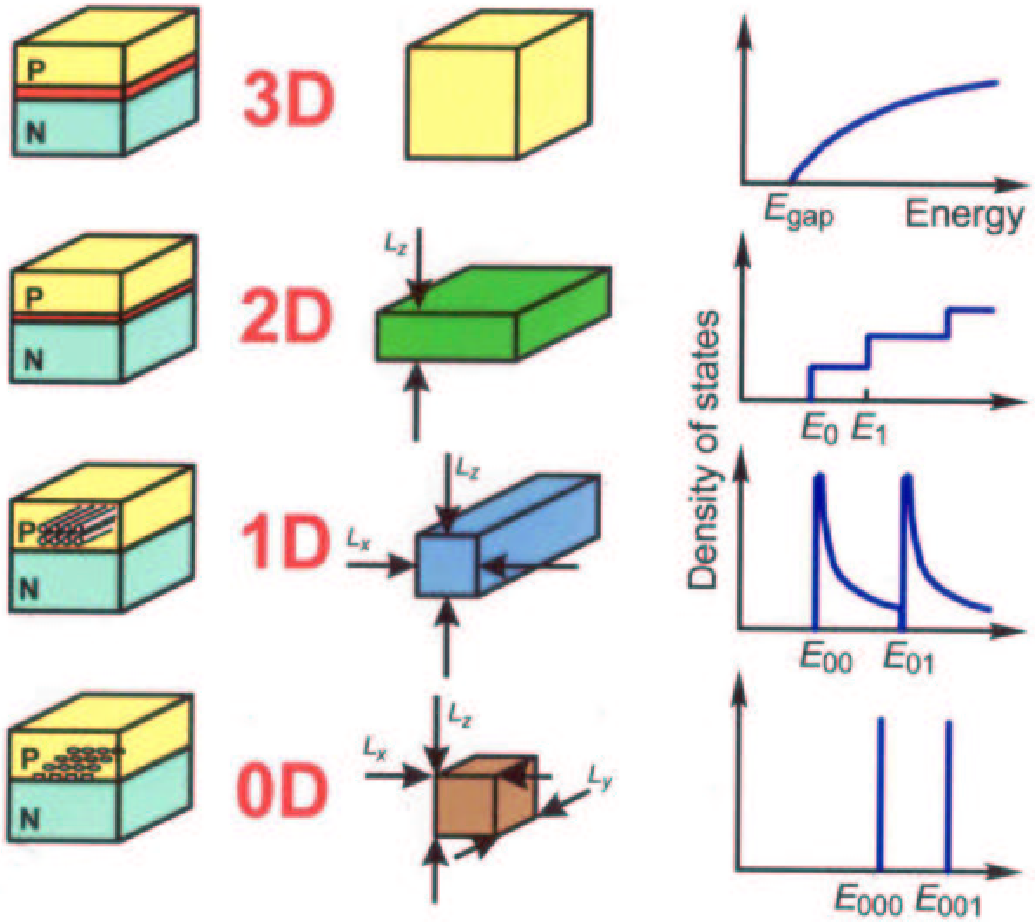
II. Important consequences for applications

- Semiconductor lasers — low threshold and CW at room temperature, DFB and DBR lasers, vertical surface emitting lasers, IR II-type heterostructure lasers.
- High efficient LED
- Solar cells and photodetectors, based on wide-gap window effect
- Semiconductor integrated optics, based on semiconductor DFB and DBR lasers
- Bipolar wide-gap transistors
- Transistors, thyristors, dynistors with photonic signal transmission
- High power diodes and thyristors Infra-red to visible converters
- Efficient cold cathodes

III. Important technological peculiarities

- Lattice-matched structures are necessity of principle
- Multi-component solid solutions are used for lattice-matching
- Epitaxial growth technology is need of principle

Impact of dimensionality on density of states



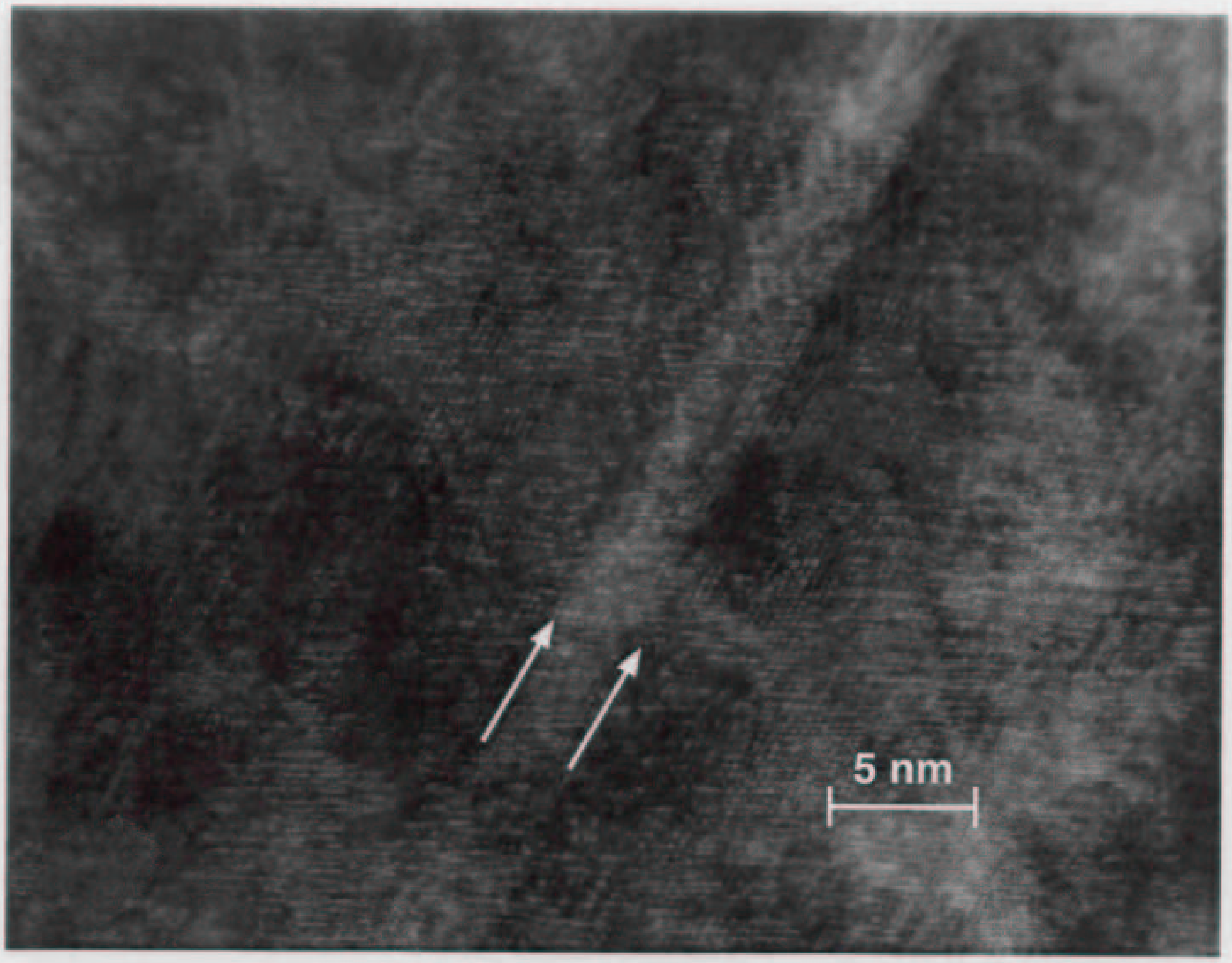
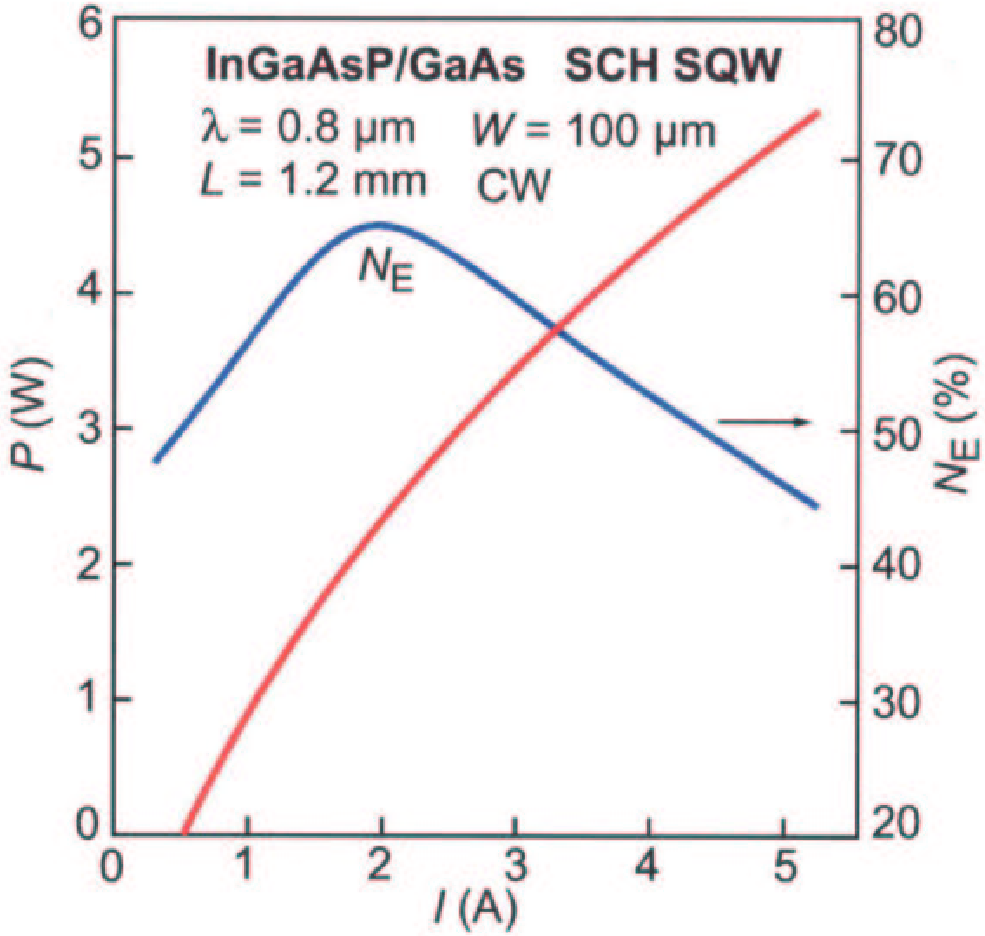
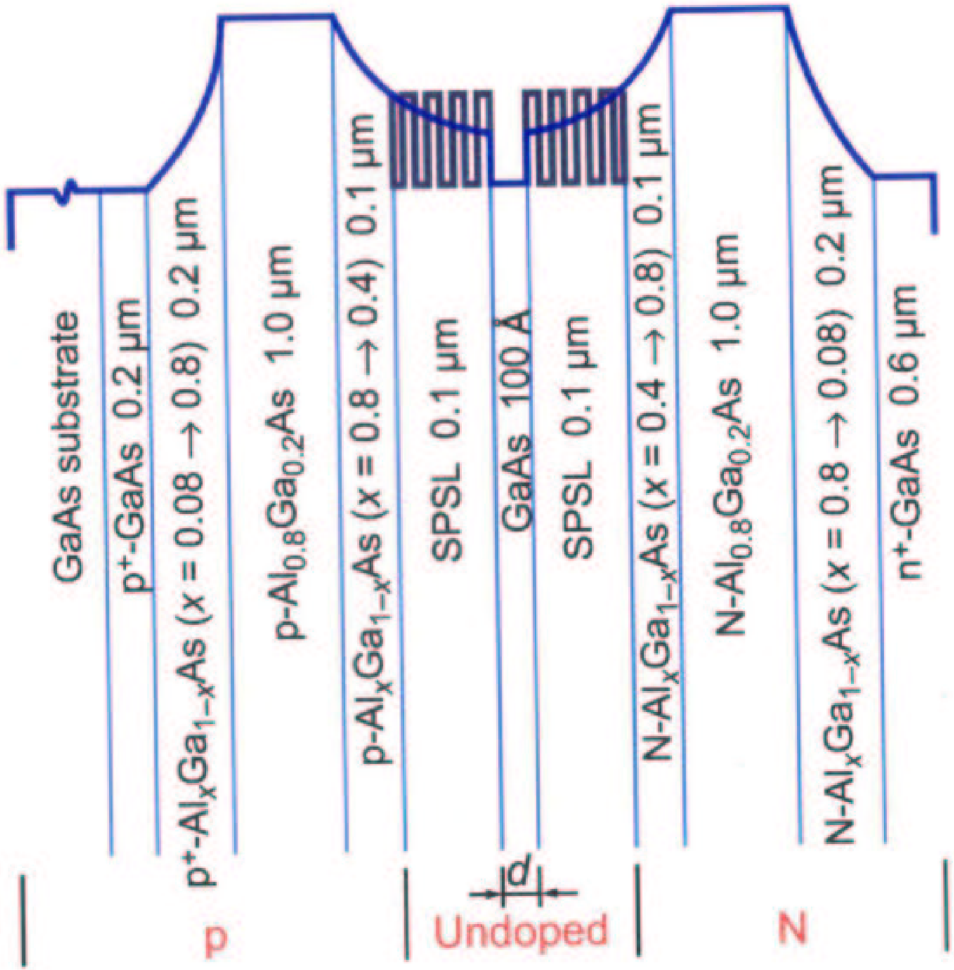


Fig. 5. Thin InGaAsP layer in InGaP/InGaAsP/InGaP/GaAs (111 A) quantum well structure grown by LPE. TEM cross-section view.

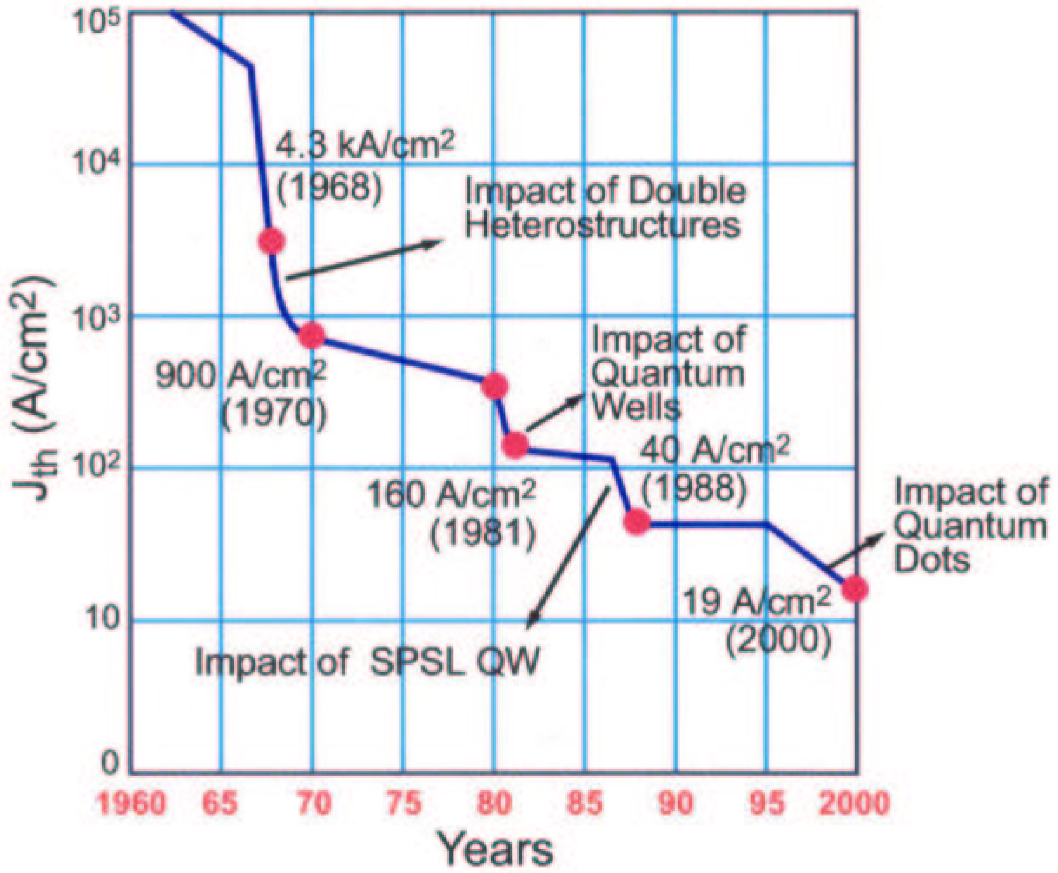
CW light-current characteristics



MBE grown SPSL QWSCH laser structure



Milestones of semiconductor lasers



- **Evolution and revolutionary changes**
- **Reduction of dimensionality results in improvements**

Quantum well and superlattice heterostructures

I.Fundamental physical phenomena

- 2D electron gas
- Step-like density-of-state function
- Quantum Hall-effect
- Fractional quantum Hall effect
- Excitons at room temperature
- Resonant tunneling in double-barrier structure and superlattices
- Energy spectrum in superlattices is determined by choice of potential and strain
- Stimulated emission at resonant tunneling in superlattices
- Pseudomorphic growth of strained structures

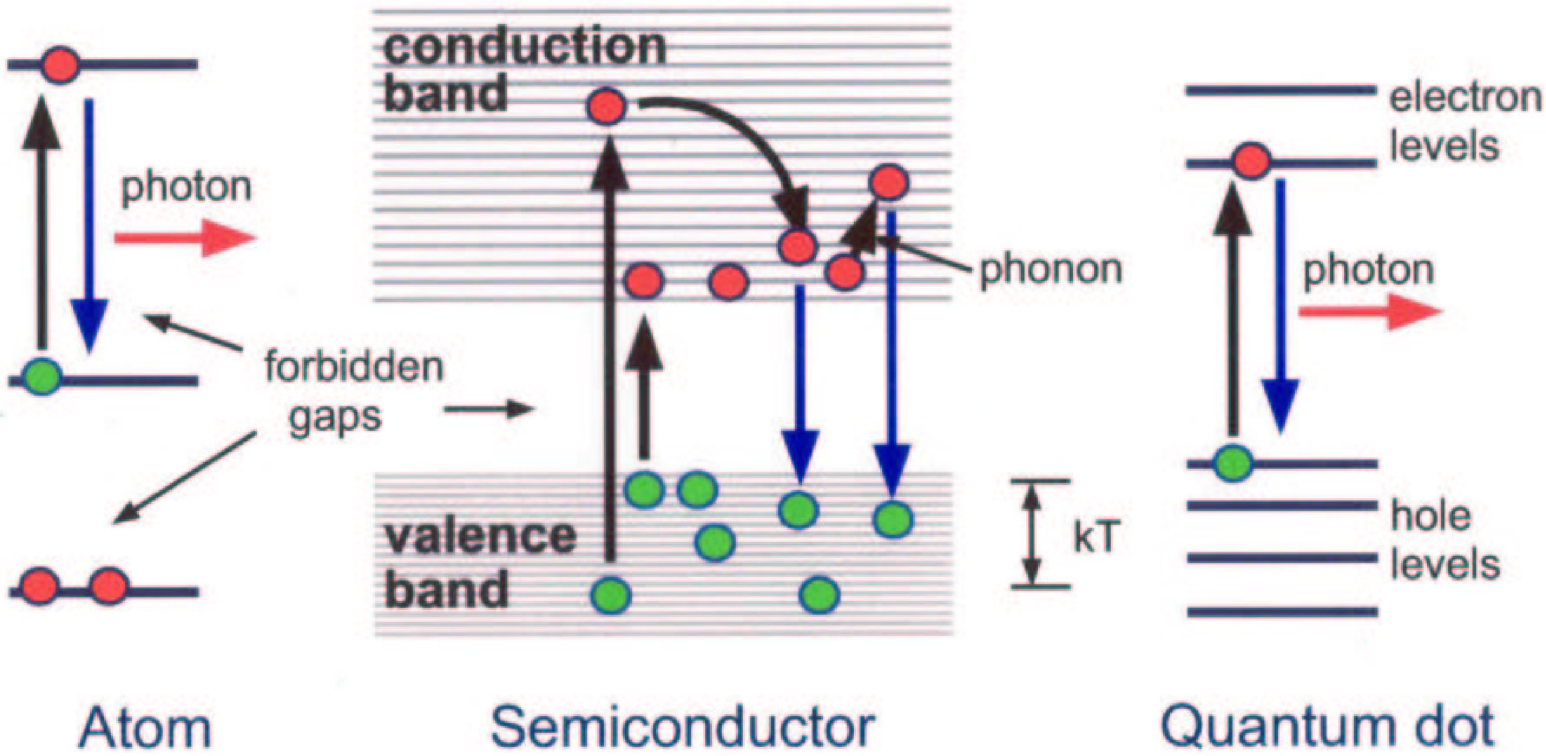
II. Important consequences for applications

- Shorter emission wavelength, reduced threshold current, larger differential gain and reduced temperature dependence of the threshold current for semiconductor lasers
- IR quantum cascade laser
- SPSL QW laser
- Optimization of electron and light confinement and waveguiding for semiconductor lasers
- 2D electron gas transistors (HEMT)
- Resonant-tunneling diodes
- Precise resistance standards
- SEEDs and electro-optical modulators
- IR photodetectors based on quantum size level absorption

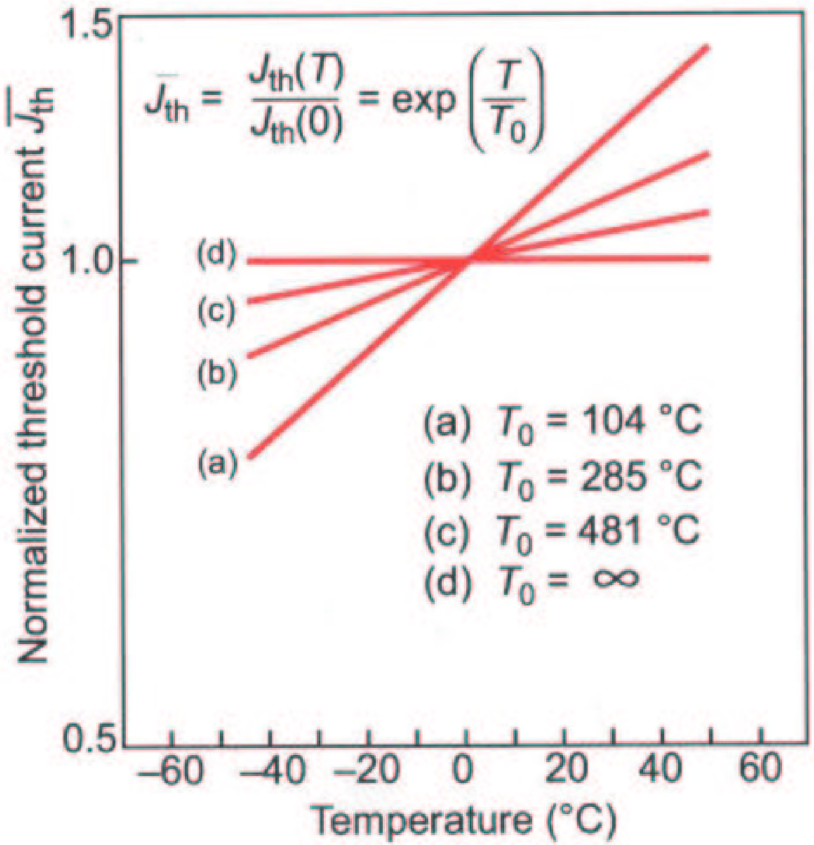
III. Important technological peculiarities

- Lattice-match is unnecessary
- Low growth-rate technology (MBE, MOCVD) are need of principle
- Submonolayer growth technique
- Blockading mismatch dislocations during epitaxial growth
- Sharp increase in the variety of heterostructure components

Quantum dot as superatom



Temperature dependence of the normalized threshold current for different DHS lasers



(a) Bulk

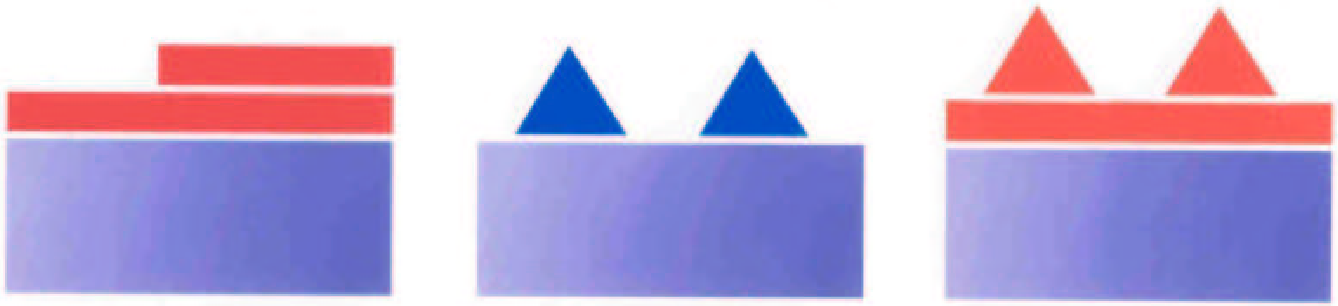
(b) Quantum well

(c) Quantum wire

(d) Quantum dot

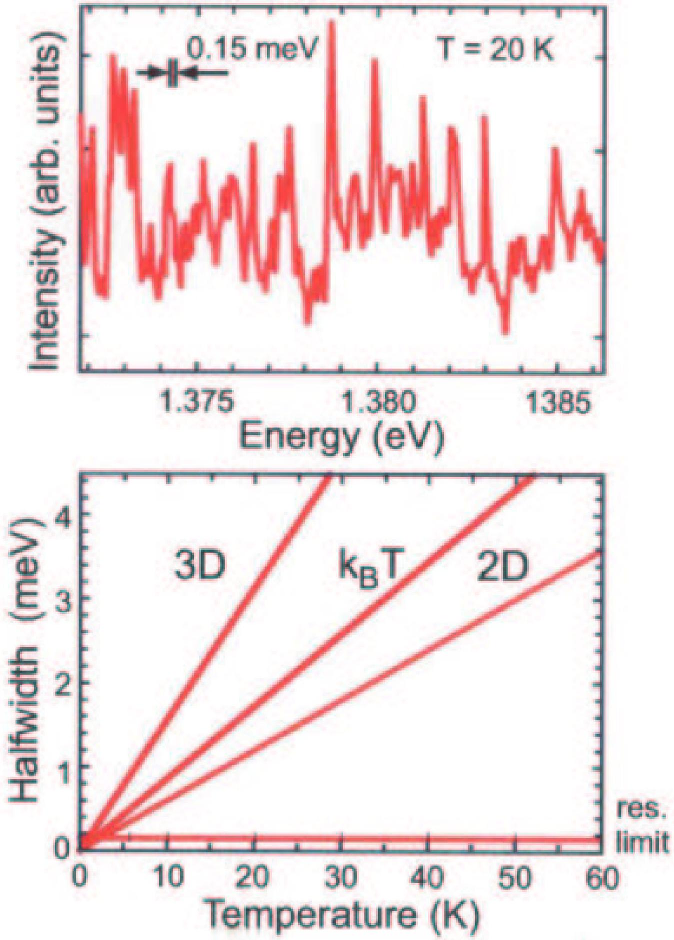
Stranski–Krastanow growth mode

- High surface energy of the substrate — thin wetting layer
- High surface energy of the film — 2D growth
- High strain energy of the film — 3D Clusters

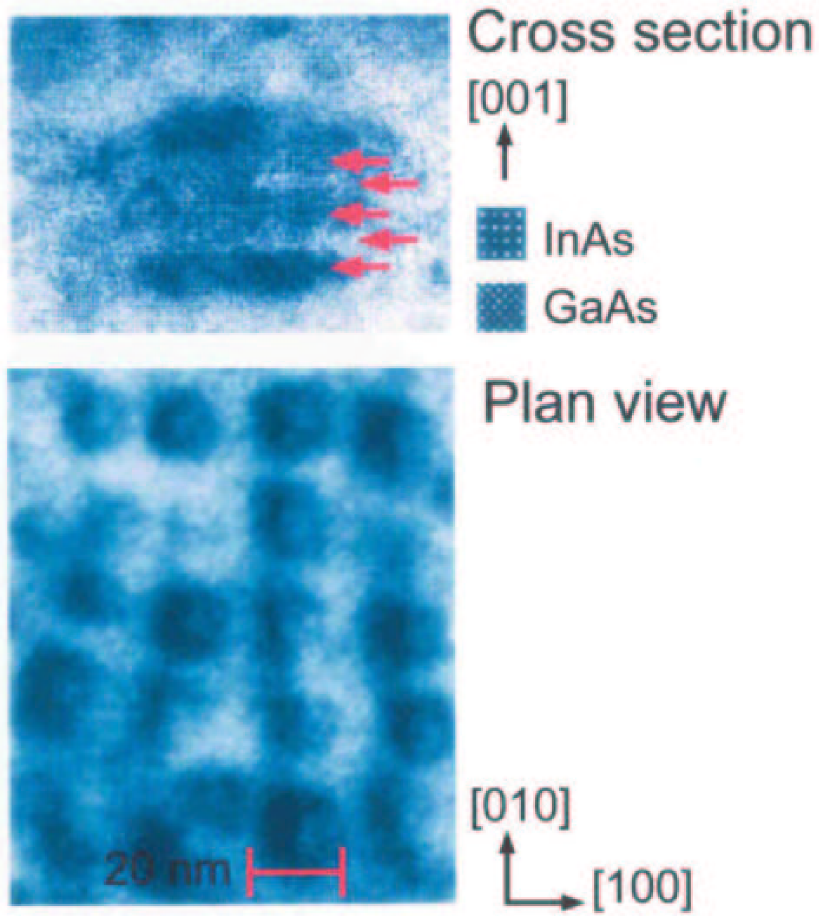


Frank–van der Merve Volmer–Weber Stranski–Krastanow

Spot focus cathode luminescence spectrum of InAs/GaAs dots



Vertical and lateral ordering of coupled InAs/GaAs quantum dots



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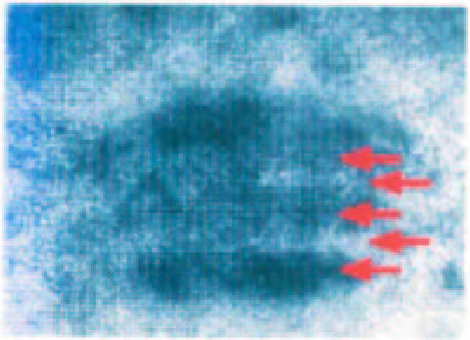
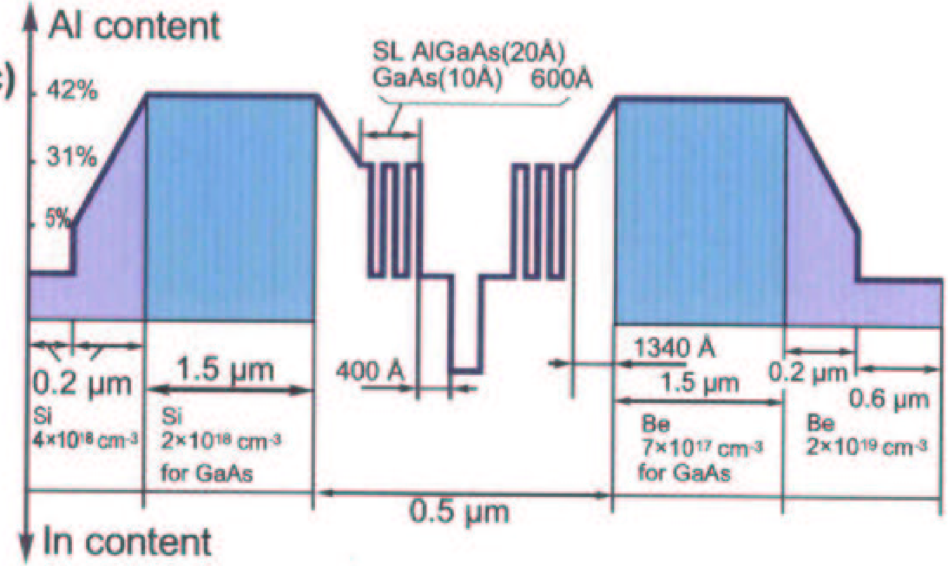
Vertically-coupled QDs (VECQDs) lasers

(a)

(b)



(c)



Quantum wire and dot heterostructures

I. Fundamental physical phenomena

- 1D electron gas (wires)
- Density-of-state function with sharp maximums (wires)
- 0D-electron gas (dots)
- δ-function type of density-of-state function (dots)
- Increasing binding energy of excitons

II. Important consequences for applications

- Reduced lasing threshold current and larger differential gain
- Diminished temperature dependence of threshold current (QWRs)
- Temperature stability of the threshold current (QDs)
- Discrete amplification spectrum and the possibility of obtaining performance characteristics similar to those of solid-state or gas lasers (QDs)
- Higher modulation factor in electro-optical modulators

III. Important technological peculiarities

- The application of self-organization effects for growth
- Epitaxial growth in V-grooves (wires)
- High-resolution lithography of HSQWL

What will be in 2012?

MAIN MATERIALS:

- AlGaAs & InGaAsP for near infrared and whole visible spectrum

- **All III–V Compounds**

MAIN STRUCTURE:

- MI DHS with separate electron & optical confinement
- MI DBR lasers

- **DHS QD Structures**

MAIN APPLICATIONS:

- Optical communication systems
- OEIC & optical computers
- IL-TV set
- All Lasers applications with power less than 1 kW CW & 1 MW pulse

- **All Lasers applications including technological**

1987 **1998**

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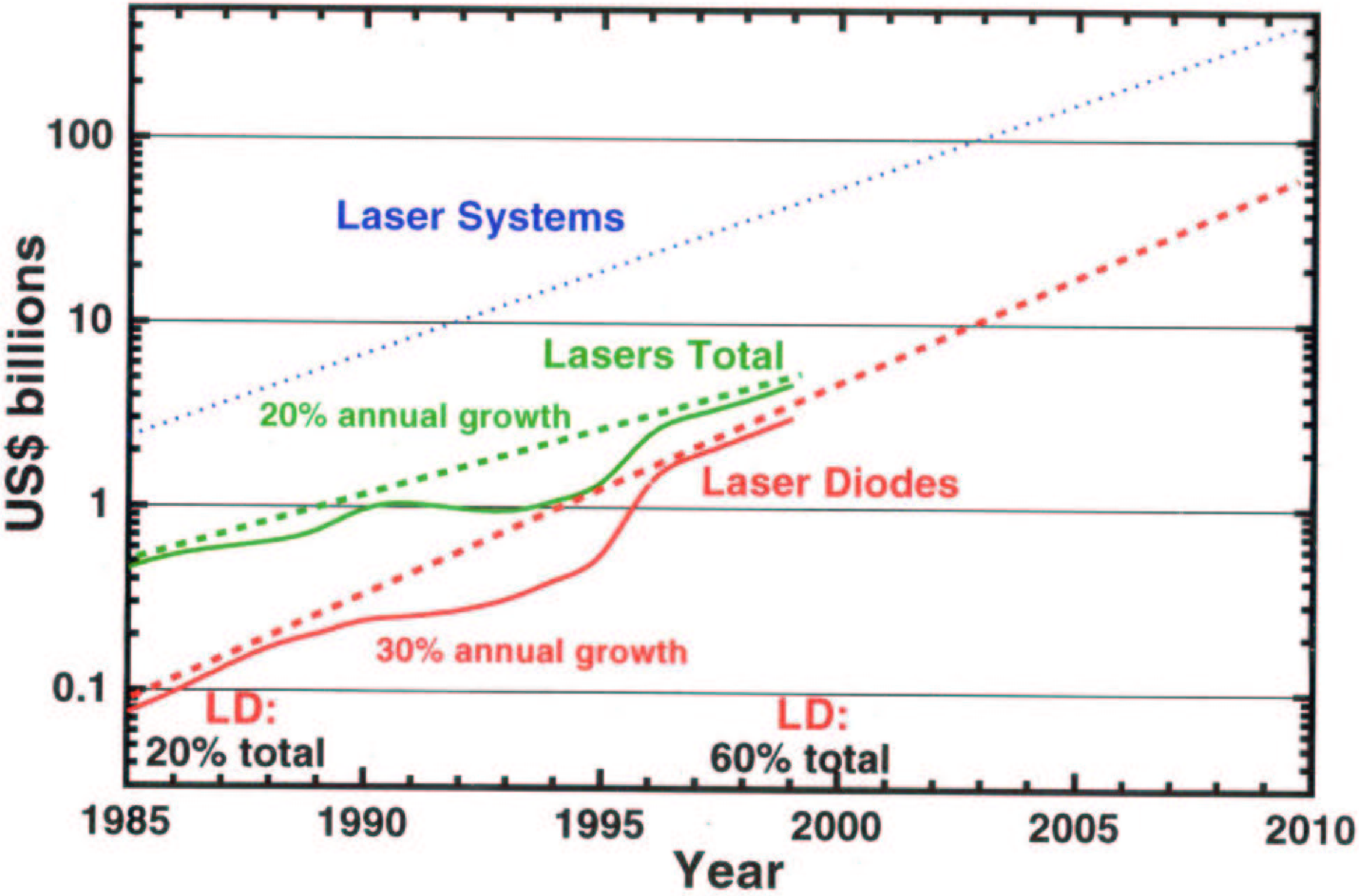
1987 **1998**

Laser Market (Source: Laser Focus World)



Summary

1. Heterostructures — a new kind of semiconductor materials:

- expensive, complicated chemically & technologically but most efficient

2. Modern optoelectronics is based on heterostructure applications

- DHS laser — key device of the modern optoelectronics
- HS PD — the most efficient & high speed photo diode
- OEIC — only solve problem of high information density of optical communication system

3. Future high speed microelectronics will mostly use heterostructures

4. High temperature, high speed power electronics — a new broad field of heterostructure applications

5. Heterostructures in solar energy conversion:

the most expensive photocells and the cheapest solar electricity producer

6. In the 21st century heterostructures in electronics will reserve only 1% for homojunctions

Special summary

(written with the help of my lady colleague Dr. A.V.Gordeeva):

The purpose was both great and bright:
No more the dark! Let there be light!
First all appeared faint and dim
And did not look like laser beam.
But we made team of gentlemen,
Who swore to fulfill the plan.

In turn we kept a dreadful watch
When growing samples for research.
We got them stable, strong and fit
To make the substances emit.
So, to release eternal light,
We did the work all day and night
And when could neither work nor think
We had the Russian vodka drink.

But afterwards it proved all right:
Whoever now feels delight,
While CD player brings him dreams,
He takes for granted laser beams
And when employing solar cells,
Gets much from quantum dots and wells.

Yet there is something that has been
So far obscure and unseen
And we must find, as years pass,
What Nature has in store for us.
Young folk have come, results are new
And to the Physical Review
My students' works are to be sent
So our life will never end.