Technologies and materials developing in ITRI-Ioffe Joint Scientific Program

results of two-year joint work on MBE-grown devices

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….

Outline

Project I	**1.3 μm LDs and VCSELs based on InGaAsN/GaAs material systems**
Project II	**Blue/Green LDs based on III-N compound semiconductors**
Project III	**High power LDs for pumping EDFA system and for frequency doubled blue lasers**

1310 nm lasers as a driving force of GaAs-based technology

Brief overview of different approaches from the point of view of MBE engineer

MBE growth of 980 nm high power lasers

Technology of lasers with "standard" active region as a solid foundation to go to new types of lasers

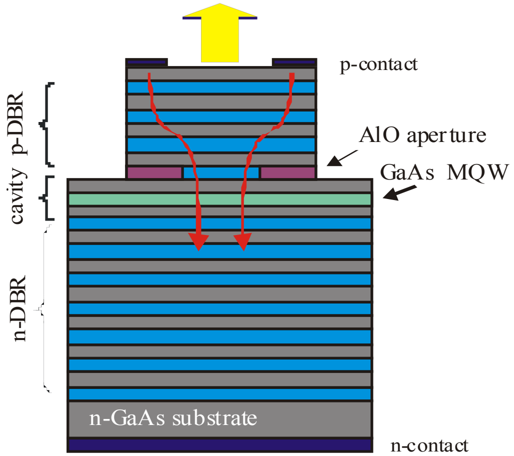
Quantum dot lasers

Advantages, problems, Ioffe background
and realization of 1310 nm QD laser with record characteristics

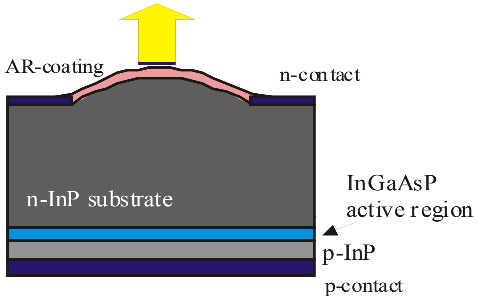
InGaAsN quantum well lasers

Diluted nitrides as a good exam for your MBE chamber
High power SM CW operation

Price-Performance Issue

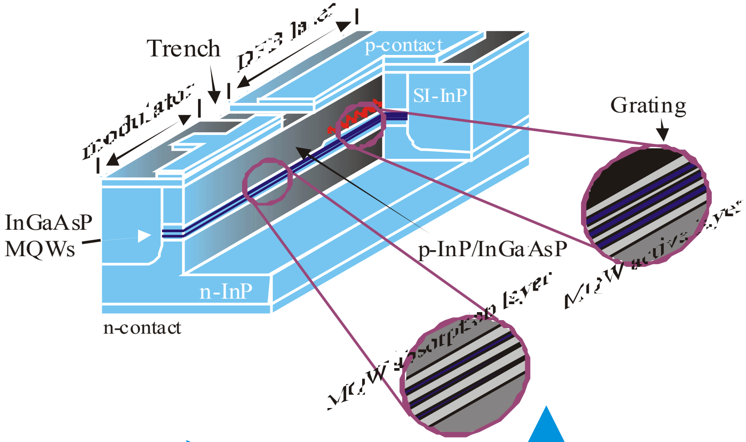


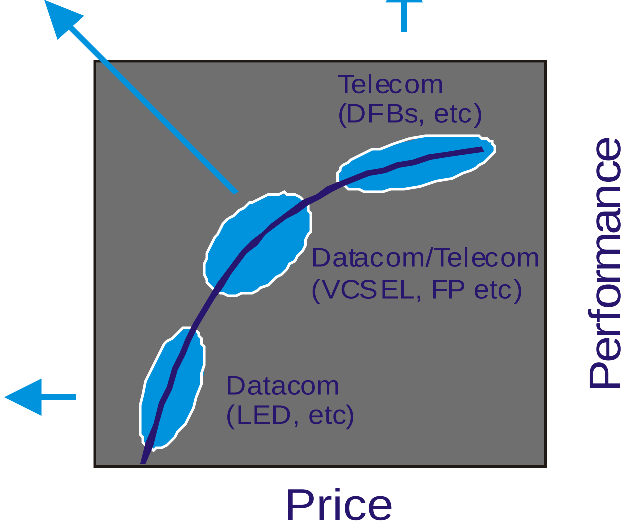
VCSELs:
medium cost lasers with high performance



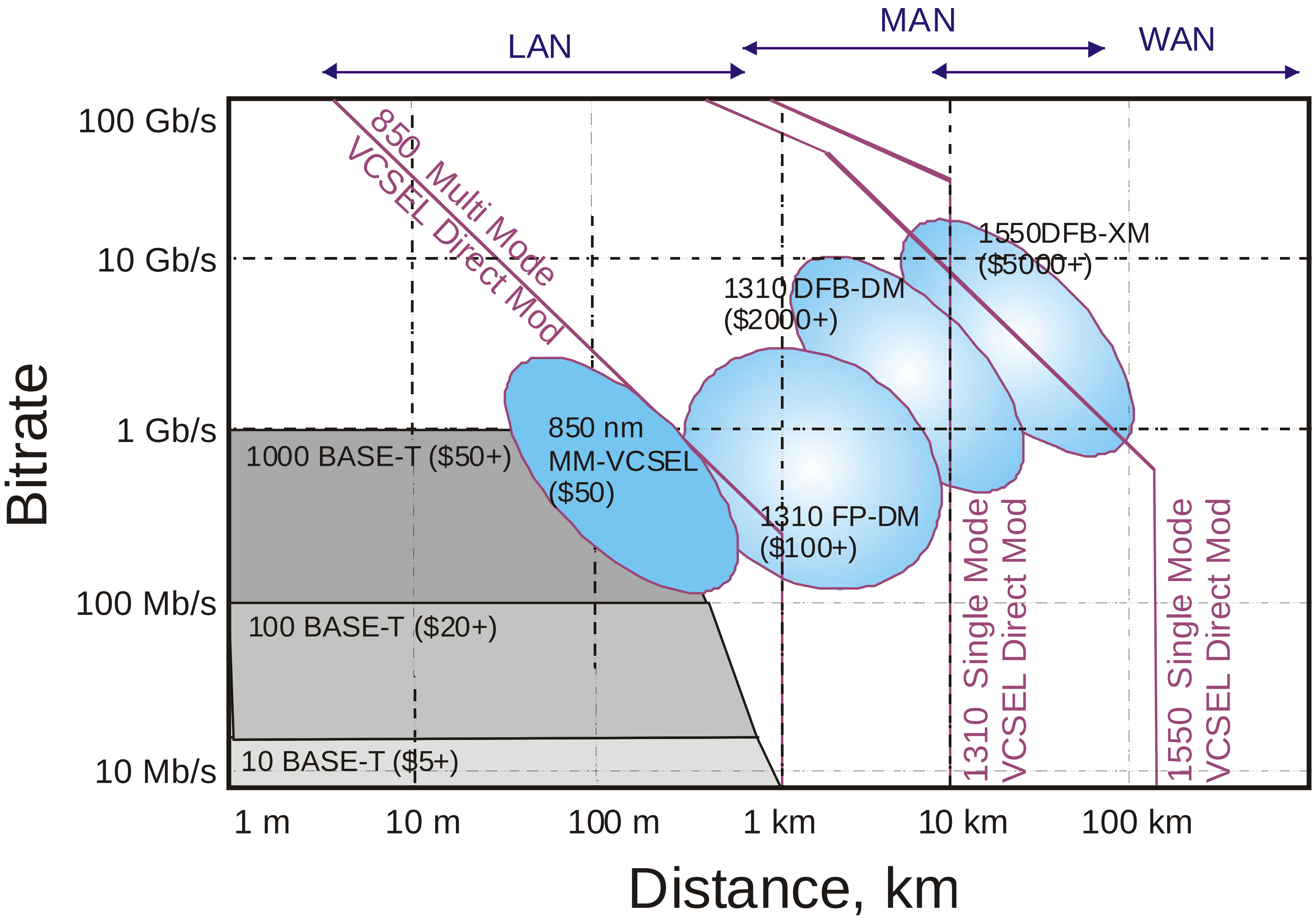
Surface emitting LEDs:
low cost diodes with low performance

Electroabsorption-modulated DFB lasers
High cost with ultra-high performance

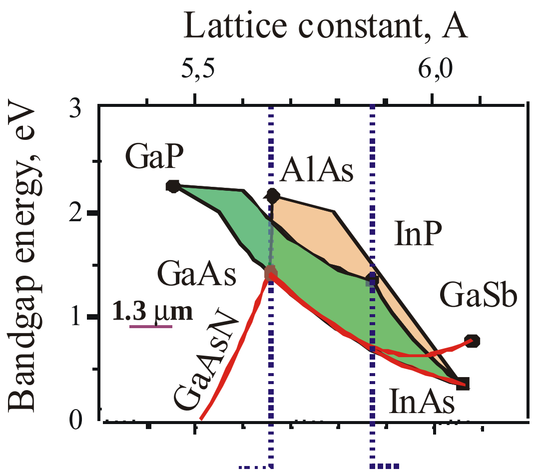




Technology landscape for fiber-optic transceivers



Challenges for long-wavelength VCSEL



Realization of 1.31 or 1.55 µm VCSELs is much more challenging than

850 nm VCSELs based on GaAs/AlGaAs QW
980 nm VCSELs based on InGaAs/GaAs QW

which are commercially available now

AlGaAs/GaAs	*InGaAsP/InP*
Good gain	Poor gain
Good carrier confinement	Poor carrier confinement
Good photon confinement	Poor photon confinement
Low temperature sensitivity	High temperature sensitivity
Low cost	High cost
ΔEc Al$_{0.3}$GaAs-/GaAs/-0.98 µm In$_{0.2}$GaAs ~ 330 meV	ΔEc InP-1.3 µm InGaAsP 160 meV

there are two choices

realization of 1.3 µm emission on GaAs-based materials
combination of InP-based active region and AlGaAs/GaAs DBR

Possible approaches and methods

material choice

object / material	DBR	active region
GaAs-based	✓	✓
InP-based	✓	✓

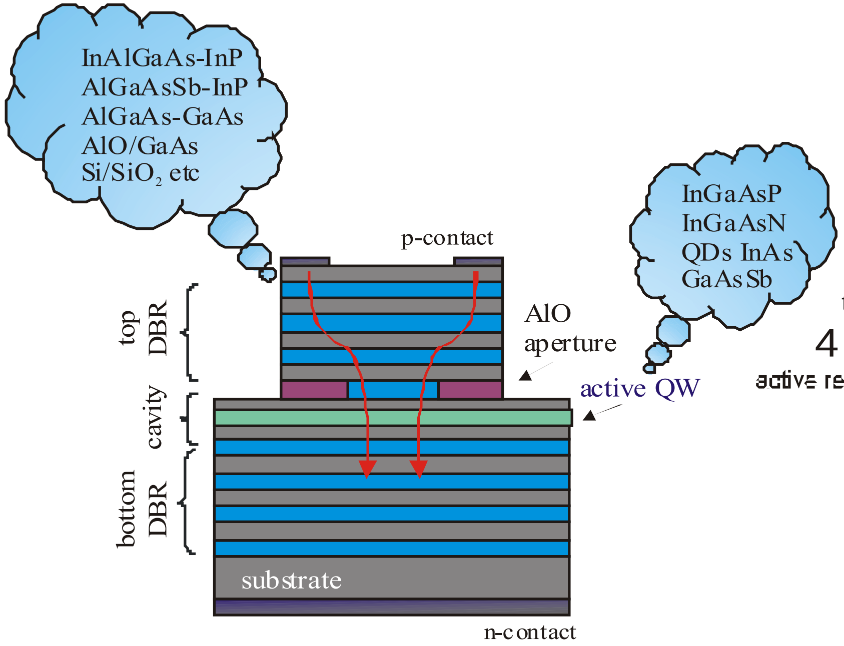
+ dielectric DBR

design choice

- fully doped mirrors
- intracavity
- up- or down- light output
- tunnel junction
- wafer bonding
- metamorphic mirrors
- optical pumping

EPI choice

- MOCVD
- MBE
- MBE-MOCVD



top DBR design

4 x 5 x 5 x 7 x 2 = 7000

active region bottom DBR EPI

main approaches:

1. Monolithically grown on GaAs InGaAsN, InAs QDs, GaAsSb - active region, AlGaAs/GaAs DBR

2. Wafer bonding InGaAsP-active region InAlGaAs DBR + fused AlGaAs DBR

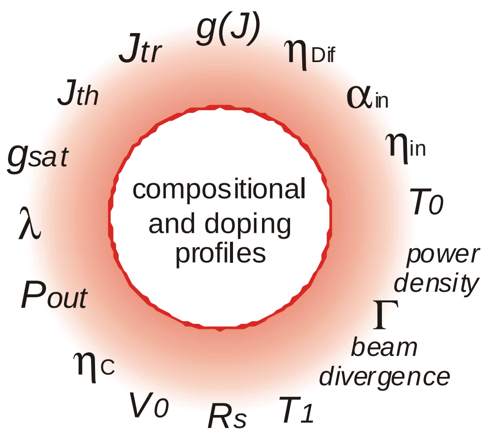
3. Optical pumping
fused 850 nm VCSEL

Laser = active region + laser structure

gain

current injection
light confinement
and propagation

Design and Growth of High Power Laser



compositional and doping profiles

$g(J)$

η_{Dif}

α_{in}

η_{in}

T_0

power density

Γ

beam divergence

T_1

R_s

V_0

η_C

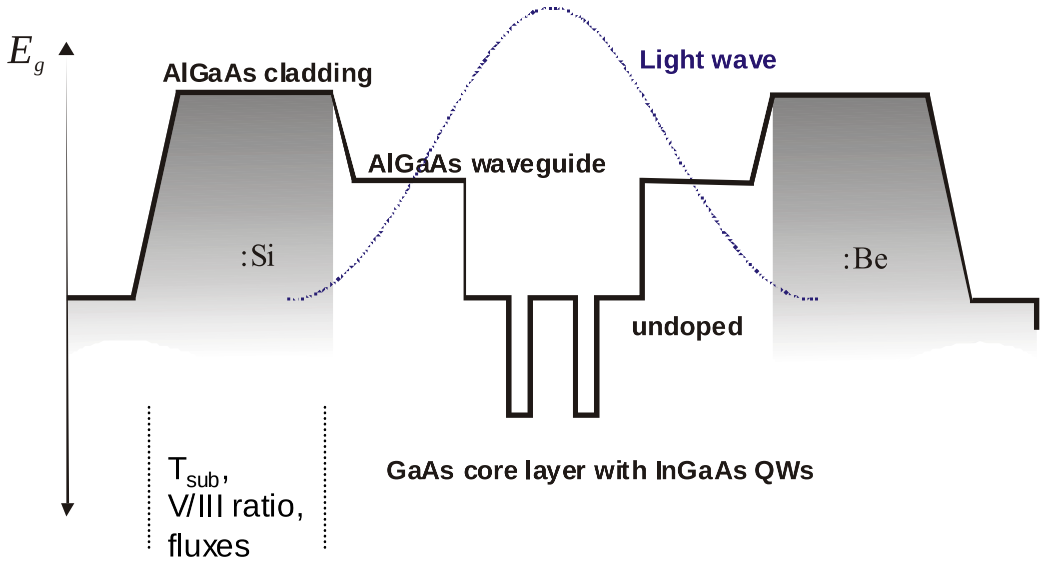
P_{out}

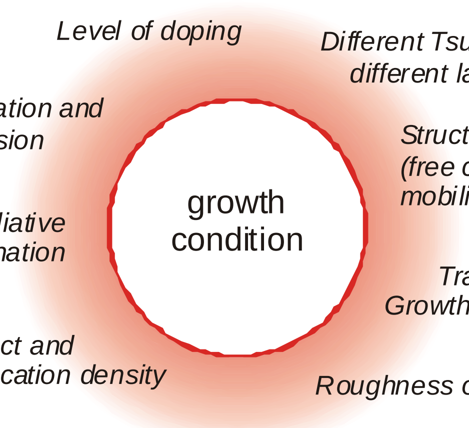
λ

g_{sat}

J_{th}

J_{tr}





growth condition

Level of doping

Different Tsub for different layers

Structure conductivity (free carrier concentration, mobility)

Transient layers
Growth interruptions

Roughness of interfaces

Chamber condition

Defect and dislocation density

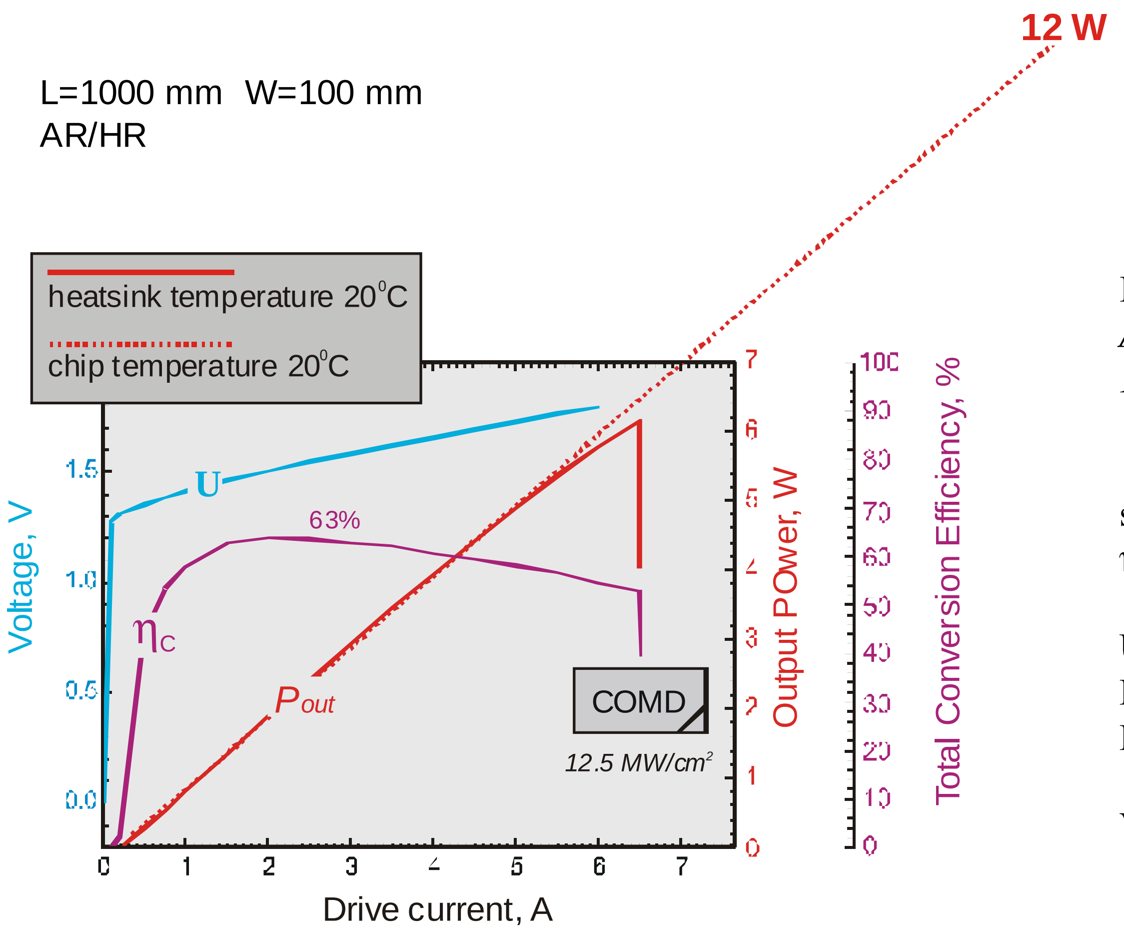
Efficiency of radiative recombination

Segregation and outdiffusion

There is a “trade off” within each circle and between circles

CW operation of broad area 980-nm laser

L=1000 mm W=100 mm
AR/HR



I_{th}=190mA (190 A/cm^2)
Analogue laser with optimized
Γ-factor shows I_{th}*=60 A/cm*^{2}

slope = 1.024W/A
η_D=81%

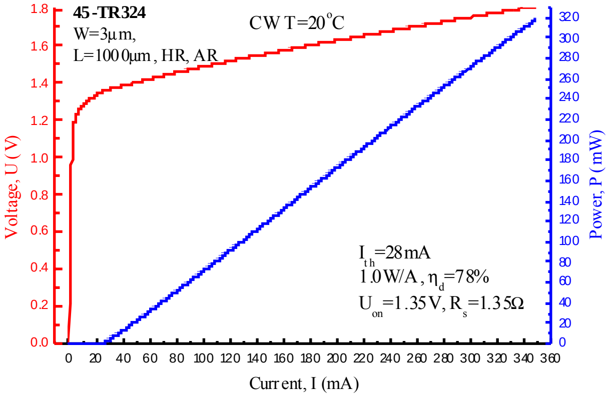
U_0=1.33V
R=80mOhm
R_S=8x10^{-5} Ohm cm^2

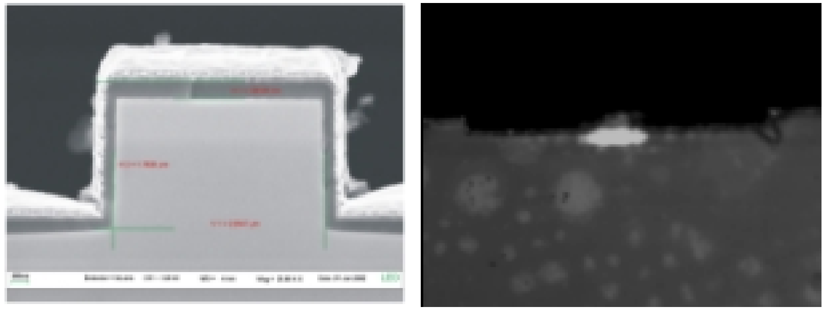
Vertical beam divergence < 35^0

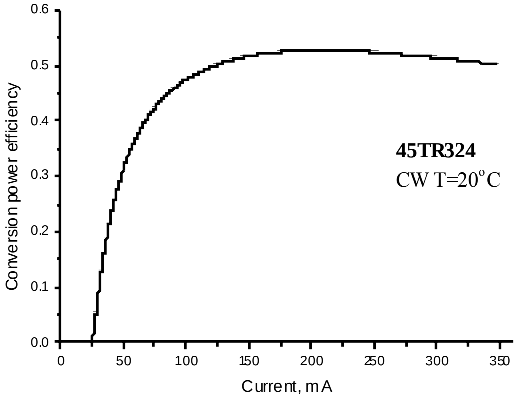
The output power is limited by COMD

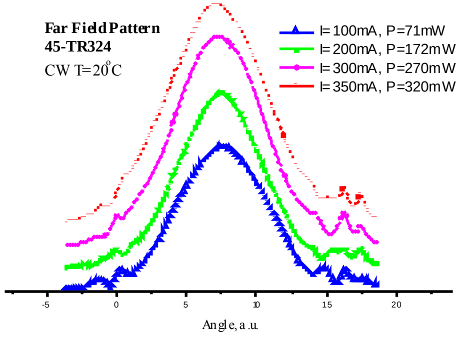
Thermal rollover is low even for 1-mm-long diode indicating much higher power can be achieved upon facet coating optimization

High power CW single lateral mode operation of 980 nm RW lasers









SM kink-free power >300 mW
wall-plug efficiency >50%

Dependence of Output Power, Voltage and Total Conversion Efficiency on Drive Current

Reliability issue is under active development now.

Background and achievement of Ioffe Institute and TUB

Technology of formation of self-organized QDs
Investigation of fundamental properties of semiconductor QDs
Theory of QD lasers
Realization of QD lasers

Russian State Prize was awarded for this work in 2001 to:
Zh.I.Alferov, L.V.Asryan, D.Bimberg, P.S.Kop'ev, N.N.Ledentsov, V.A.Shchukin, R.A.Suris, V.M.Ustinov

List of some major results in QD laser technology

❖ First demonstration of SK QD laser,	*Ledentsov et al, Semiconductors 28, 1484, 1994*
❖ Laser with highest output power for SK QD	*Kovsh, El. Lett., 35, 1161, 1999*
❖ Realization of 1.3 µm QD laser	*Zhukov et al, Appl.Phys.Lett. 75, 1926, 1999*
❖ 1.3 µm high power SM RW QD laser	*Ledentsov et al, IEEE J. of Sel.Top.inQ.E.,6,439, 2000*
❖ First 1.3 µm GaAs based VCSEL,	*Lott et al, El.Lett., 36, 1384, 2000*
❖ High power lasers for 0.94 µm based on submonolayer QDs	*Zhukov et al, Electron. Lett., 35, 1845, 1999*

Recent achievements in Ioffe Institute in QD technology

940 nm laser based on submonolayer QDs with the highest CW output power (> 6W) ever reported for any type of QD lasers

A.R.Kovsh A.E.Zhukov, N.A.Maleev, S.S.Mikhrin, D.A.Livshits, Y.M.Shernyakov, M.V.Maximov, N.A.Pihtin, I.S.Tarasov, V.M.Ustinov, N.N.Ledentsov, D.Bimberg, Zh.I.Alferov
Microelectronic Journal, 2003

1.3 μm QD lasers with record combination of characteristics such as J_{th} <150 A/cm^2, η_D >80% and T_0 >120K for any kind of near-1.3-micron lasers

A.R.Kovsh, N.A.Maleev, A.E.Zhukov, S.S.Mikhrin, A.P.Vasil'ev, Yu.M.Shernyakov, M.V.Maximov, D.A.Livshits, V.M.Ustinov, N.N.Ledentsov, D.Bimberg, Zh.I.Alferov,
Electr.Lett., 38(12),2002

Joint work and development are useful for ALL Projects including those which are not directly involved in the Joint Program

Laser = active region + laser structure

gain

current injection
light confinement
and propagation

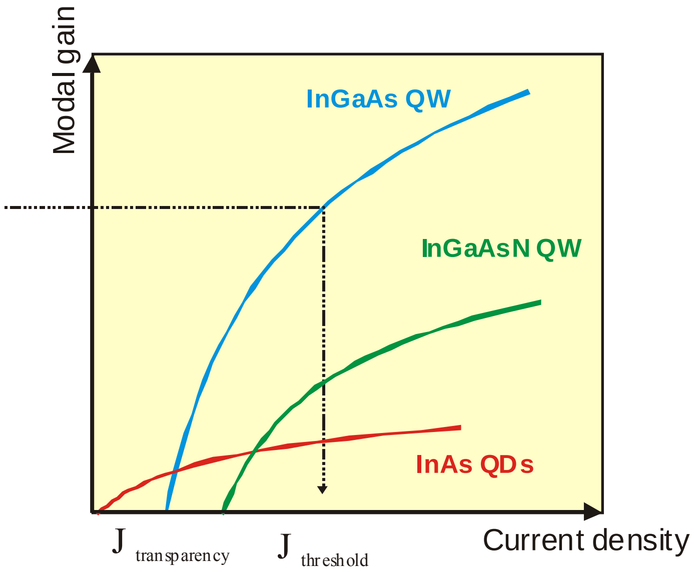
Gain-current curve as one of the main characteristics of laser active region

$$g_{\mathrm{mod}} = \Gamma_z g_{th} = \alpha_i + \alpha_m = \alpha_i + \frac{1}{L}\ln\left(\frac{1}{R}\right)$$

Total losses

$$\eta_D = \eta_i \frac{\alpha_{mir}}{\alpha_{mir} + \alpha_i}$$

$$\alpha_{mir} = \frac{1}{L}\ln\frac{1}{R}$$

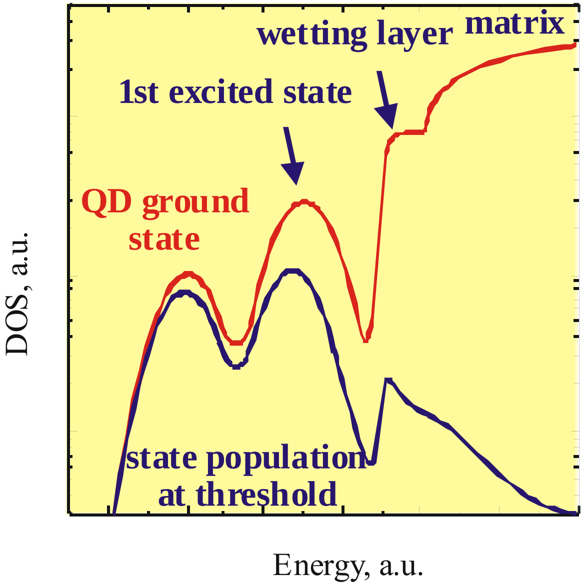


Higher output loss -> higher η_D

Reduced differential gain leads to degradation of laser performance especially for short cavity devices (high threshold, low differential efficiency, low T_0*)*

QD – fundamental problems related to QD formation
InGaAsN – technical problems related to cleanness of materials

Problems of self-organized QDs which have to be solved to get high laser performance



Gain saturation

Loss Multiplication effect

Internal loss = waveguide imperfection
+ free carriers in claddings
+ free carriers in wavegude
+ ...

$$\eta_D = \eta_i \frac{\alpha_{mir}}{\alpha_{mir} + \alpha_i}$$

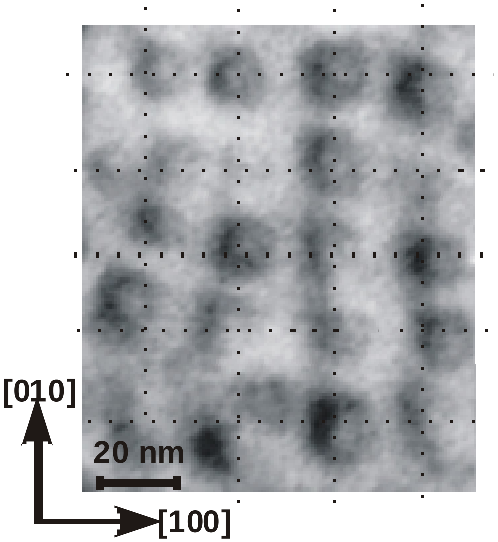
Low gain limits the range of possible mirror loss

High density of states in matrix states “pins” Fermi level at higher position even in the case of high localization

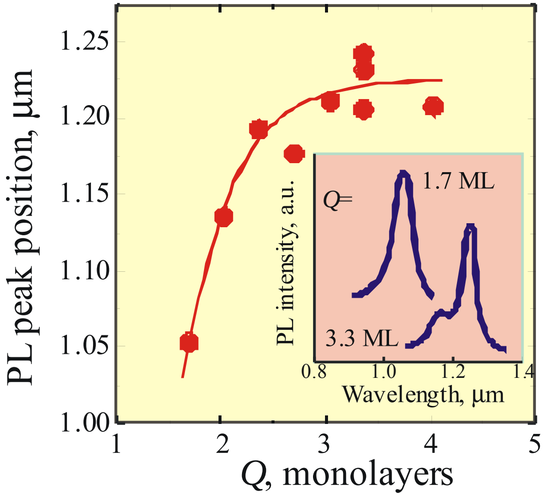
It leads to high contribution of upper states to the threshold current and increase internal loss.
In this case the quality of matrix plays also crucial role

Structural and optical properties of InAs QDs in GaAs matrix

Plan-view TEM

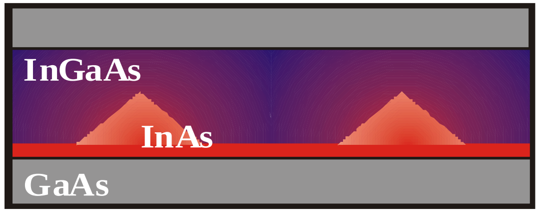


Room-temperature PL



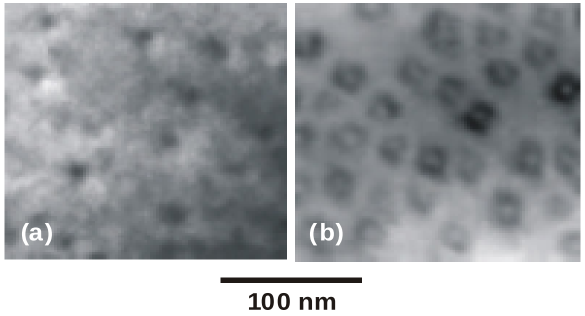
Similar to the case of InGaAs QW there is a red limit of possible wavelength
Special procedure has to be developed to extend wavelength to 1.3 µm

Formation of QDs emitting at 1.3 µm



MBE growth
1. Formation of self-organized InAs QDs
2. Capping by InGa(Al)As layer

Plan-view of TEM image



Possible mechanisms for
red-shift of PL peak position :

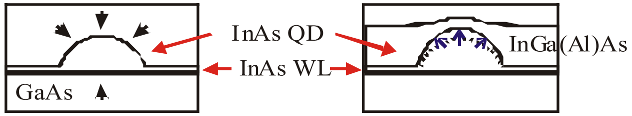
①

Reduced band-gap of surrounding material

②

Abrupt interfaces due to reduced diffusion
(interdiffusion ~ Δ n)

③



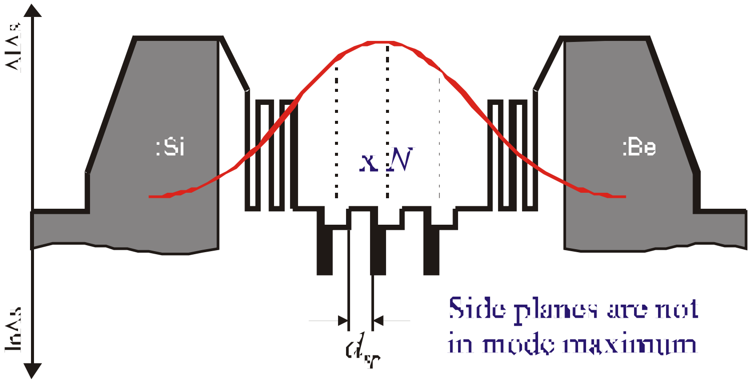
Reduced strain in QDs due to relaxation of lattice constant in growth direction

④

Increased QD sizes (InAs accumulation near QDs)

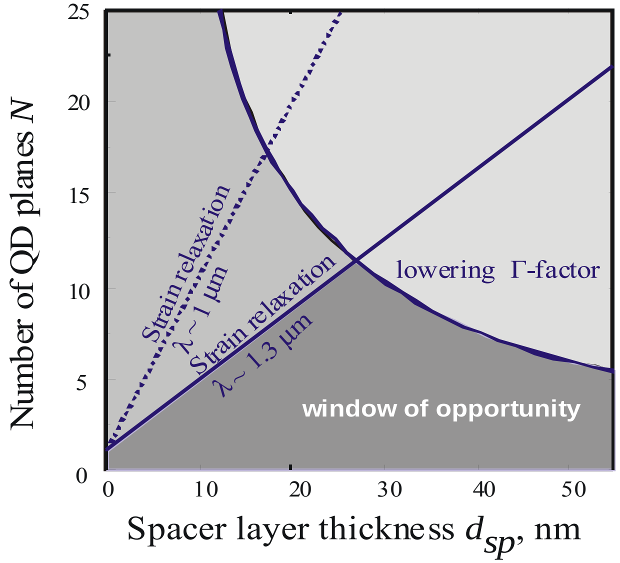
This technology is well established in different modifications in many research groups over the world

Multiple stacking is a key technology for realization of high performance QD lasers



Side planes are not in mode maximum

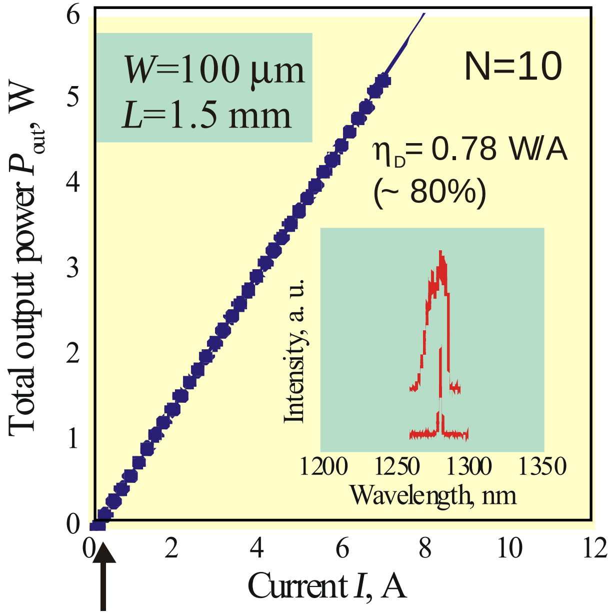
Number of QD planes vs spacer thickness



Maximum number of QD planes is limited due to strain relaxation (depends on wavelength) in combination with Γ-factor compression

Laser based on 10 layers of QDs

Light-current curve (pulsed)



I_{th}=220 mA (147 A/cm^2)

For lasers based on 5 or 10 layers

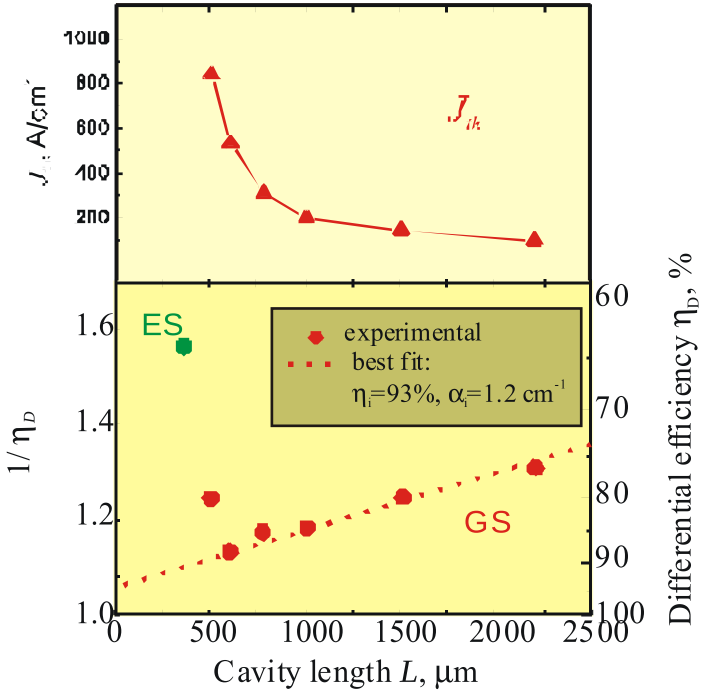
J_{th} <150 A/cm^2 (100 A/cm^2)
η_D>70% (88%)
T_0>100 K (150K for 1.5 mm *L*)
in 20C-50C range

High external differential efficiency in combination with low threshold current and required spectral range

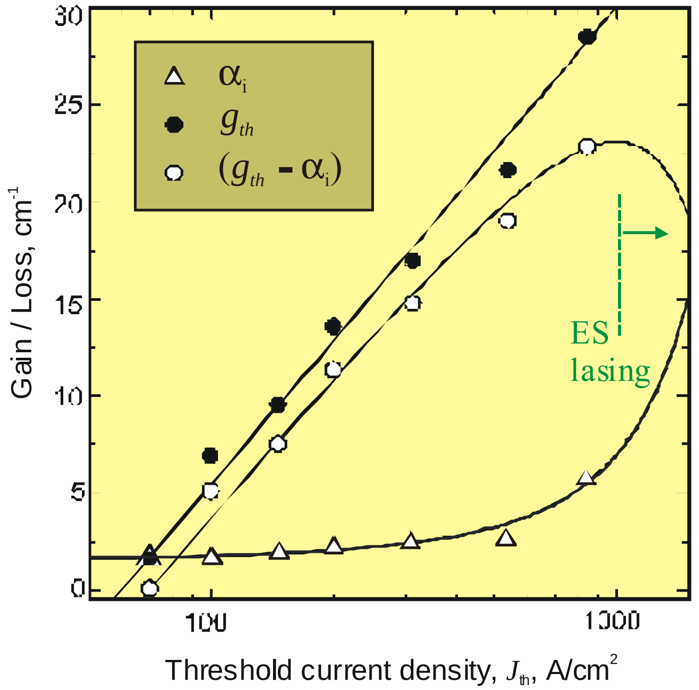
Successful realization of multiple stacking allowed demonstration of unbeatable laser performance in 1.3 µm range

Effect of loss multiplication in QD lasers

J_{th} and Efficiency vs cavity length



Gain - current



$$g_{th} = \alpha_{in} + \alpha_{mir}$$

$$\eta_D = \eta_i \frac{\alpha_{mir}}{\alpha_{mir} + \alpha_i} \qquad \alpha_{mir} = \frac{1}{L} \ln\left(\frac{1}{R}\right)$$

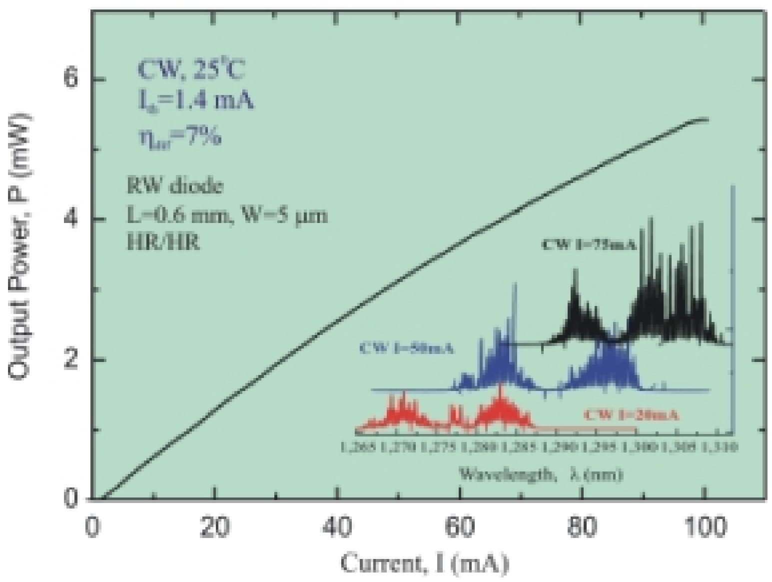
$$\alpha_i(J_{th}) = 1.5 \times \exp(J_{th} / 650)$$

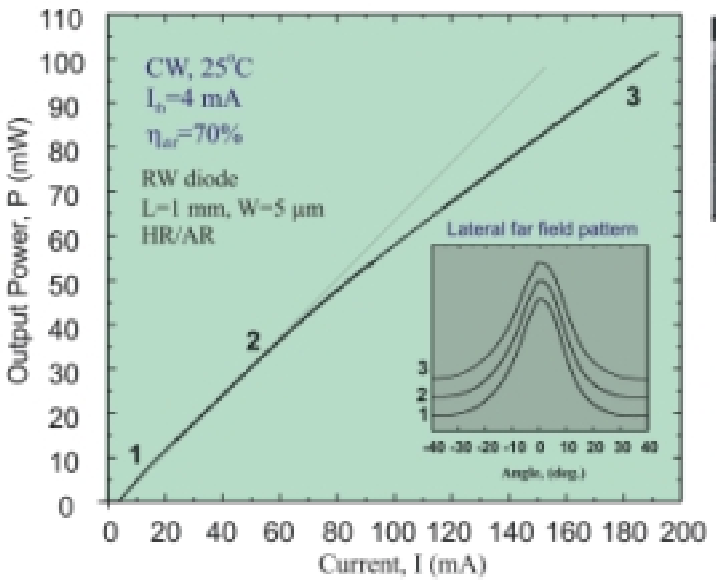
$$g_{th}(J_{th}) = 10.7 \times \ln(J_{th} / 60)$$

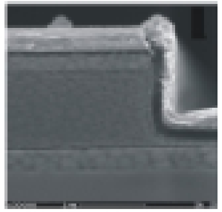
Increment in internal loss with threshold current limits the possible mirror loss

Single lateral mode operation of QD lasers

Output power vs drive current


Diode with low mirror loss


Diode with high mirror loss


SEM image

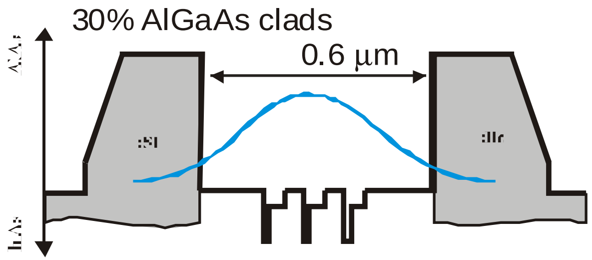
The lowest value of threshold current for unburied RW diodes
1.4 mA

Low threshold current
high differential efficiency
reasonable T_0 (~80 K)
all together

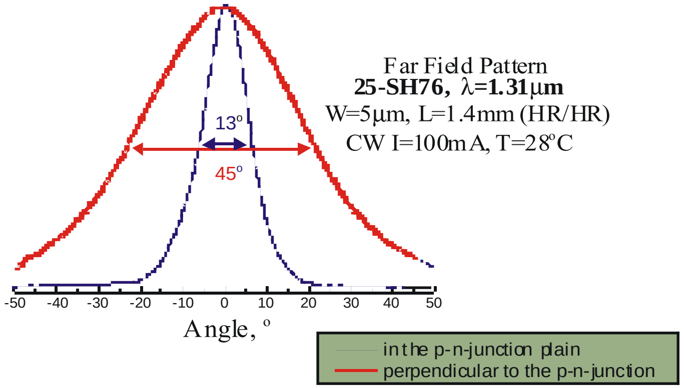
If the threshold is almost zero do you need high T_0 ?

QD laser with improved beam divergence

5 layers of QDs

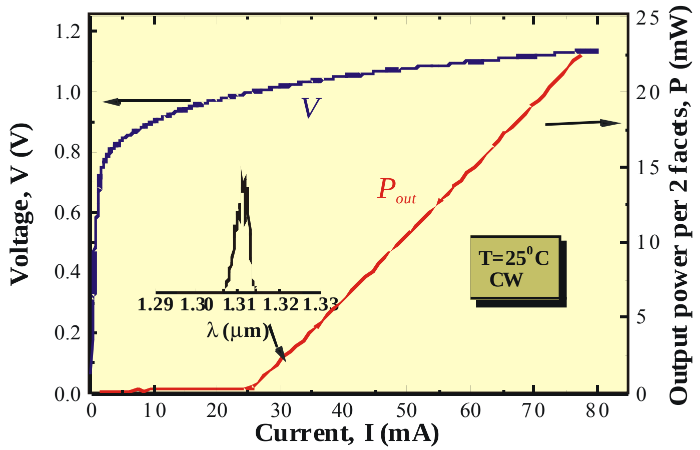


high Γ factor - large beam divergency
narrow beam - low Γ-factor



Far Field Pattern
25-SH76, λ=1.31µm
W=5µm, L=1.4mm (HR/HR)
CW I=100mA, T=28°C

W=5 µm, L=3 mm, as cleaved



λ=1.31 µm beam divergency 45^0

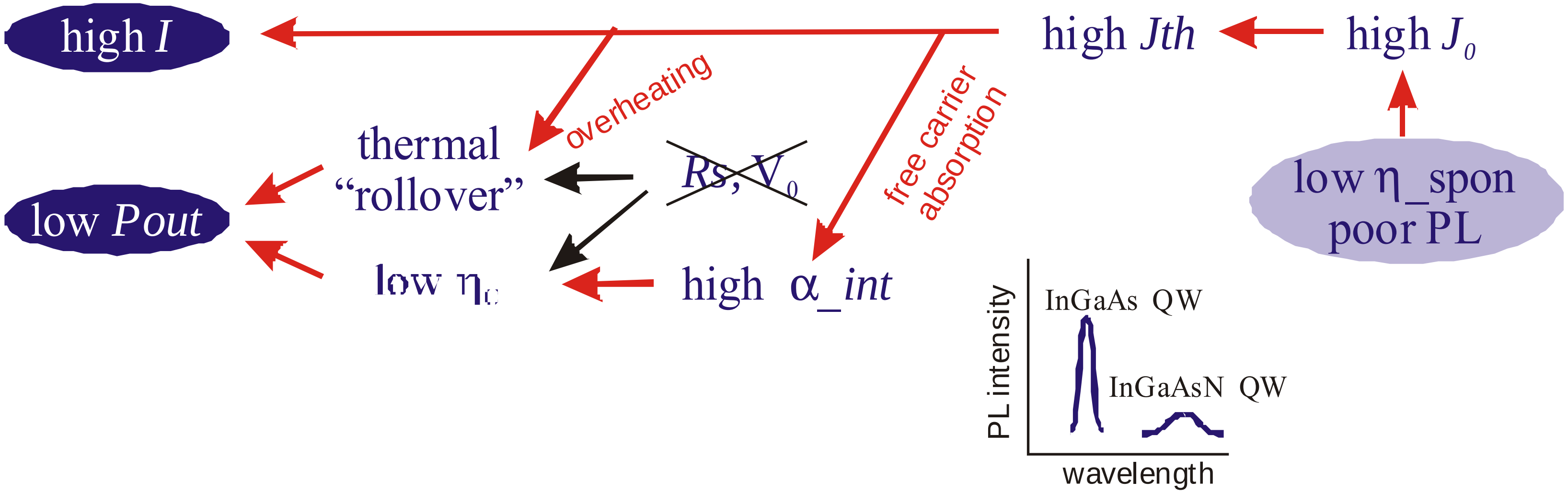
threshold	*efficiency*	*I-V*
I_{th}=26 mA J_{th}=173 A/cm^2	0.43 W/A η_{Dif}=45%	R_s=1.0 Ω V_0=1.0 V

First realization of 1.31 µm QD laser with high performance in low-Γ-factor design

State-of-the-art of InGaAsN technology when the project was initiated

1. The broad variety of laser characteristics indicates that technology of low-N-containing GaAs-based materials is still immature

2. The InGaAsN-LDs are inferior to InGaAs-counteparts



high *I*

high *Jth*

high J_0

overheating

free carrier absorption

thermal "rollover"

~~Rs, V_0~~

low *Pout*

low η_c

high α_*int*

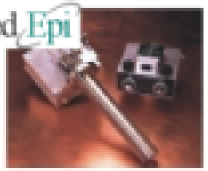
low η_spon
poor PL

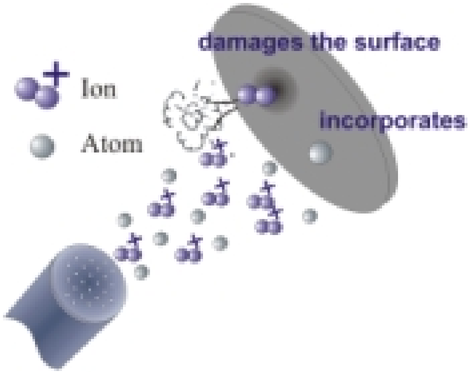
Let's reveal the reasons responsible for degradation of PL and eliminate them

Nitrogen Plasma Source to grow InGaAsN materials

UNI-Bulb RF Plasma Source

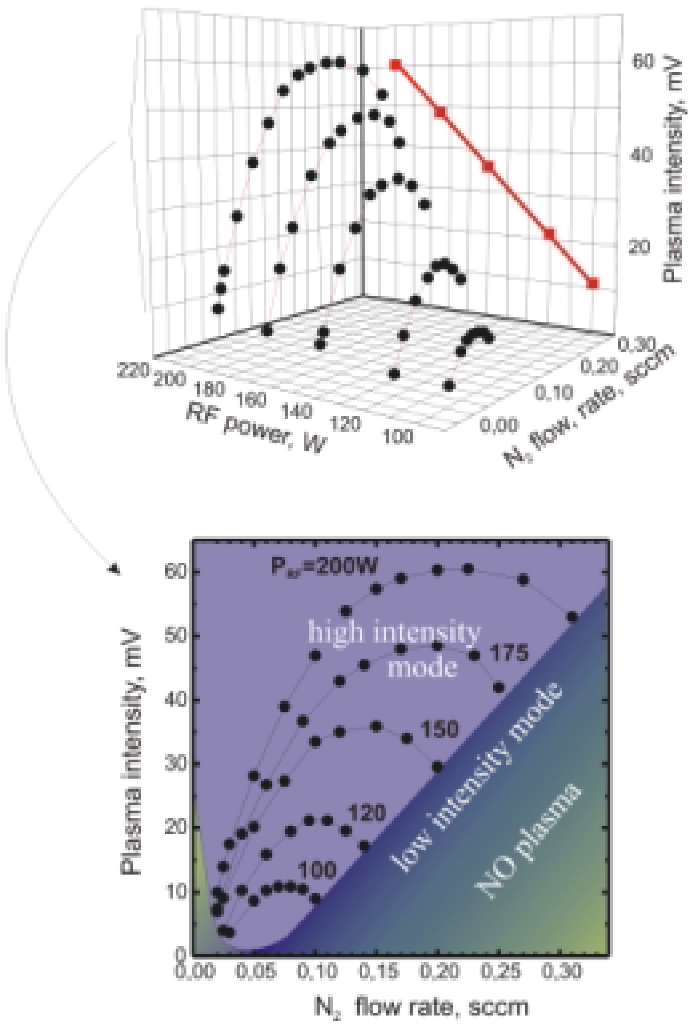
Applied Epi





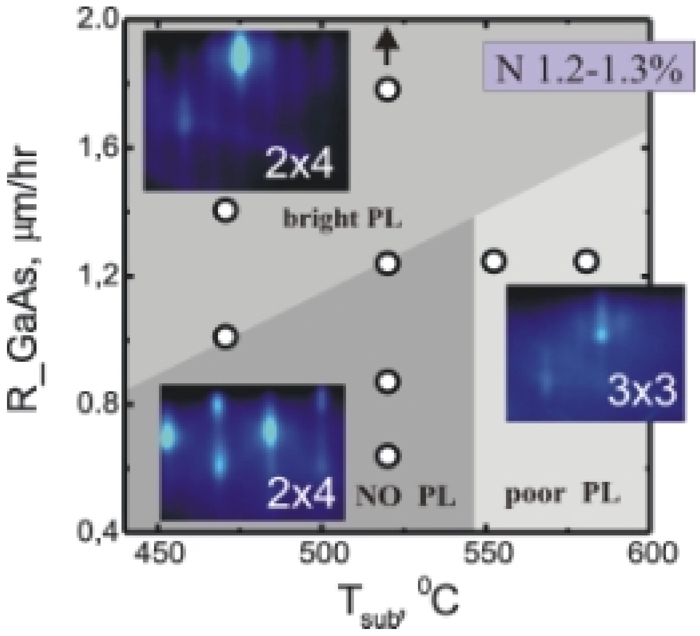
Changeable parameters of Plasma Source

RF power
N_2 flow rate
aperture design



Careful optimization of plasma cell design and operation can significantly decrease effect of ion damage

Phase-diagram of the growth of GaAsN



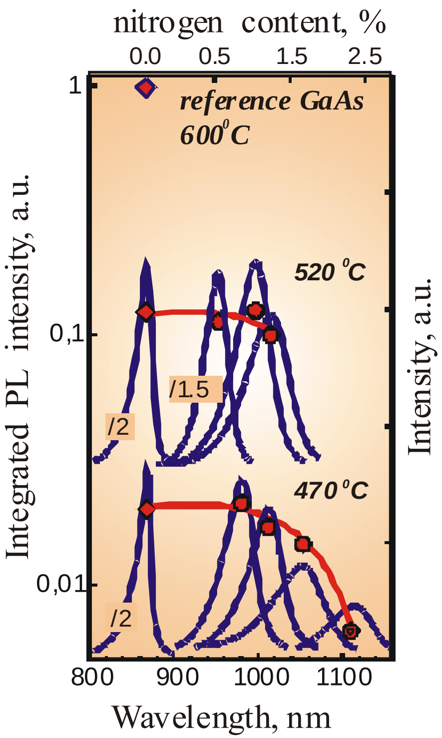
"Phase separation" can be suppressed by higher growth rate or by lower growth temperature

The presence of Indium enhances the effect of phase separation shifting the boarder to the left

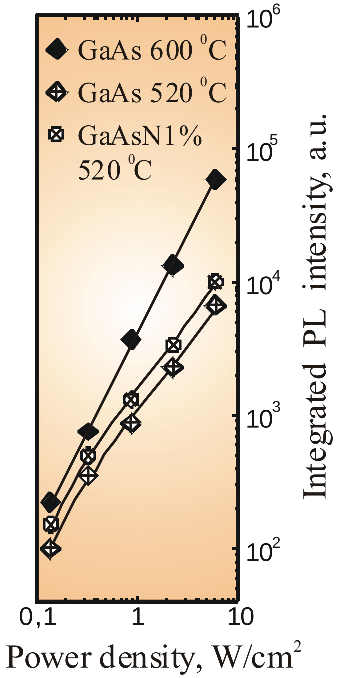
Even without Nitrogen highly strained InGaAs QW wants to go to QDs

LOW TEMPERATURE GROWTH
is necessary to grow high structural quality N-containing material

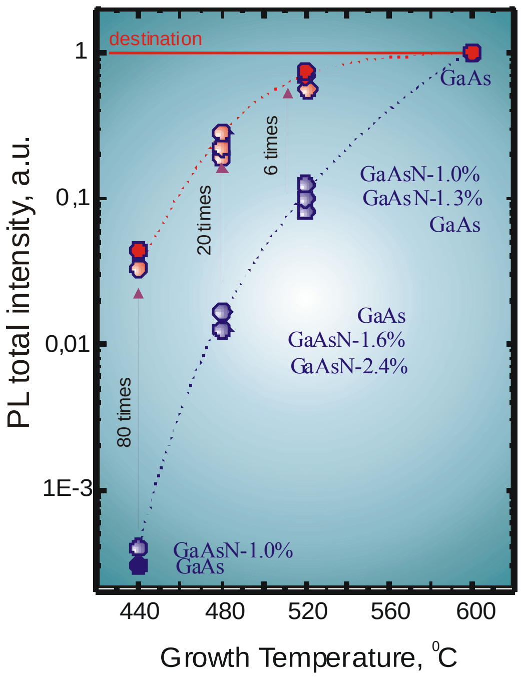
Low temperature growth of bulk GaAsN material



PL spectra of GaAs(N) layers (right axis), dependence of integrated PL intensity of GaAs(N) layers on PL wavelength grown at different temperatures (left axis)



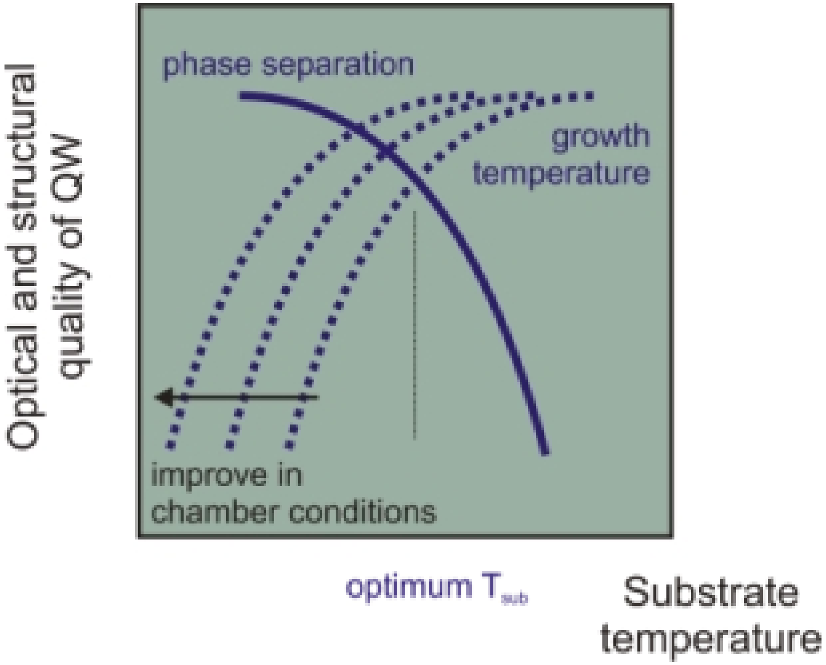
Dependence of integrated PL intensity on excitation power for GaAs grown at 600 °C and GaAs and GaAsN$_{001}$ grown at 520 °C.



Dependence of integrated PL intensity on growth temperature for different structures with and without annealing

Low temperature growth is the main reason of poor optical quality of N contained structures

Philosophy of the InGaAsN growth



The Nature sets the solid curve

whereas

The dot curve can be controlled by human beings

MBE equipment in ITRI/OES of semi-production level

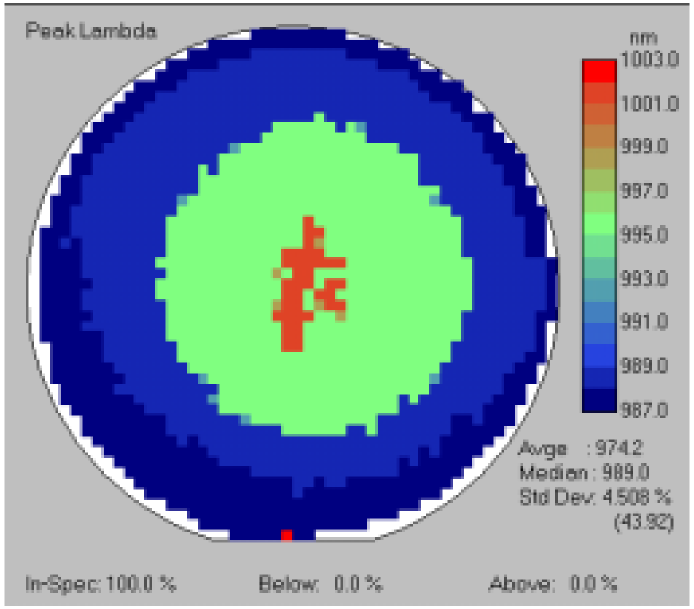
Two systems Riber Epineat connected by vacuum line
1 x 4 inch or 3 x 2 inch wafers

Low temperature growth in "big" machine (vertical reactor) is much more challenging compared with reactors of laboratory scale

Improvement of uniformity of nitrogen incorporation by special design of separate chamber for N source

$\Delta\lambda > 10$ nm

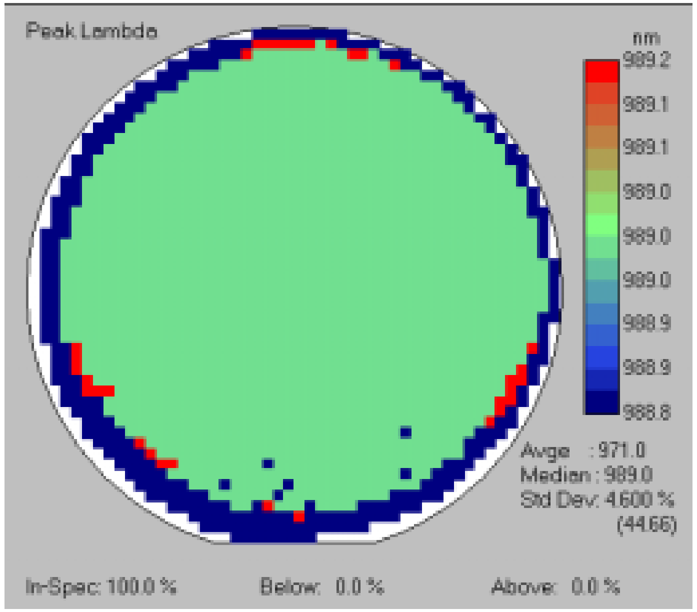
$\Delta\lambda < 1$ nm



Avge : 974.2
Median : 989.0
Std Dev: 4.508 %
(43.92)

In-Spec: 100.0 %
Below: 0.0 %
Above: 0.0 %

before



Avge : 971.0
Median : 989.0
Std Dev: 4.600 %
(44.66)

In-Spec: 100.0 %
Below: 0.0 %
Above: 0.0 %

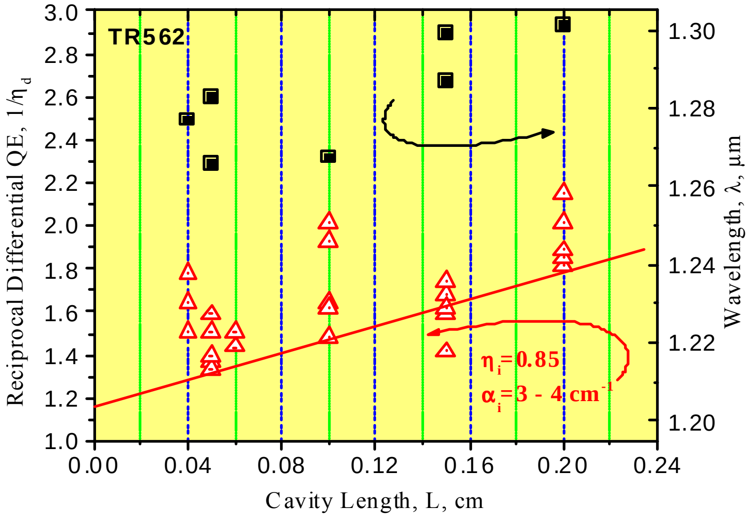
after

Mapping of PL peak position of PL from $GaAsN_{0.01}$

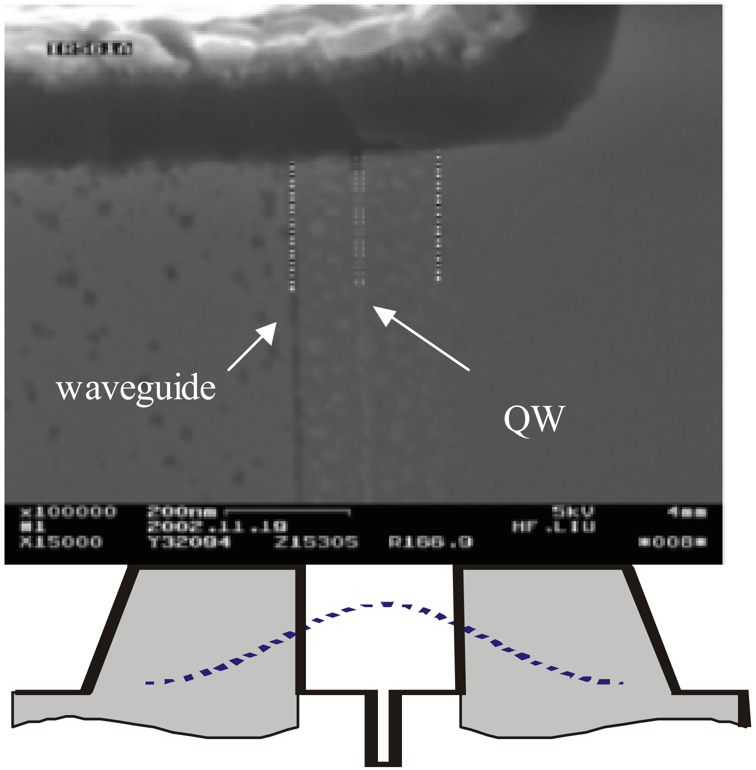
Realization of 1.3 μm InGaAsN laser

L=1 mm, W=10 μm

- Internal quantum efficiency: $\eta_i > 85\%$,
- Threshold current density: $J_{th} < 700$ A/cm^2
- slope efficiency = 0.67 W/A
- Characteristic temperature: $T_0 = 121$ K



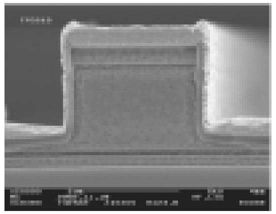
SEM image after BOE



InGaAsN/GaAs SQW

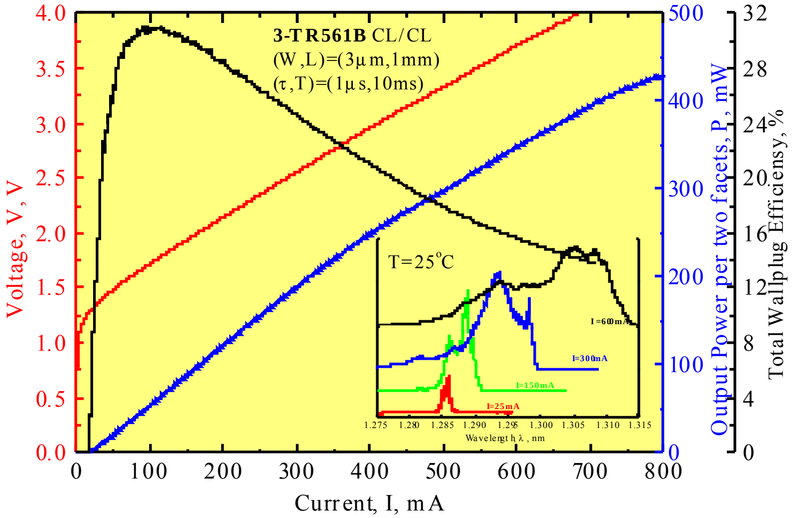
High internal quantum efficiency @ Low internal loss

Threshold current density is to be improved further

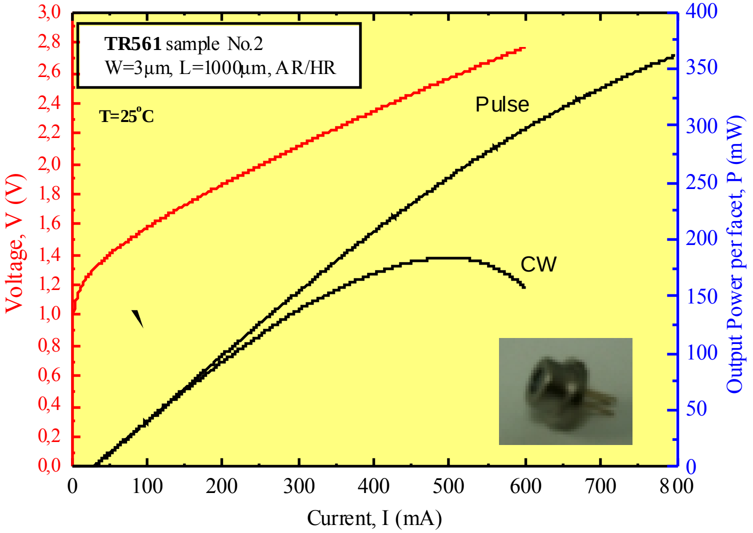


Single lateral mode CW high power laser based on SQW InGaAsN

before packaging



TO46



I_{th}=20.6 mA
Slope 0.67 W/A

I_{th}=22 mA
Slope 0.59 W/A

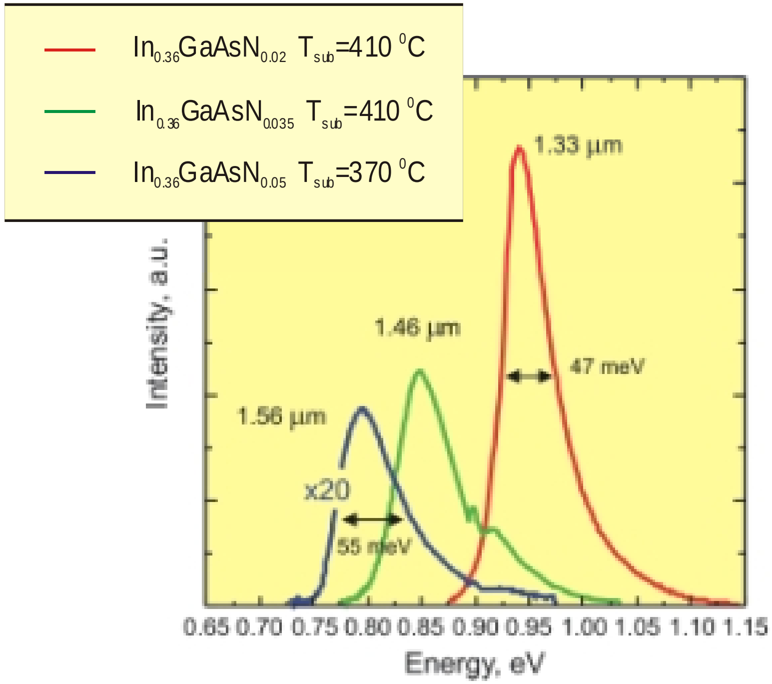
The highest ever reported SM CW power for 1.3 μm GaAs-based laser **180 mW**

Top results in 1.3 μm RW lasers based on InGaAsN

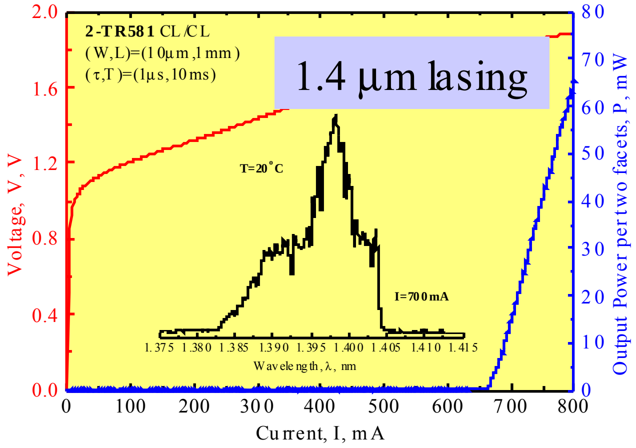
Ridge waveguide lasers	Method Company	Threshold current I, mA	Threshold current density J_{th}, kA/cm^2	Slope efficiency W/A	T_0 K
DQW 700x4 μm CL/CL	MBE Infineon AG	31	1.1	0.42	110
SQW 800x4 μm HR/CL	MBE TU Wurzburg	21	0.65	0.52	150 (special design)
SQW 1000x3 μm CL/CL	MBE ITRI/OES	21	0.7	0.67	85

toward 1.55 μm devices on GaAs

Room temperature PL spectra of InGaAsN QW



I-V and L-I curve of 1.4 μm laser

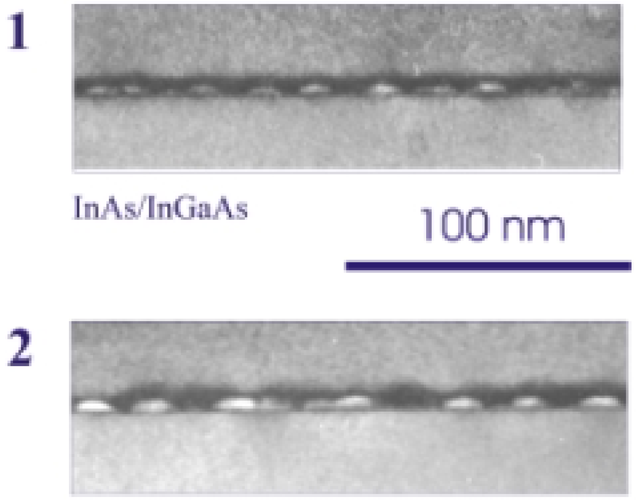


very first result

too High threshold	6.7 kA/cm^2
but High efficiency !!!	0.5 W/A

There is strong evidence of perspective for GaAs based lasers to cover the whole wavelength range of telecommunication

Alternative way to go
InAs/InGaAsN QDs for 1.55 μm application

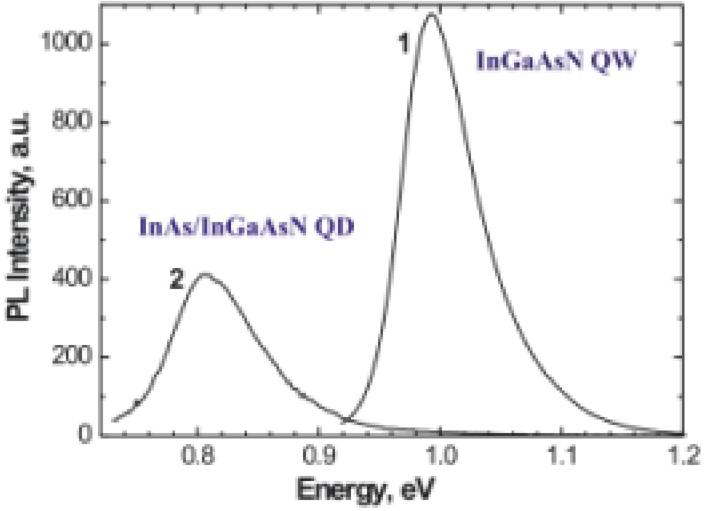


InAs/InGaAs

InAs/InGaAsN

1.55 μm
InAs/InGaAsN QDs

1.3 μm
InGaAsN QW or InAs/InGaAs QDs



A.Yu.Egorov, V.A.Odnoblyudov et al MBEXII conf, USA, Sept 2002

Let’s combine advantages (*and avoid disadvantages*) of both approaches

Vertical Laser = active region + laser structure

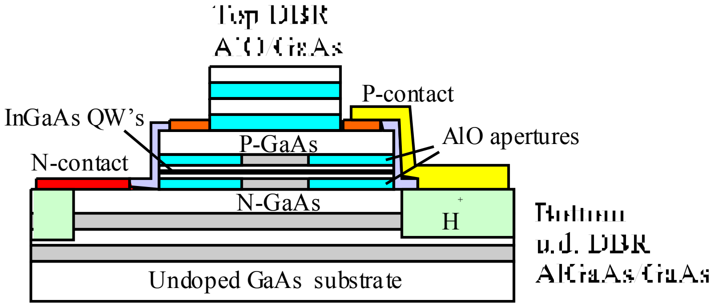
gain

current injection
light confinement
and propagation

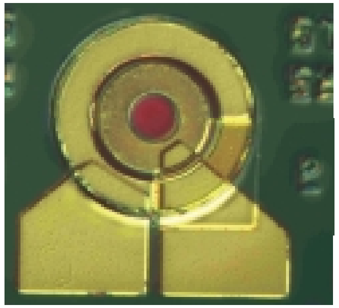
DBR, cavity

980 nm intra-cavity contacted QW VCSEL

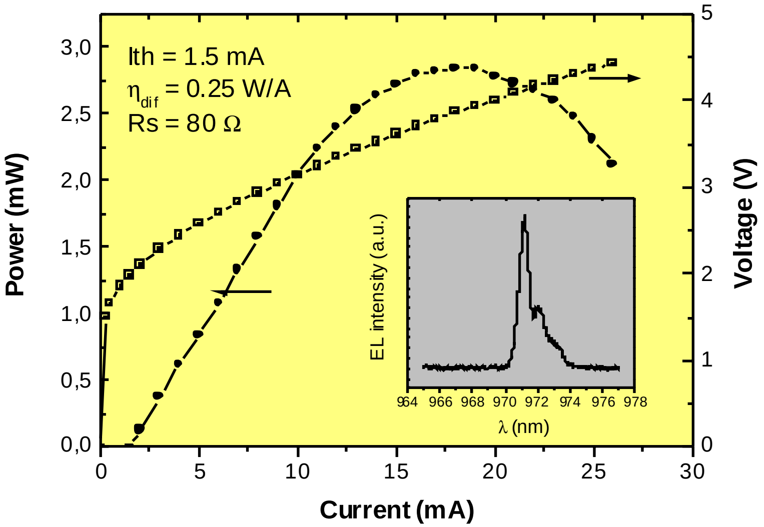
Scheme



SEM image

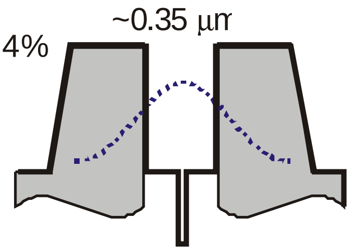


L-*I* and *I*-*V* curves



Technology intracavity-contacted VCSEL with the state-of-the-art performance has been developed using active region based on 980 nm InGaAs QW

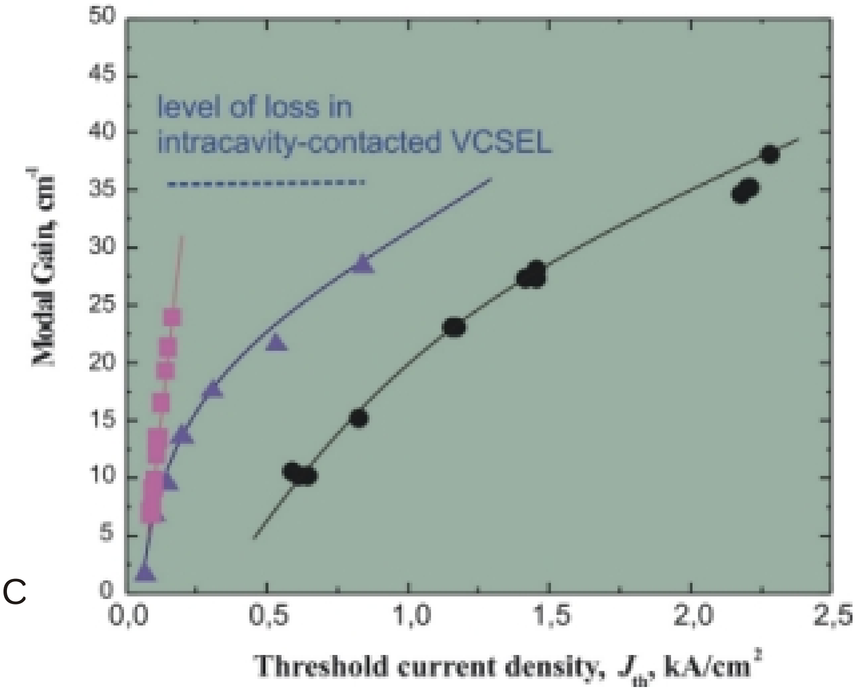
1.3 μm gain media for VCSEL



all lasers are about the same Γ-factor design
(0.016 for 65A QW)

- ● 1.3 μm SQW InGaAsN 420°C
- ▲ 1.3 μm QDs (10 layers)
- ■ 1.04 μm SQW InGaAs QW 500°C

Dependence of modal gain on current density



extracted from dependences of
J_{th} and η_D on cavity length

Both InGaAsN QW and InAs QDs can be used as an active region of VCSEL

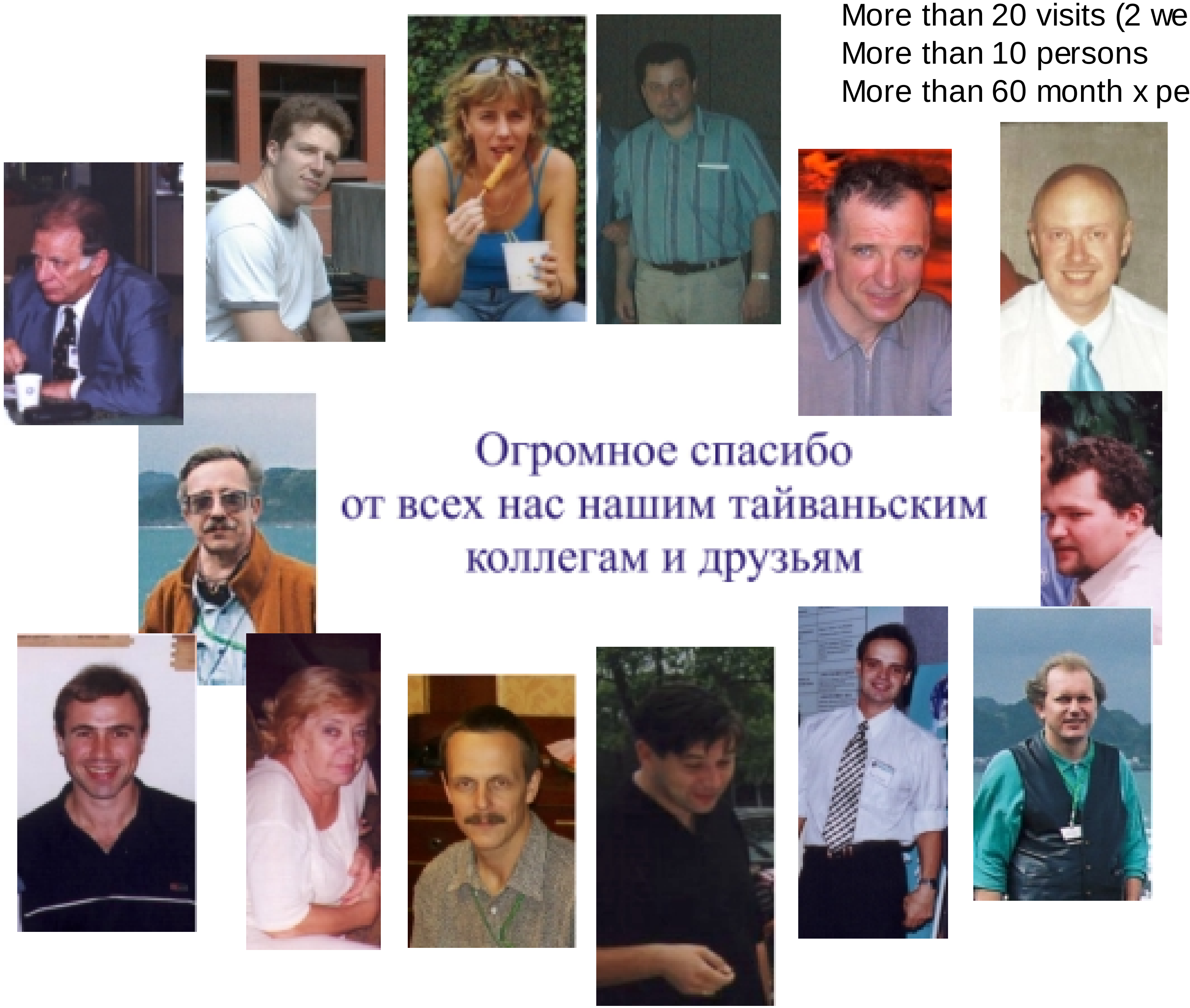
Device results which characterize the level of technology developed within ITRI-Ioffe Joint Program

- 980 nm high power lasers (broad area and SM) with the state-of-the-art level of performance (total conversion efficiency of 60% in low-Γ-factor design)
- 1.3 µm QD lasers with a record vertical beam divergence
- 1.3 µm SM QD lasers with the lowest threshold for any kind of unburied lasers (1.4 mA)
- First realization of InGaAsN lasers with high performance by MBE setup of production level
- 1.3 µm SM high power InGaAsN lasers with the record characteristics (highest power ever reported for long-wavelength GaAs-based lasers 180 mW)
- 980 nm intracavity contacted VCSEL with state-of-the-art level of performance

Currently under development:

- Reliability issue
- 1.3 µm VCSEL based on both InGaAsN QW and InAs/InGaAs QDs
- 1.55 µm lasers based on InGaAsN QW and InAs/InGaAsN QDs

More than 20 visits (2 weeks – one year)
More than 10 persons
More than 60 month x person



Огромное спасибо
от всех нас нашим тайваньским
коллегам и друзьям

our very big thank to our Taiwanese
colleagues and friends

Conclusion

Let’s keep making best lasers together