THz-QCLs based on three-well modules & injector barrier effects on device performance

<u>Hui Luo</u>, Sylvain R. Laframboise, Z. R. Wasilewski, H. C. Liu

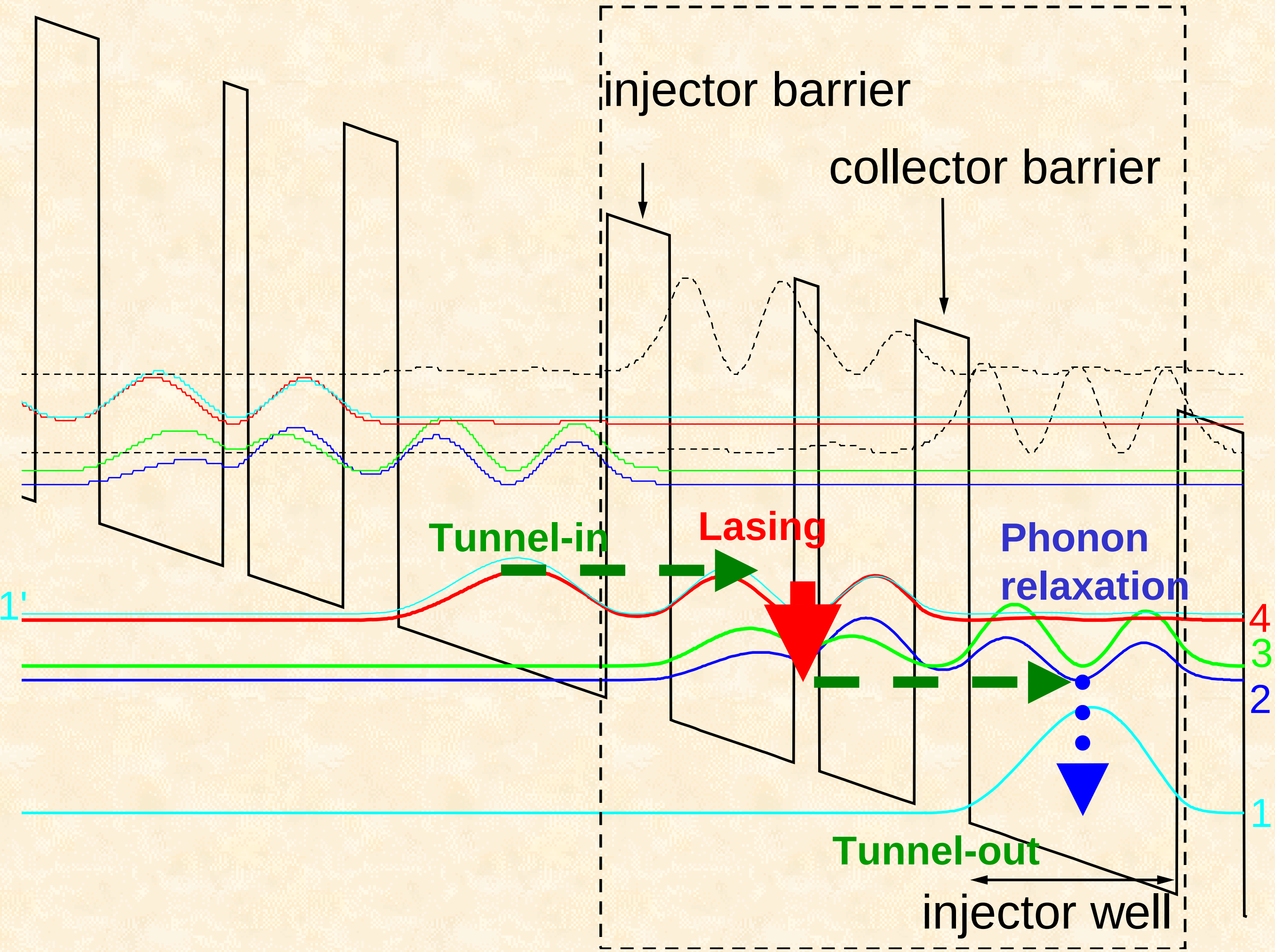
Institute of Microstructural Sciences (IMS)
National Research Council Canada (NRC)

ITQW07, September 10-14, 2007, Ambleside, Cumbria, UK

- three-well resonant phonon THz-QCL
- effects of varying injector barrier thickness on device performance

NRC · CNRC

Three-well resonant phonon module



Only 1 well is used for both phonon depopulation & carrier injection.

- ✓ Simple to design.
- ✓ Reduce thickness ~120A per module (~20%), grow more "useful stuff" ?
- ✓ Less states, less ISB absorption, beneficial towards longer wavelength.
- X Injector always conducting, increase parasitic current.

NRC·CNRC

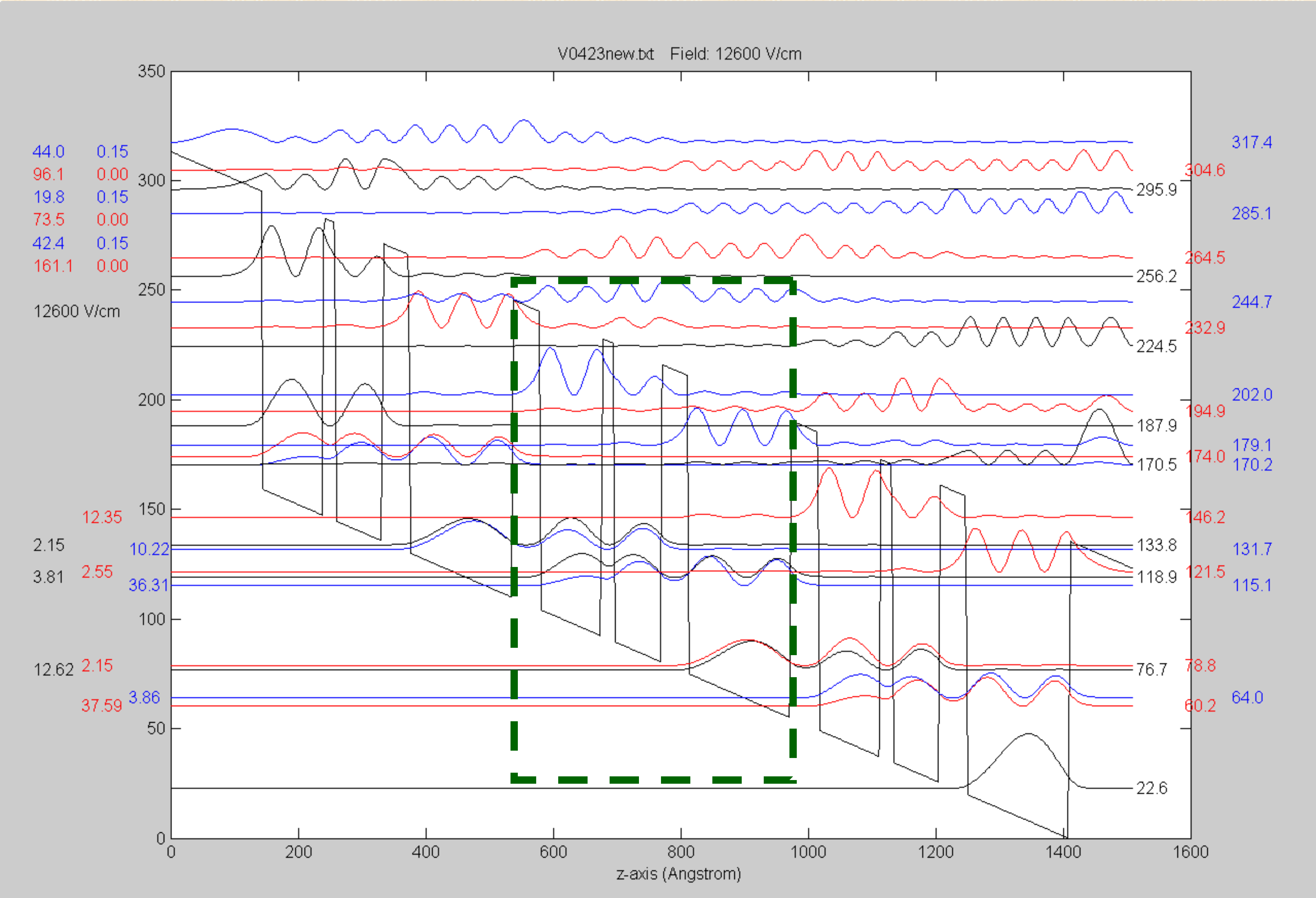
Design steps of 3 well module

Frirst, choose material system with proper barrier height (commonly GaAs/Al_{15}GaAs, ~135meV) Is there an optimum barrier height?

Then, 7 design parameters (3 well/barrier pairs + doping):

- Phonon/injector well: the well supports two energy states with E21 = LO phonon energy (~36meV)
- Lasing wells (two coupled wells and intra-barrier), determined by required lasing frequency and transition consideration (diagonal/vertical) Detailed analysis/comparison?
- 3 "independent" parameters: for systematic study
  - Injector barrier
  - Collector barrier
  - Doping value

NRC · CNRC



Under alignment bias of ~55meV/module:

E_{54}~13meV (lasing), z_{54}~4.7nm, f_{54}~0.5;

E_{32}~36meV (phonon);

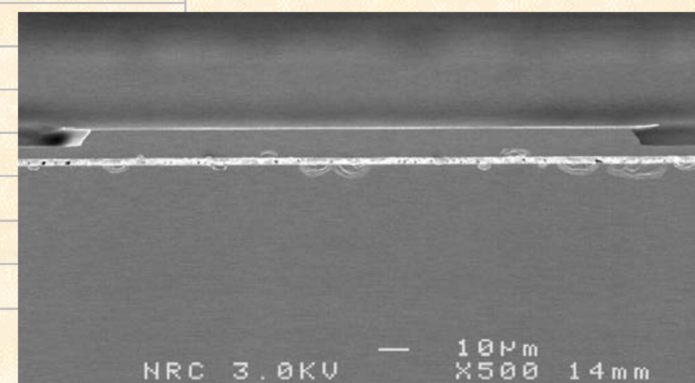
E_{65}~2.2meV (injector); E_{43}~3.8meV (collector)

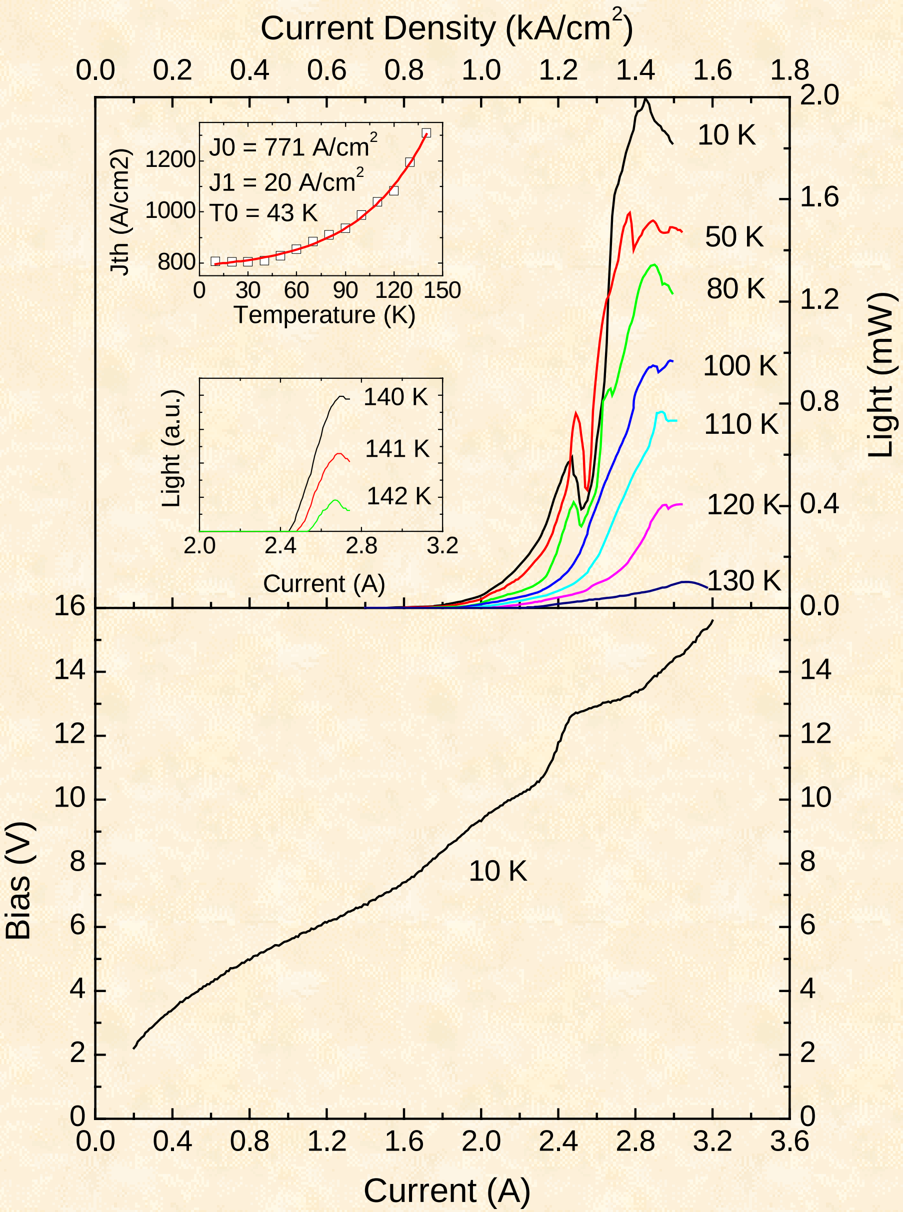
τ_{54}~7ps @150K, τ_{32}~0.5ps.

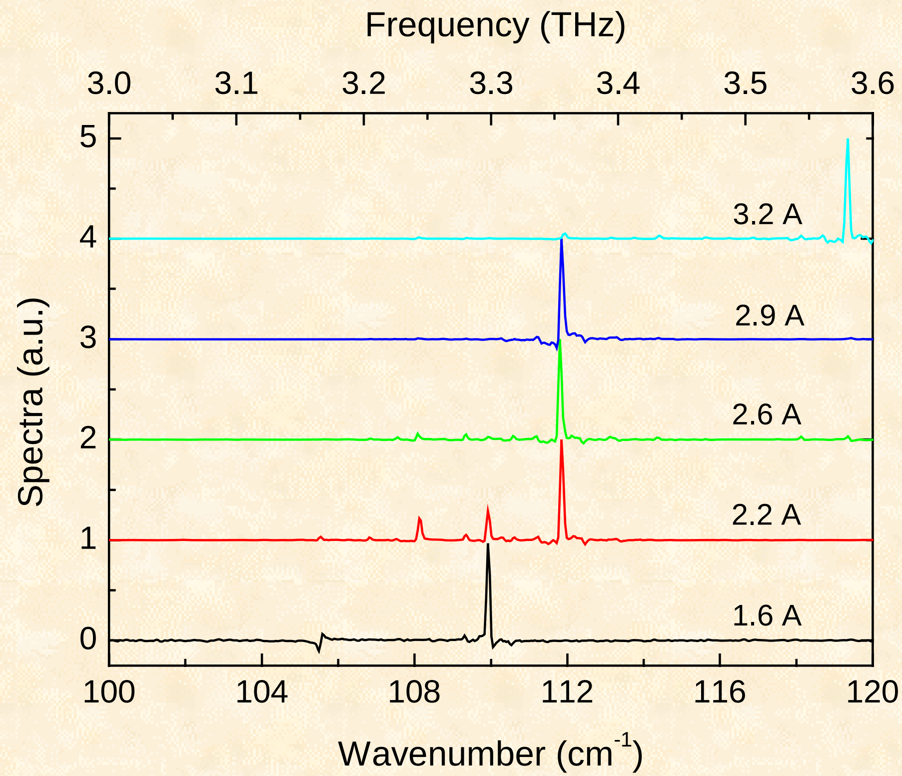
NRC·CNRC

	Material	d [A]	monolayer number	doping [cm-3]	depth [A]	
negative bias	LTG GaAs	30.0	250°C grown		30	
	GaAs:Si	100.0		5.0E+19	100	
	GaAs:Si	500.0		5.0E+18	500	
	GaAs	100.0			100	
	AlGaAs	44.1			44	
	GaAs	161.1			161	
injector barrier	AlGaAs	44.1	17			see Note 1
well 1	GaAs	96.1	34			Repeat times
barrier 1	AlGaAs	19.8	7			216
well 2	GaAs	73.5	26			one period [A]
collector barrier	AlGaAs	42.4	15			437
phonon well	GaAs:Si	161.1	57	~1e17	94382	see Note 2
	AlGaAs	44.1			44	
	GaAs	100.0			100	
positive bias	GaAs	4000.0		3.0E+18	4000	
etch stop	$Al_{0.55}Ga_{0.45}As$	2000.0			2000	
etch stop	AlAs	50.0			50	
buffer layer	GaAs	1000.0			1000	
Total Epi thickness (um)					**10.25**	
substrate	Semi Insulating GaAs					
Note 1	Stop and align to Al-Ga cell intersect axis					
Note 2	doping in the center phonno well to give ~3.6×10^{10} cm^{-2} per period. For example, 36A doped to 1e17					

- 3.6e10 cm^{-2} doping
- 216 repeats
- Metal-metal waveguide
- Wet etching ~6um
- 200um by 1mm laser







Pulse results (2us, 500Hz):

J_{th} ~ 800 A/cm2

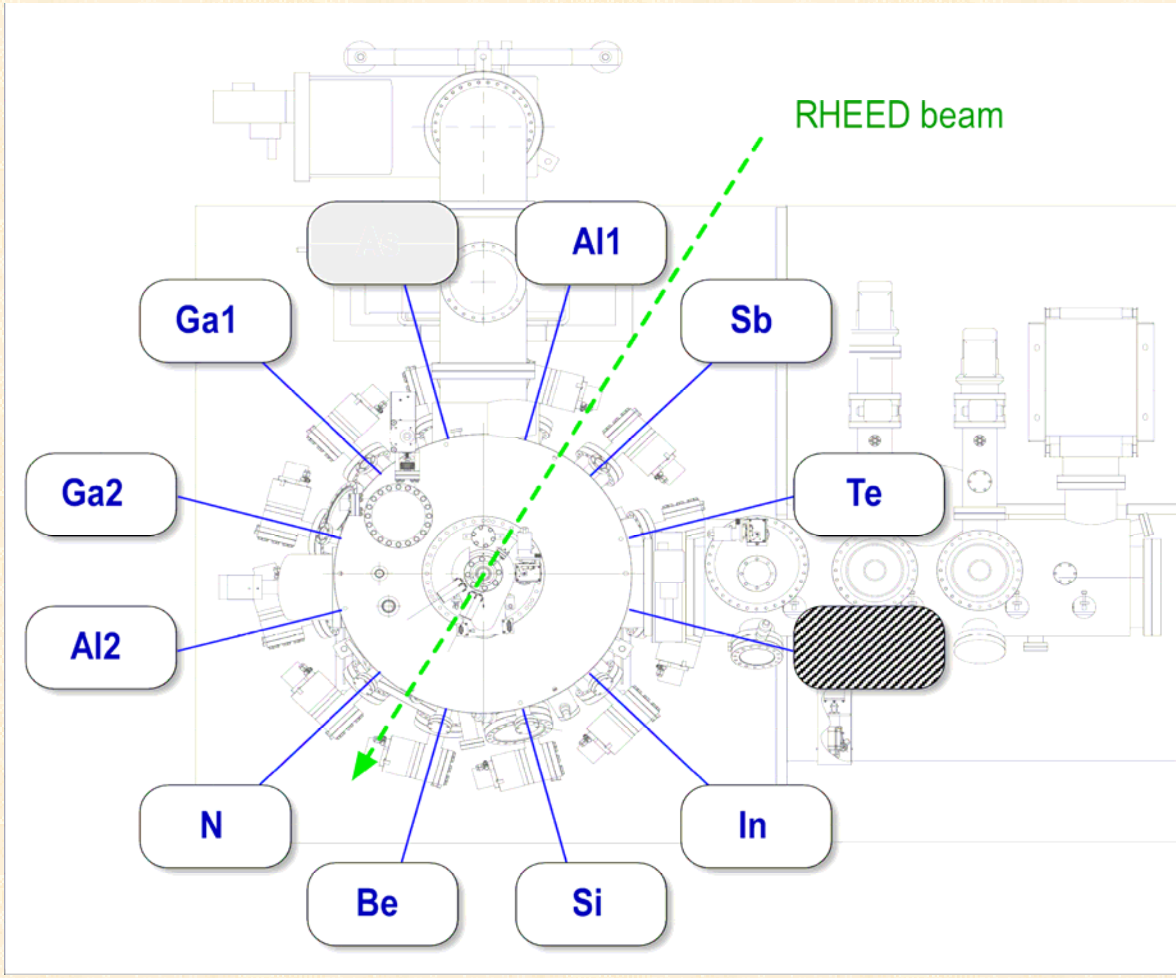
T_{max} ~ 142K

T_0 ~ 43K

P_{max} ~ 2mW

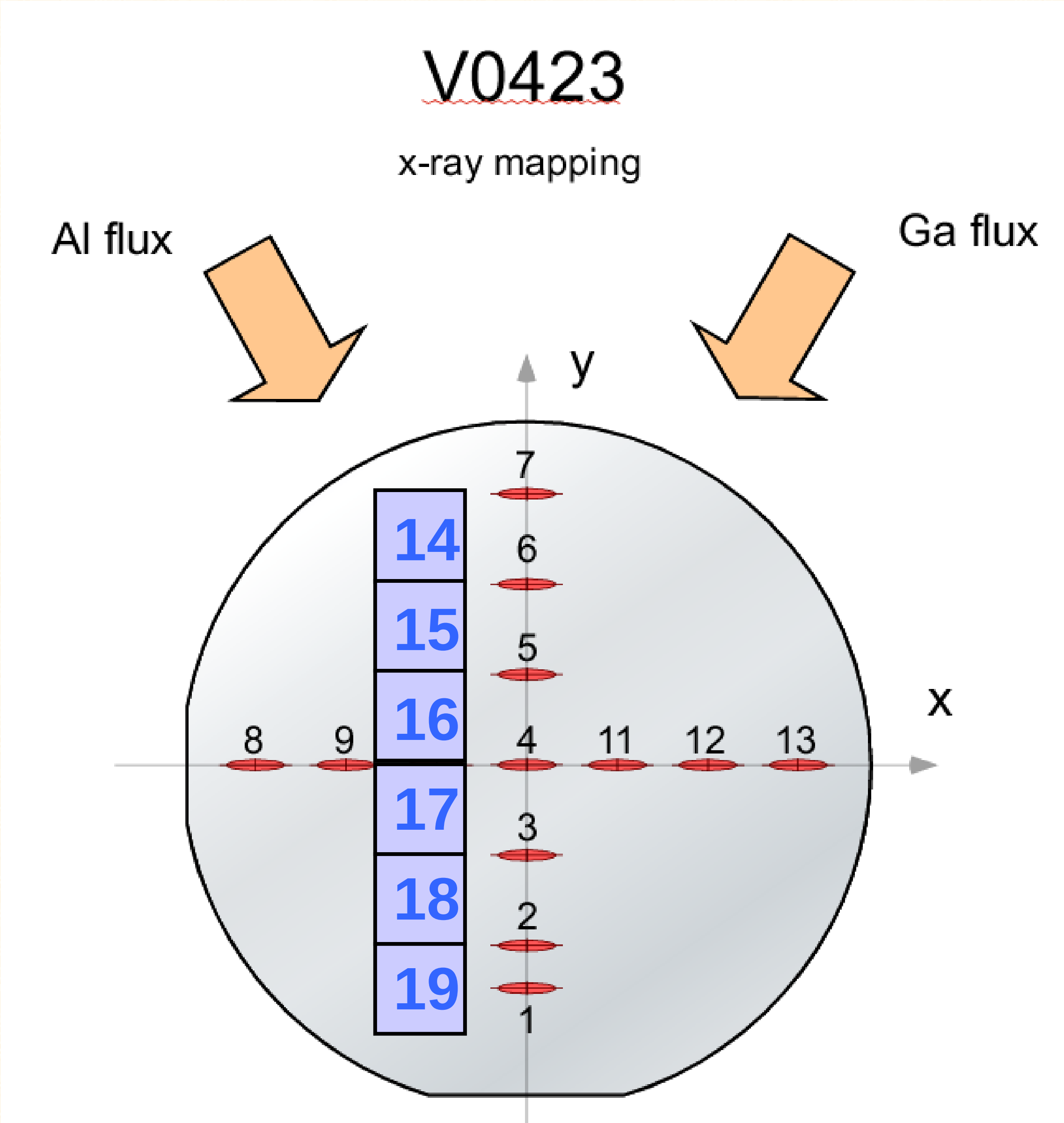
NRC · CNRC

Grow samples with varying injector barrier



- Samples grown on a single 3" wafer by MBE.
- Stop wafer rotation during injector barrier growth to get gradient thickness distribution;
- Align wafer major flat perpendicular to Al1/Ga1 bisection, using RHEED pattern;
- Long growth, ~20 hrs.

X-ray mapping results



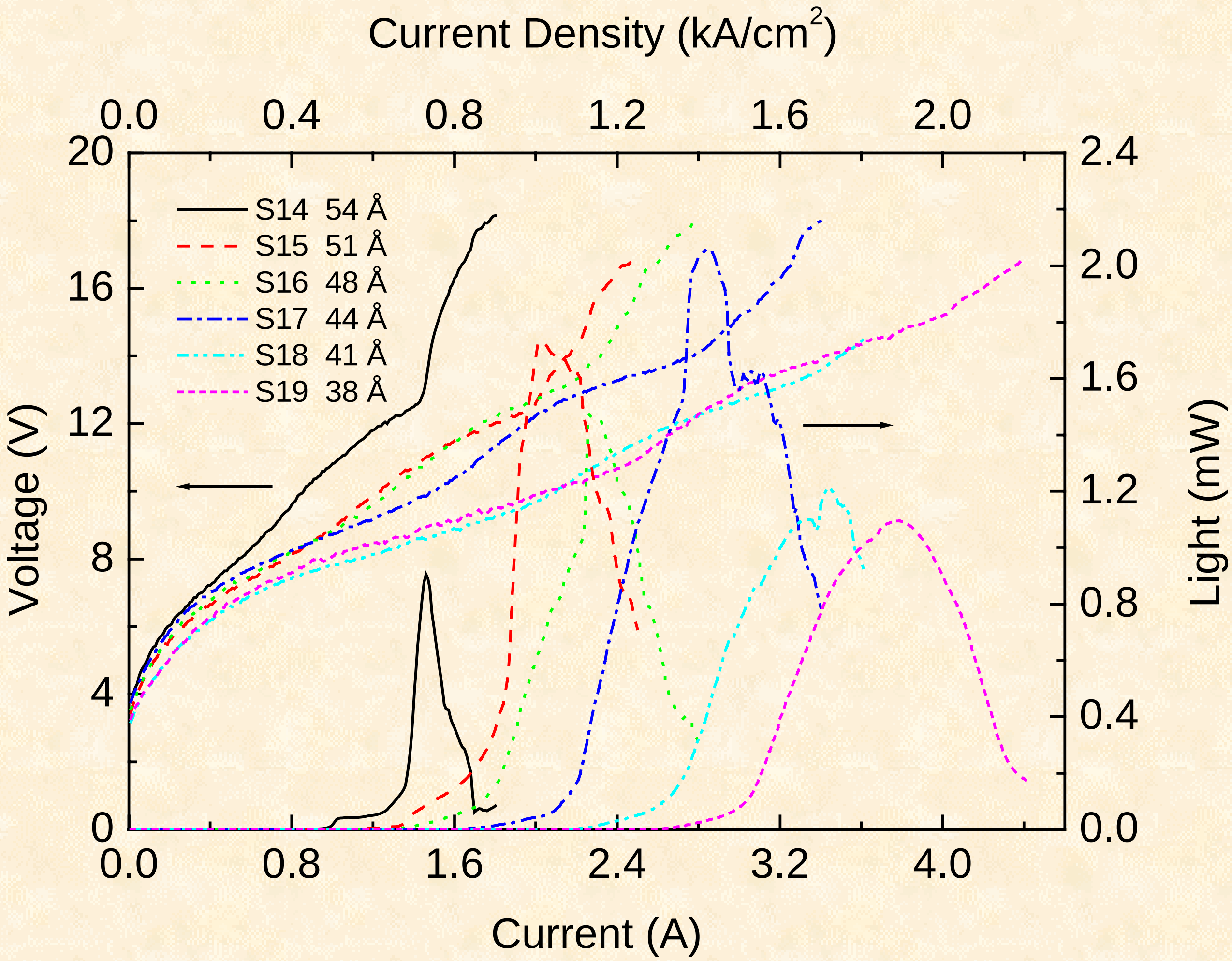
- Injector barrier thickness estimated with 13 point x-ray mapping & flux distribution modeling.

Injector barrier varies linearly from 54A to 38A, from sample 14 to 19.

Negligible compositional change.

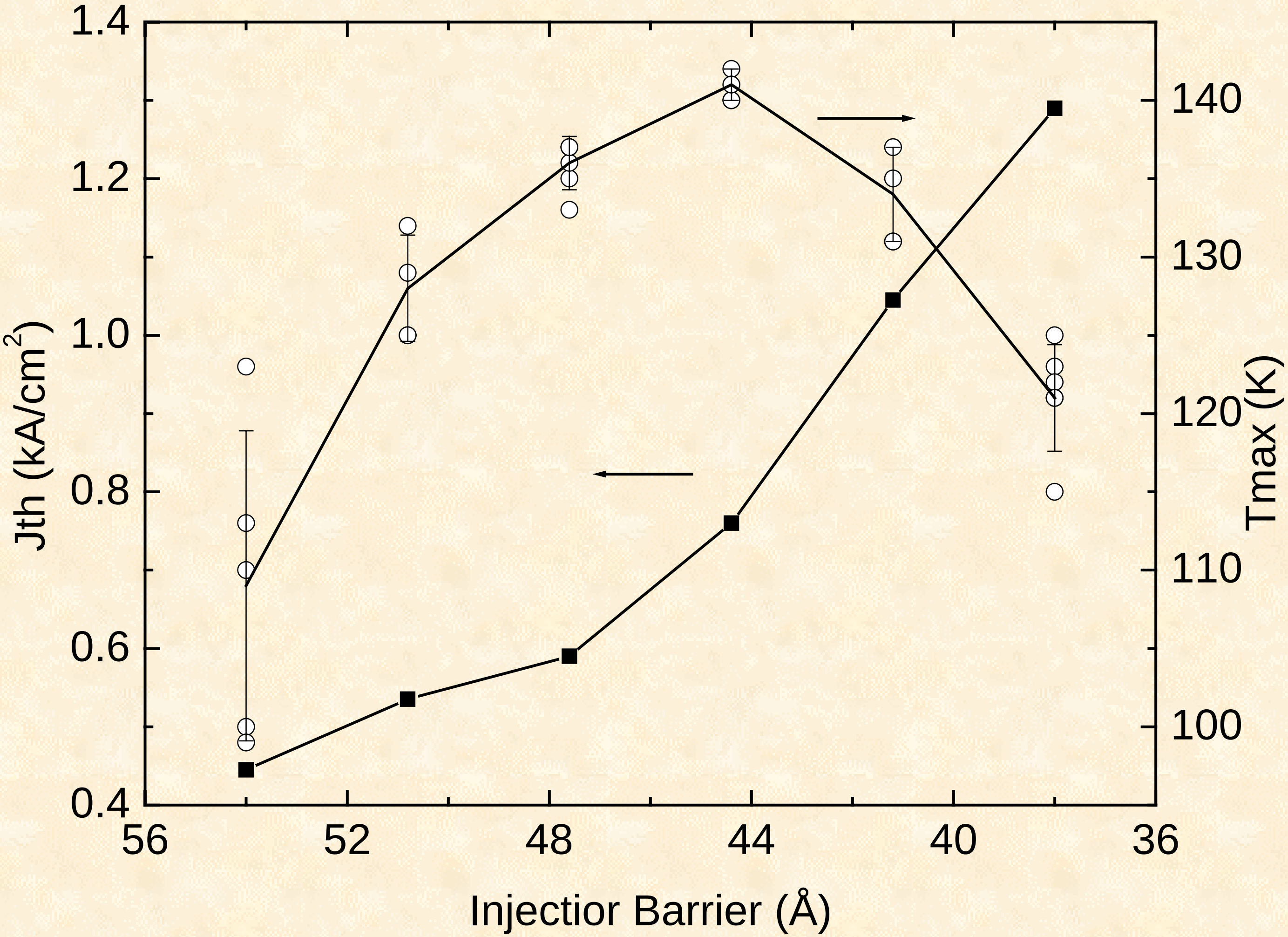
NRC·CNRC

LIV characteristics at 10K



- All samples lased, with similar spectrum.
- J_{th} increases with thinner injector barrier.
- Bias field is similar for all samples.

J_{th} & T_{max} versus injection barrier thickness

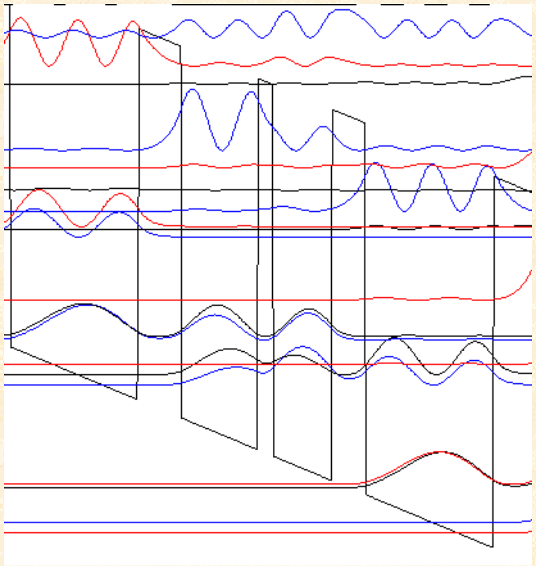


- J_{th} increases monotonically with thinner injector barrier;
- Optimum barrier exists for highest T_{max}.

At least 4 devices from each sample; each circle represents 1 device; Error bars is standard deviation.

NRC · CNRC

Wavefunctions of varying injector barrier

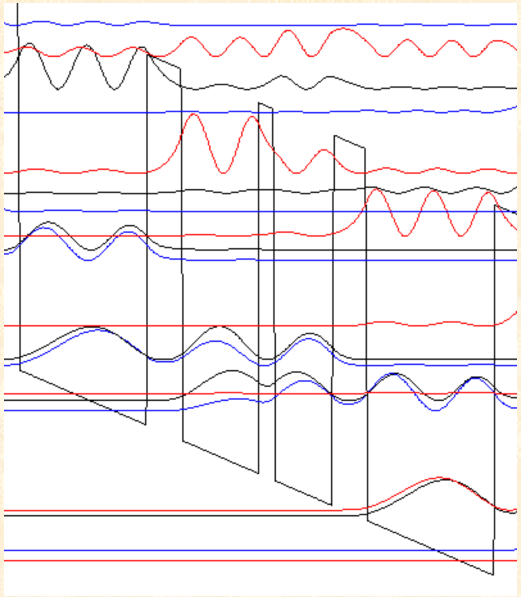


54A

<u>E_{65}~1.3meV (injector)</u>

E_{54}~13meV (lasing)

E_{43}~3.8meV (collector)

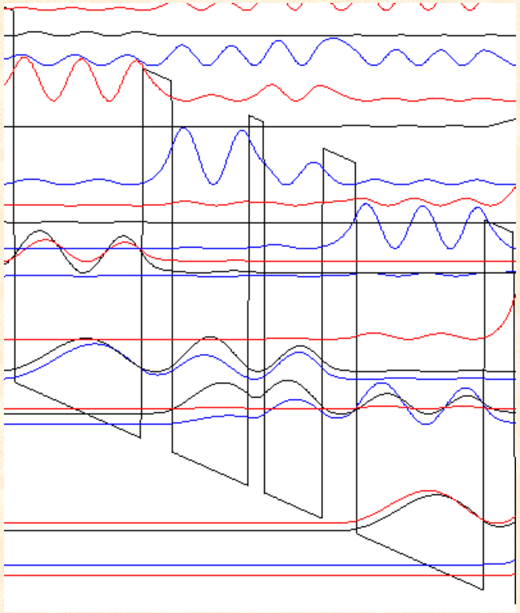


44A

<u>E_{65}~2.1meV (injector)</u>

E_{54}~13meV (lasing)

E_{43}~3.8meV (collector)



38A

<u>E_{65}~2.9meV (injector)</u>

E_{54}~13meV (lasing)

E_{43}~3.9meV (collector)

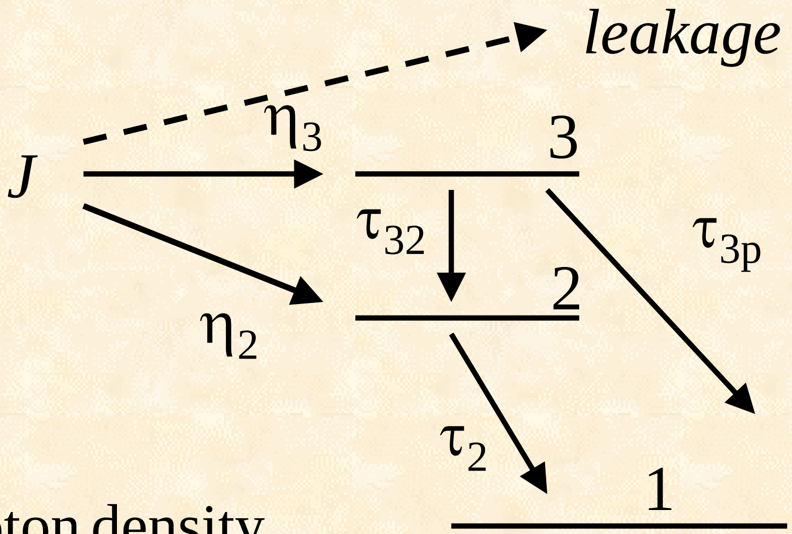
NRC·CNRC

Discussion: Rate equation

$$\frac{dn_3}{dt} = \eta_3 \frac{J}{q} - \frac{n_3}{\tau_3} - g v_g n_{ph}$$

$$\frac{dn_2}{dt} = \eta_2 \frac{J}{q} + \frac{n_3}{\tau_{32}} + g v_g n_{ph} - \frac{n_2}{\tau_2}$$

$$\frac{1}{\tau_3} = \frac{1}{\tau_{32}} + \frac{1}{\tau_{3p}}$$



where n_3, n_2, n_{ph} are 2D electron/photon density

$$\Delta n_{2D} = n_3 - n_2 = \frac{J}{e}\left[\eta_3 \tau_3 \left(1 - \frac{\tau_2}{\tau_{32}}\right) - \eta_2 \tau_2\right]$$

$$g \propto \Delta n_{2D}$$

Discussion: continued

$$\Delta n_{2D} = \frac{J}{e}\left[\eta_3\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)-\eta_2\tau_2\right] \equiv \frac{J}{e}\tau_{eff}$$

When injector barrier reduces, less selective injection, η_3 decreases, and η_2 increases, τ_{eff} reduces, so J_{th} has to increase.

Why optimum barrier thickness for T_{max}?

- For too thick injector barrier, $\eta_3 >> \eta_2$, population inversion is maintained at higher temperature. However, J is limited , Δn not large enough for g_{th}. T_{max} is limited by J_{max}.

- For too thin barrier, $\eta_3 \sim \eta_2$, τ_{eff} reduces. T_{max} is limited by τ_{eff}.

More comprehensive modeling is needed for quantitative understanding.

NRC · CNRC

Summary

3-well design realized with promising results.

Effects of varying injector barrier:

- Jth increases monotonically with reducing barrier thickness.
- There exists an optimum injector barrier thickness for Tmax.

Effects of varying collector barrier?

Acknowledgement:

Funding by NRC Genome and Health Initiative (GHI)

G. C. Aers
J. C. Chao
E. Dupont
C. Y. Song
A. Boucherif
D. Duranton
R. Dudek
E. Fortin
P. Marshall
I. Sproule
R. Wang.

NRC · CNRC