The CECOM Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

III

OPTO-ELECTRONICS IN III-V SEMICONDUCTORS:

MATERIALS AND DEVICES

May 3, 1988

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This workshop on "Opto-Electronics in III-V Semiconductors: Materials and Devices" represents the third of a series of intensive academic/ government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC. Some of the topics discussed in the workshop include: ——

cont'd pg. 2

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SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

OPTOELECTRONIC WORKSHOP

ON

OPTO-ELECTRONICS IN III-V SEMICONDUCTORS MATERIALS AND DEVICES

Organizer: ARO-URI-University of Rochester
and CECOM Center for Night Vision and Electro-Optics

1. INTRODUCTION

2. SUMMARY -- INCLUDING FOLLOW-UP

3. VIEWGRAPH PRESENTATIONS

   A. Center for Opto-Electronic Systems Research
      Organizer -- Gary Wicks

      Optical Properties and Technologies of III-V Materials
      Gary Wicks

      Superlattice Disordering
      Susan Houde-Walter

      Optical Interactions in Indirect Bandgap:
      III-V Semiconductors and Silicon
      Dennis Hall

      III-V Optoelectronics for Optical Communication.
      Thomas Brown

   B. CECOM Center for Night Vision and Electro-Optics
      Organizer -- L. N. Durvasula

4. LIST OF ATTENDEES

1. INTRODUCTION

This workshop on "Opto-Electronics in III-V Semiconductors: Materials and Devices" represents the third of a series of intensive academic/ government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, CCNVEO.

2. SUMMARY AND FOLLOW-UP ACTION

Rudy Buser started the workshop with a short talk. He mentioned two areas of III-V's which are of interest at NVEOC: focal plane arrays of 10 μm detectors; and monolithic integration--sources; detectors, etc.

Ward Trussel spoke about NVEOC's interest in high power laser diode arrays for YAG pumping.

Several NVEOC personnel expressed interest in high power/high efficiency visible (green) lasers with good beam quality. One way of doing this is by doubling the diode pumped YAG lasers. Dennis Hall received some interest when he mentioned the possibility of green GaP lasers.

George Simonis spoke of interest in optoelectronics at Harry Diamond Labs. Their activities include: doping superlattices for optical modulation; resonant tunneling (mainly theory); piezoreflectance studies of III-V heterostructures, and lightwave research for microwave radar applications.

The original plan was for L. N. Durvasula and I to get together for a short while at the end of the workshop to decide how future interactions might proceed. Time did not allow this, however, and we agreed to discuss these items on the phone. I tried several times without success during the week following the workshop to contact Dr. Durvasula. Finally I sent him a letter stating a few specific areas where there appeared to be good overlap between research areas at UR and interests at NVEOC. Also stated in the letter was my feeling that the formal presentation structure was appropriate for the first workshop, but subsequent interactions should consist of smaller, less formal groups and more dialogue.

I would estimate that 30 NVEOC personnel attended the workshop.

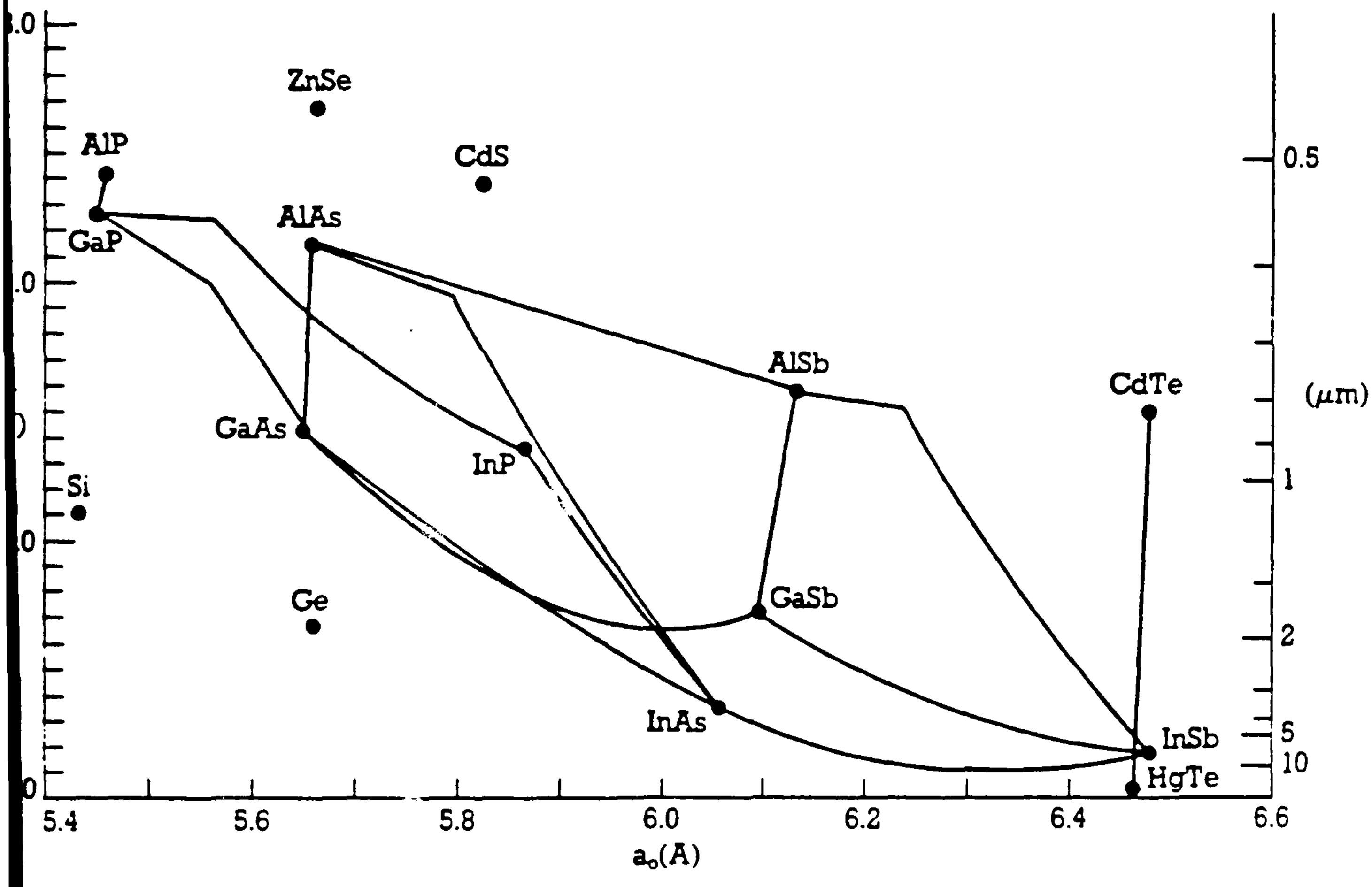
CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

OPTICAL PROPERTIES AND TECHNOLOGIES OF III-V MATERIALS

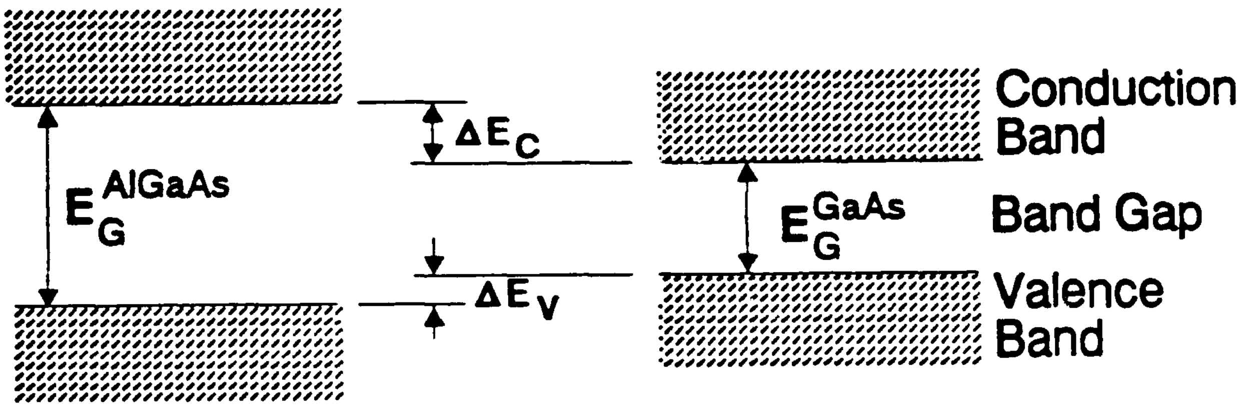
Outline

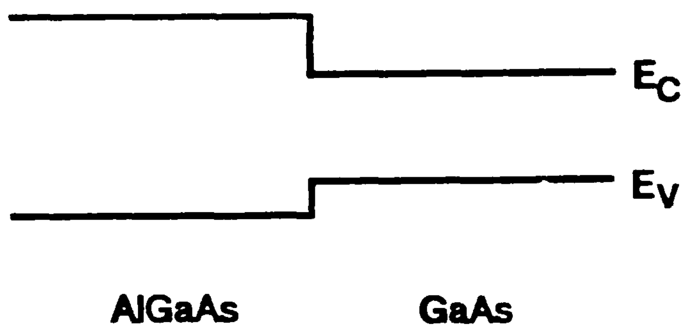
- Crystal growth technologies
- Bulk materials properties
- Properties of quantum wells and superlattices
- Device fabrication technologies

ENERGY GAP (in eV and μm) VERSUS LATTICE CONSTANT AT 300K FOR COMPOUND SEMICONDUCTORS

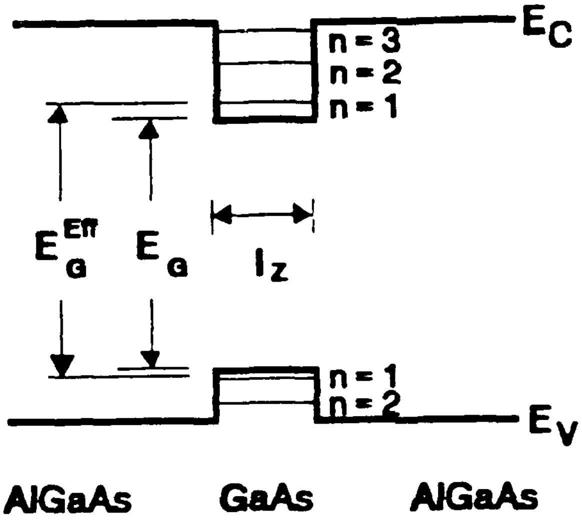


Heterojunction Energy Bands

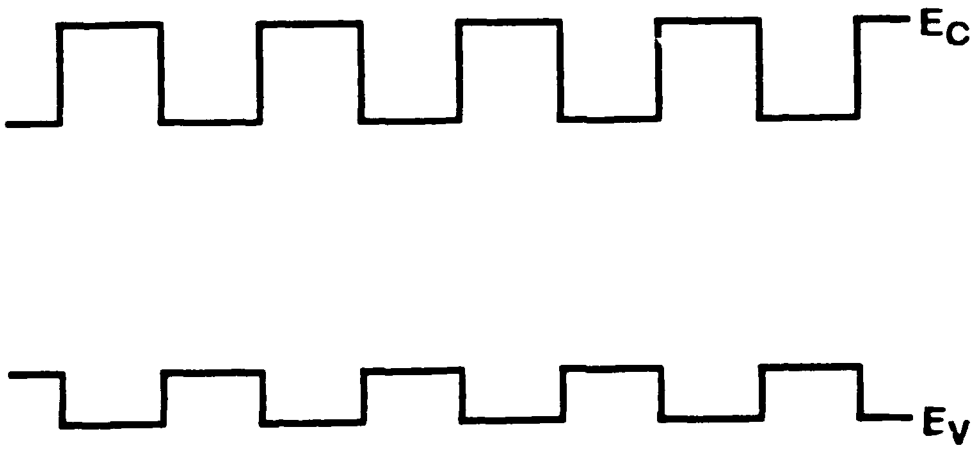




Quantum Well



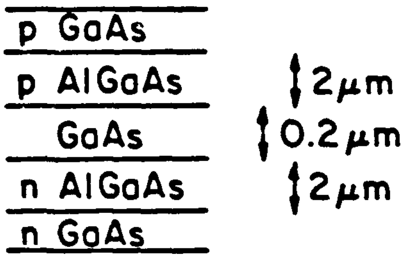
Superlattice (type I)

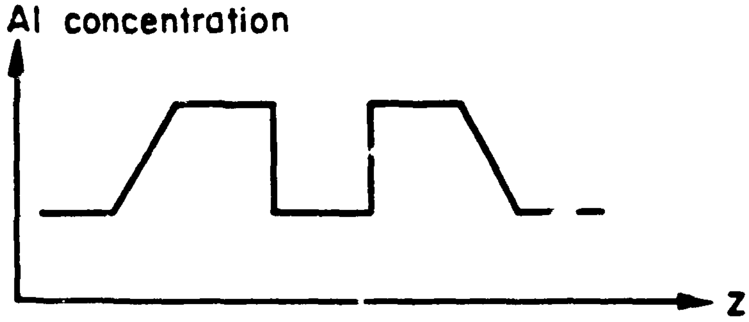


Important Epitaxial Structures

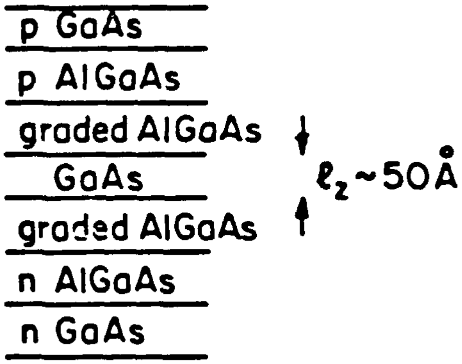
Lasers

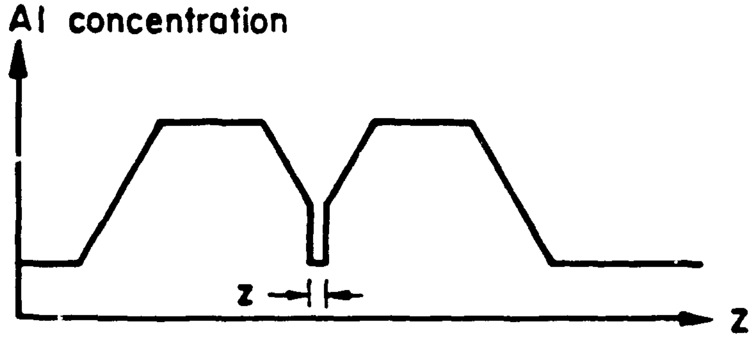
Double Heterostructure (DH)





Graded refractive index-separate confinement heterostructure (GRINSCH)





Other Versions

multi-quantum well

constant composition, separate confinement heterostructure

III-V Materials for Lasers

- $\lambda = 2.2\ \mu m$ – GaInAsSb/AlGaAsSb DH

☆ • $\lambda = 1.7 - 1.2\ \mu m$ – GaInAsP/InP DH

- $\lambda = 1.2 - 0.9\ \mu m$ – pseudomorphic GaInAs/AlGaAs QW's

☆ • $\lambda = 0.9\ \ 0.68\ \mu m$ – $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ QW's

- $\lambda = 0.65\ \mu m$ – $Ga_{.52}In_{.48}P$/AlGaInP

III-V's for Long Wavelength Photodetectors

•Lowest bandgap bulk III-V is $InAs_{.39}Sb_{.61}$

$\lambda < 9\ \mu m$

•Strained InAsSb Quantum Wells

$\lambda < 12\ \mu m$

•Intraband transitions in the conduction band of superlattices

2 A/W at $\lambda = 10\ \mu m$

note: only radiation polarized along growth axis is detected

Crystal Growth Technologies

•Bulk Growth Techniques

–Bridgeman

–Liquid Encapsulated Czochralski (LEC)

•Epitaxial Growth Techniques

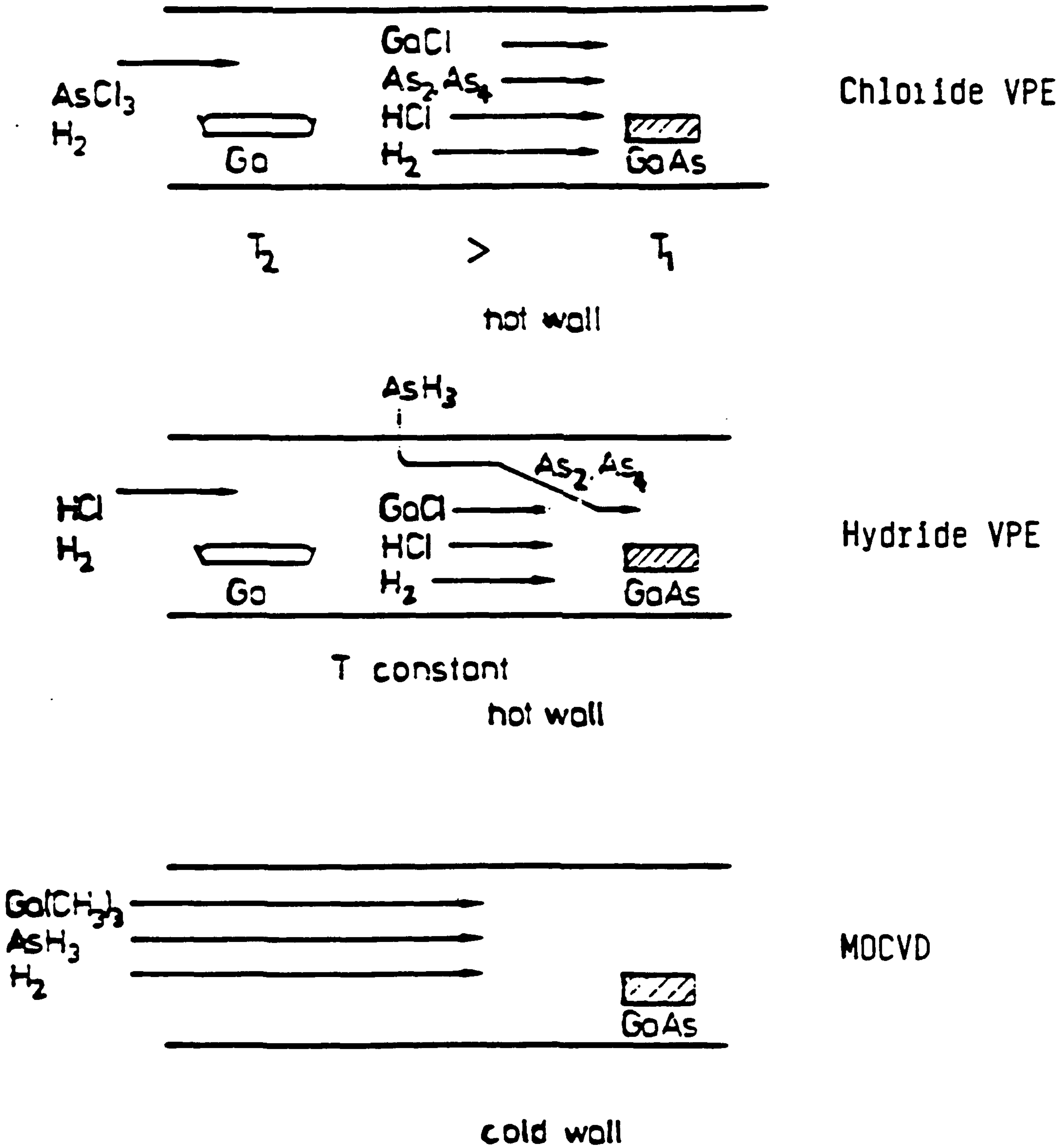
–Liquid Phase Epitaxy (LPE)

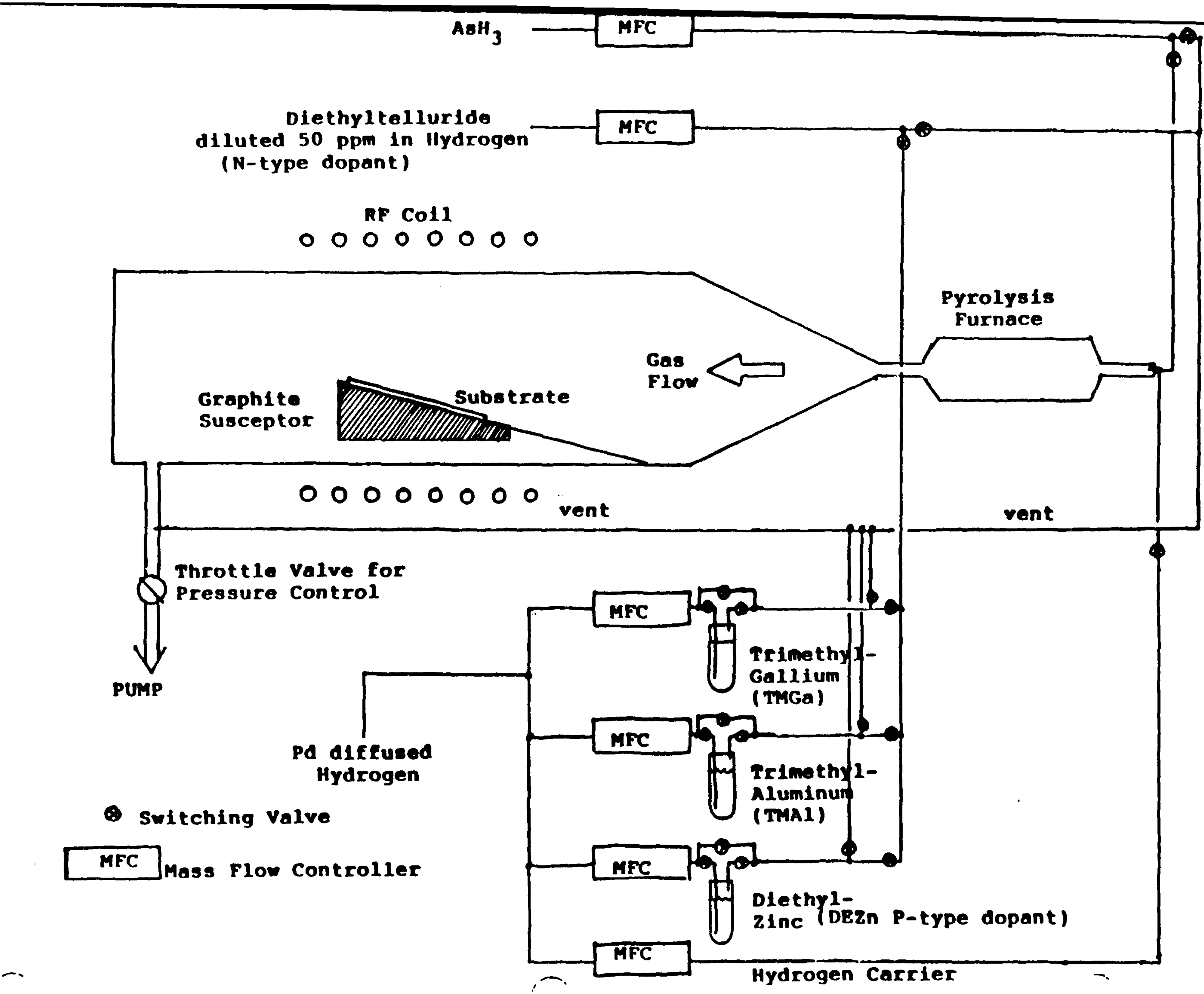
–Vapor Phase Epitaxy (VPE)

–Molecular Beam Epitaxy (MBE)

–Metal Organic Chemical Vapor Deposition (MOCVD)

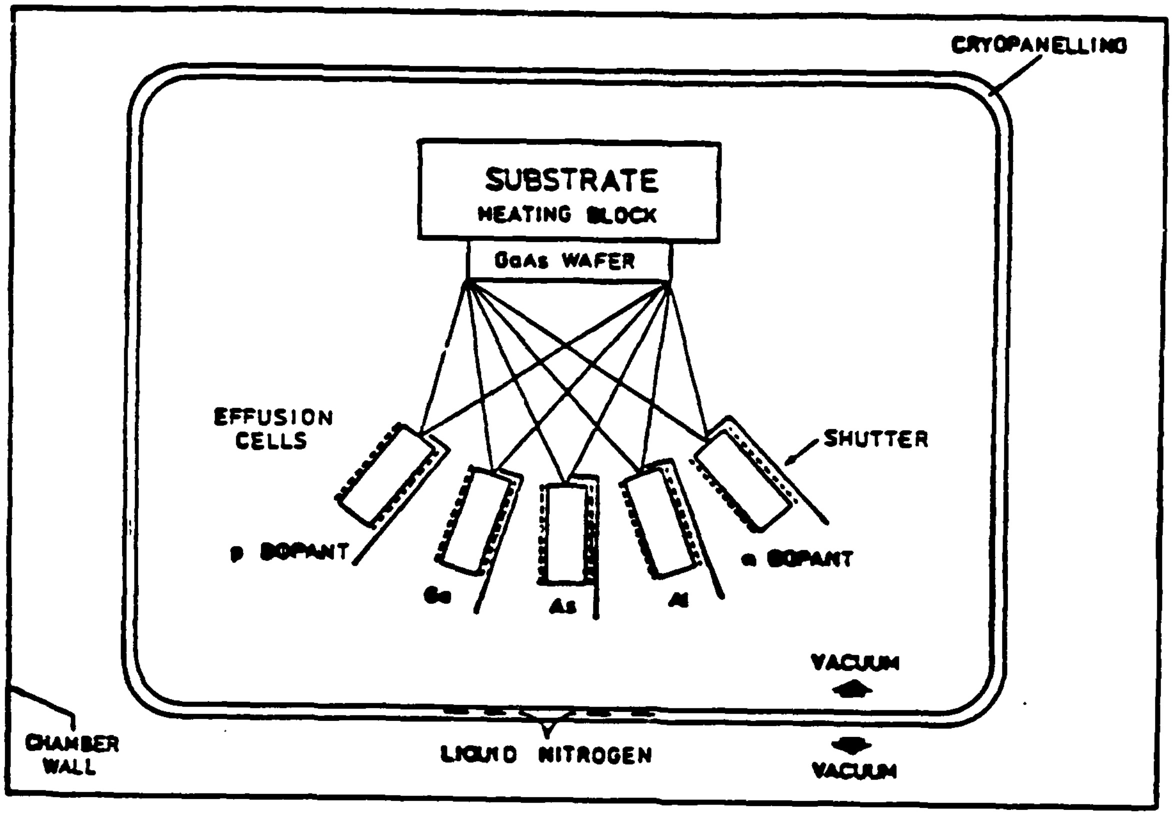
VAPOR PHASE EPITAXY



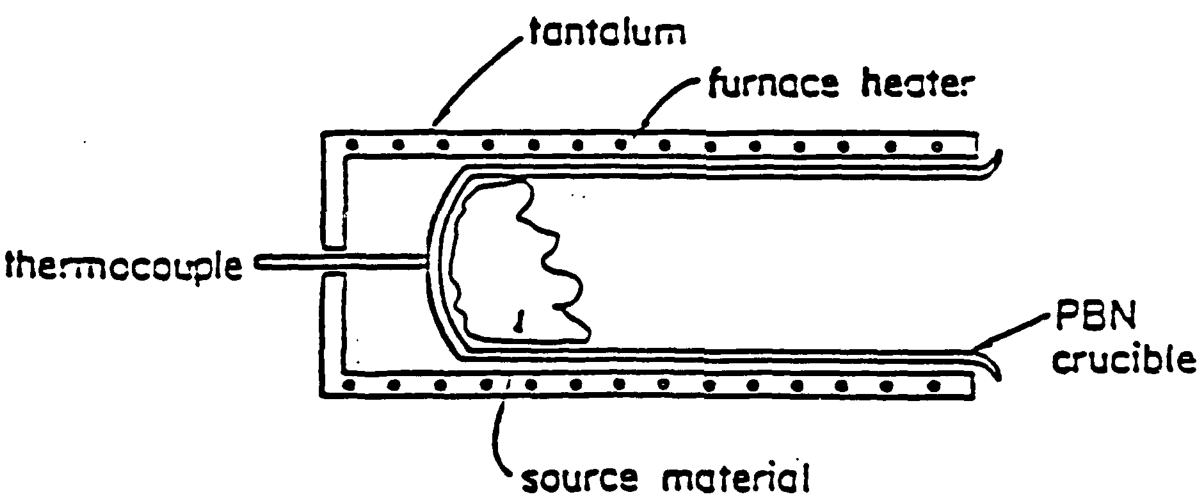


AsH_3
MFC
Diethyltelluride
diluted 50 ppm in Hydrogen
(N-type dopant)
MFC
RF Coil
Pyrolysis
Furnace
Gas
Flow
Graphite
Susceptor
Substrate
vent
vent
Throttle Valve for
Pressure Control
PUMP
MFC
Trimethyl-
Gallium
(TMGa)
MFC
Trimethyl-
Aluminum
(TMAl)
MFC
Diethyl-
Zinc (DEZn P-type dopant)
MFC
Hydrogen Carrier
Pd diffused
Hydrogen
Switching Valve
MFC
Mass Flow Controller

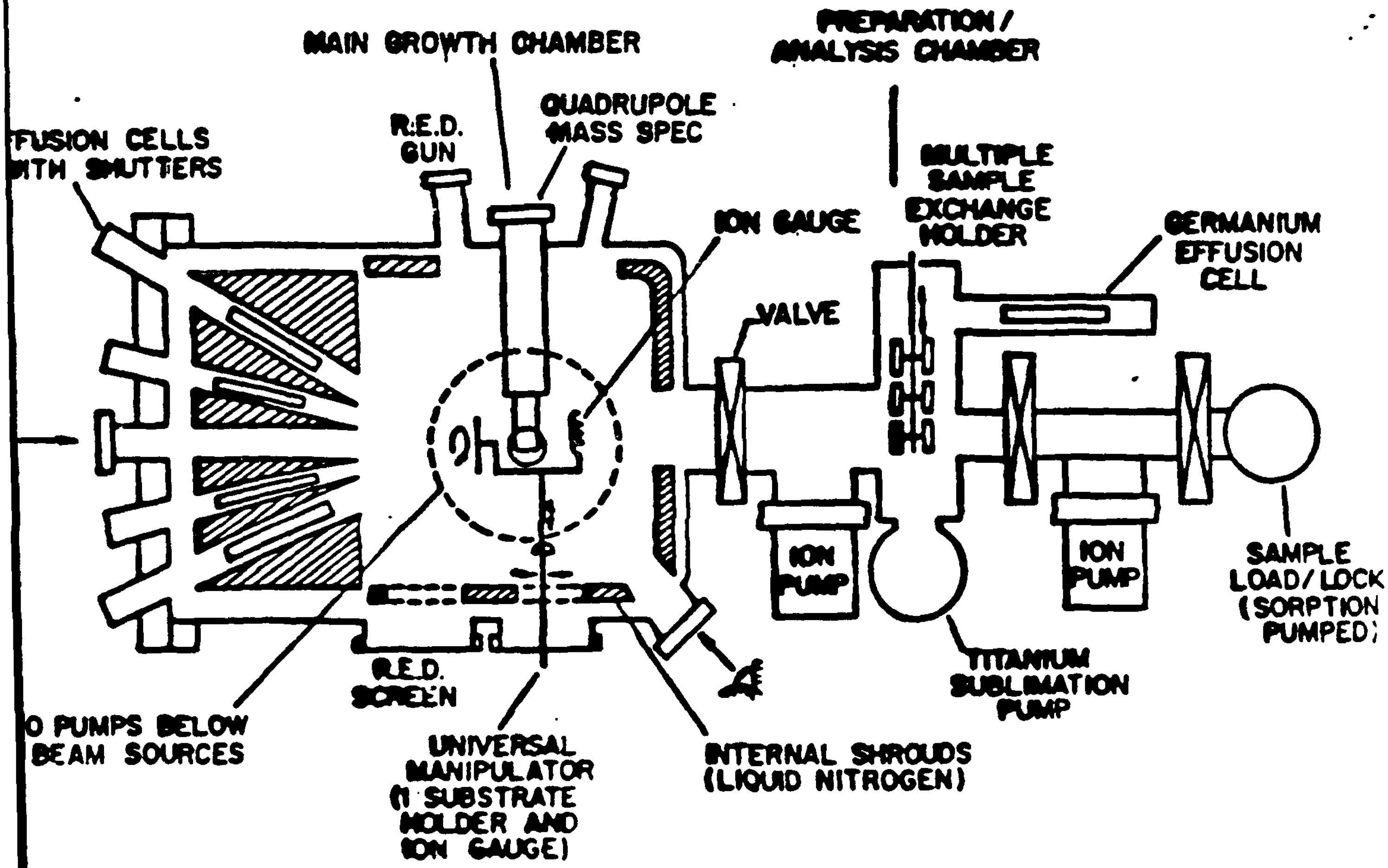
MOLECULAR BEAM EPITAXY



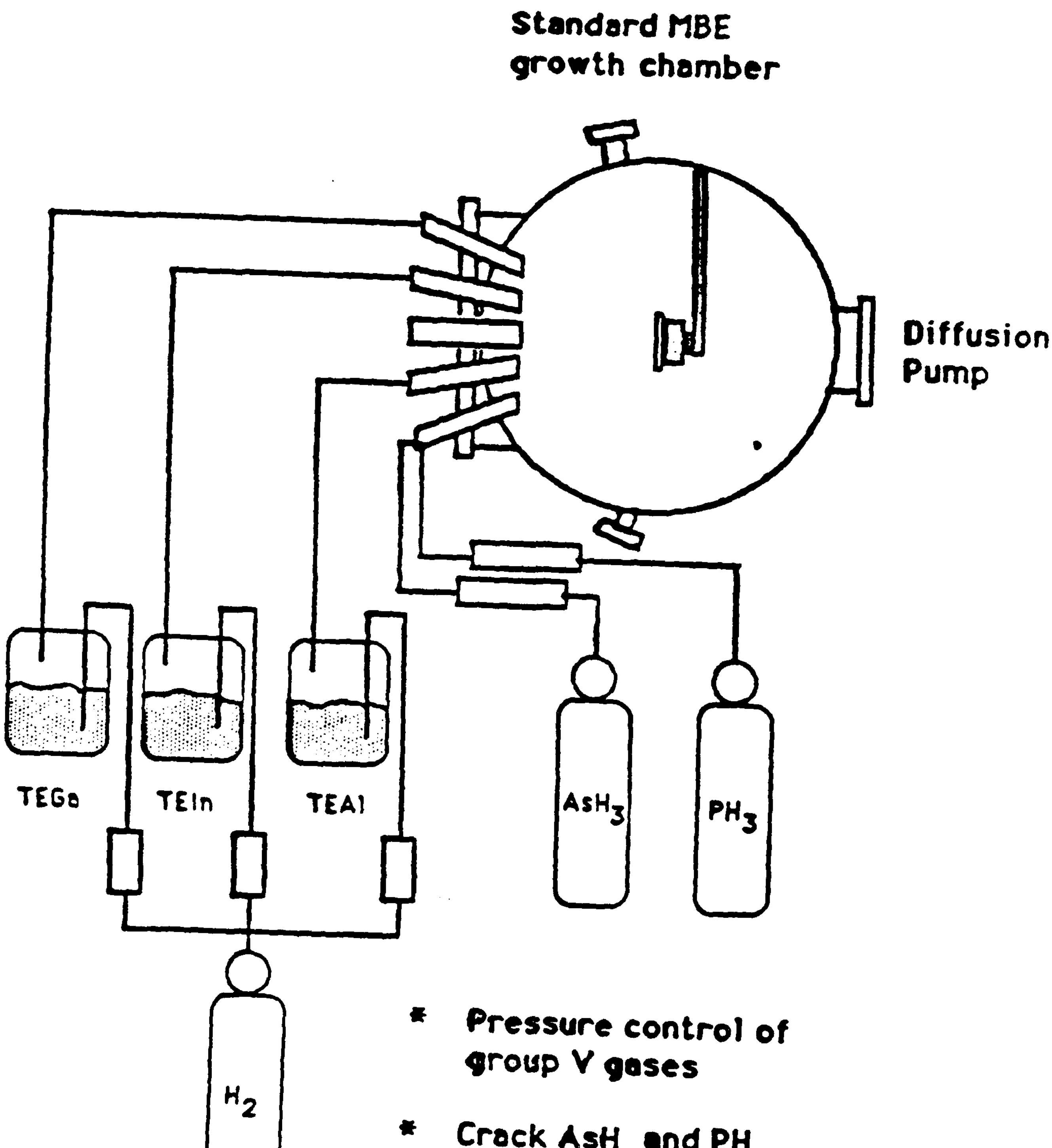
EFFUSION CELL



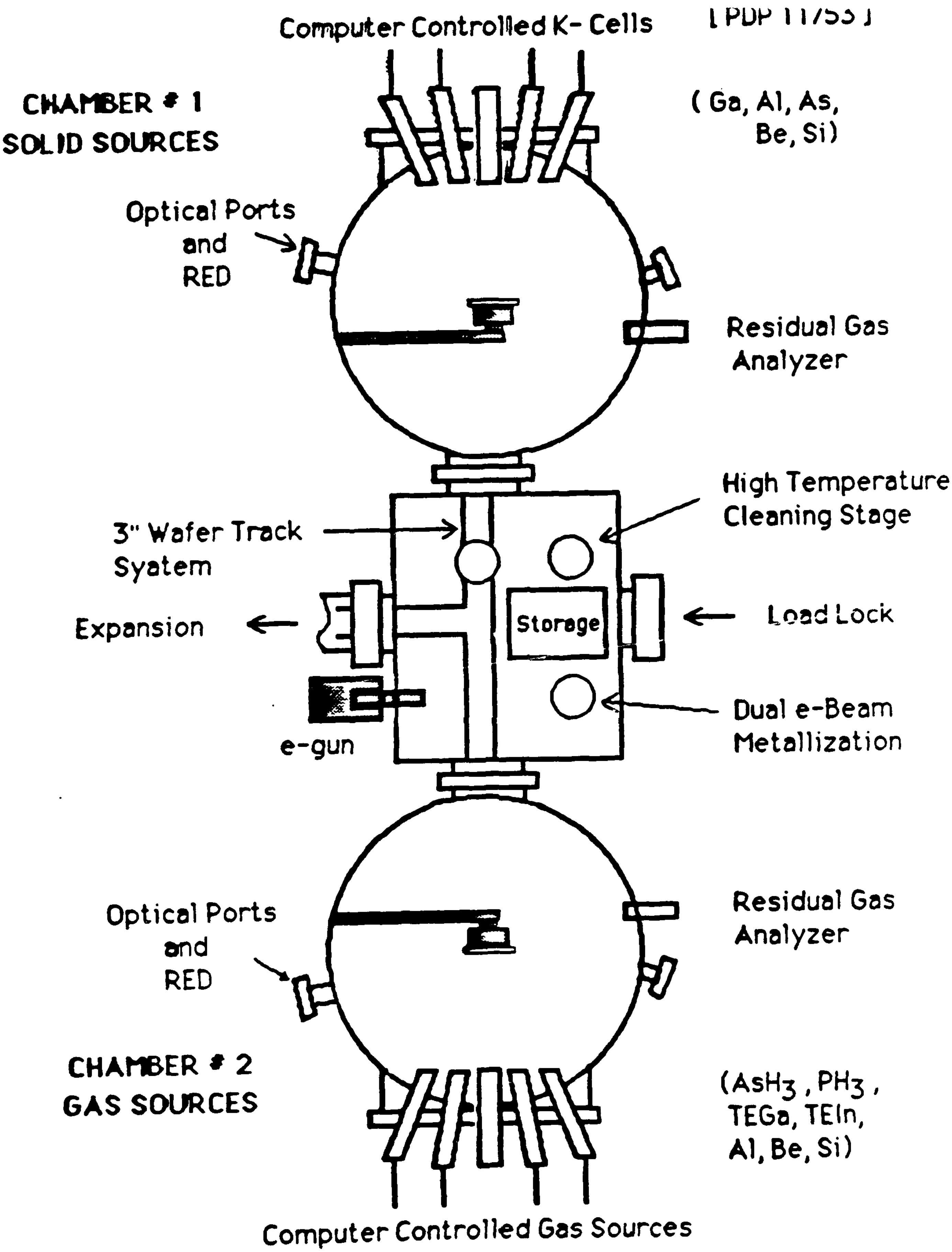
Molecular Beam Epitaxy (MBE)



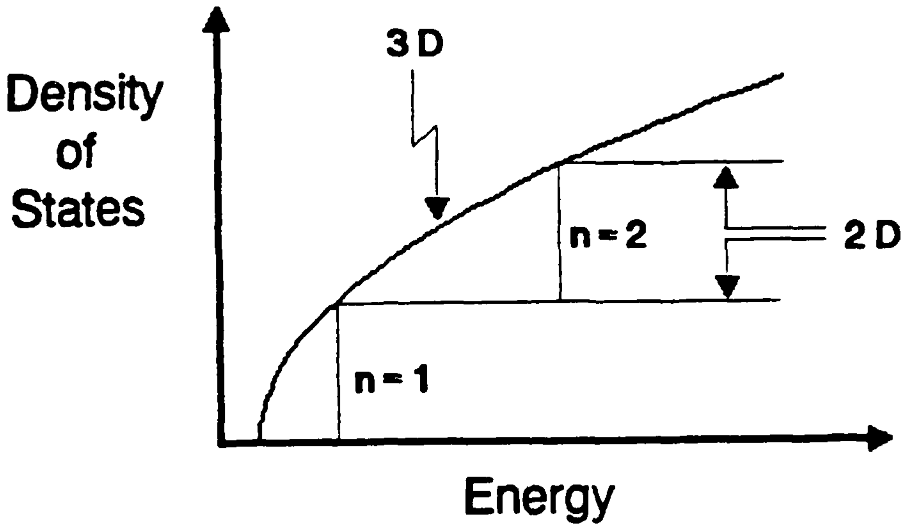
Gas Source MBE System
MOMBE



* Pressure control of group V gases
* Crack AsH_3 and PH_3 in same cell

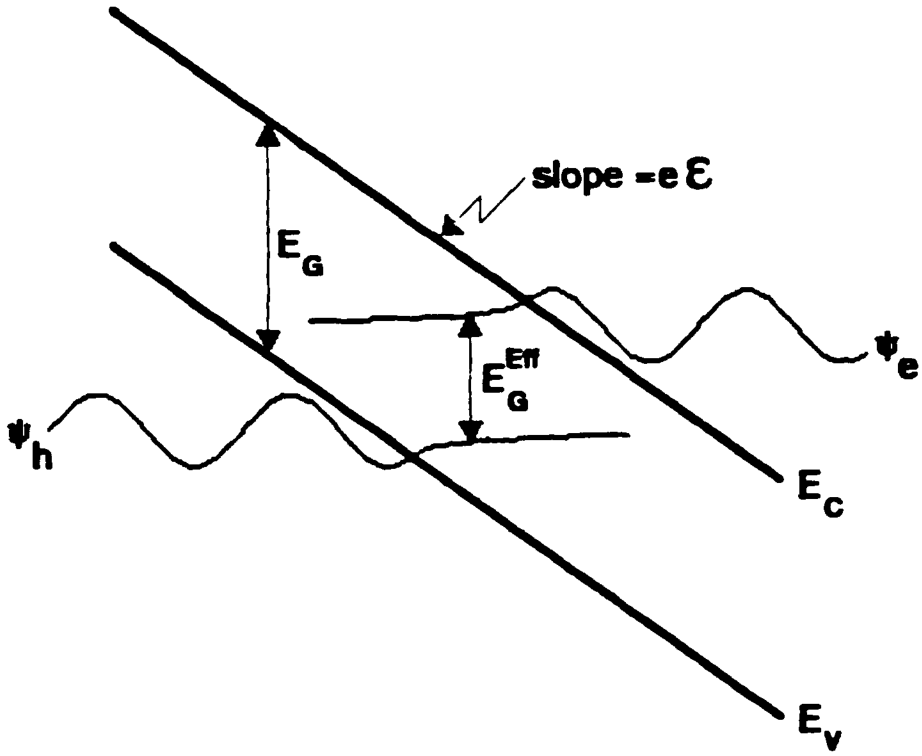


Computer Controlled K- Cells
[PDP 11/55]
CHAMBER # 1
SOLID SOURCES
(Ga, Al, As,
Be, Si)
Optical Ports
and
RED
Residual Gas
Analyzer
High Temperature
Cleaning Stage
3" Wafer Track
Syatem
Expansion
Storage
Load Lock
e-gun
Dual e-Beam
Metallization
Residual Gas
Analyzer
Optical Ports
and
RED
CHAMBER # 2
GAS SOURCES
(AsH3, PH3,
TEGa, TEIn,
Al, Be, Si)
Computer Controlled Gas Sources


3 D
Density
of
States
n = 2
2 D
n = 1
Energy

Electrooptic Effects in III-V's

Bulk materials – Franz-Keldysh Effect



$$\frac{\Delta E_G}{\Delta \mathcal{E}} \sim \frac{5\ \text{meV}}{10\ \text{KV/cm}}$$

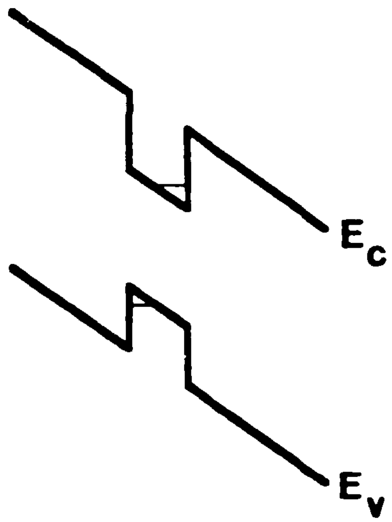
Shift Absorption Edge ➡ Change refractive index :

$$\frac{\Delta n/n}{\Delta \mathcal{E}} \sim \frac{5 \times 10^{-7}}{10\ \text{KV/cm}}$$

Electrooptic Effects in III-V's

Quantum Wells – Excitonic Effects

Case 1. Electric field // Growth axis



•Change shape of potential well ➜ shift exciton energy levels ➜ shift absorption *edge* ➜ *change refracive index.*

Case 2. Electric field ⊥ Growth axis

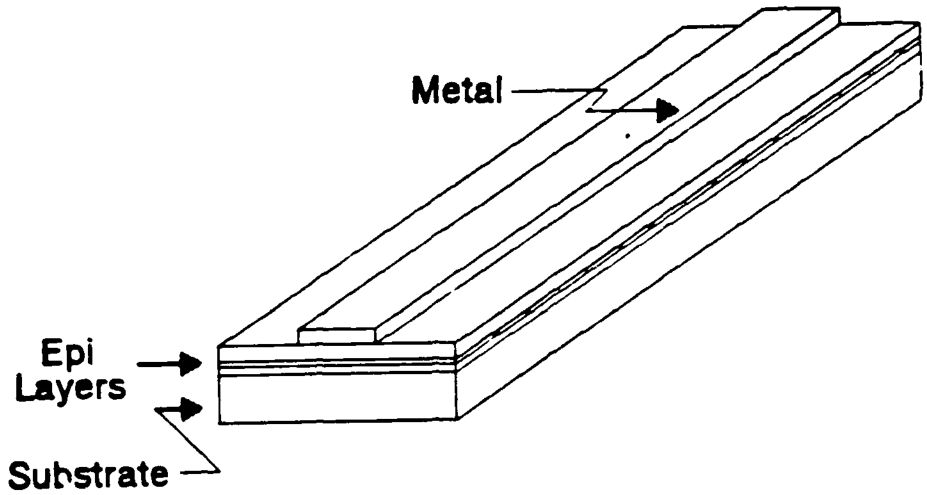
•Field ionize exciton ➜ remove excitonic features from absorption spectrum ➜ change refracive index.

•The excitonic absorption in quantum wells leads to very large electroopticeffects:

$$\frac{\Delta n / n}{\Delta \varepsilon} \sim \frac{5 \times 10^{-2}}{10\,\mathrm{KV/cm}}$$

$$\frac{\Delta \alpha}{\Delta \varepsilon} \sim \frac{100\ \mathrm{cm}^{-1}}{10\,\mathrm{KV/cm}}$$

Edge Emitting Laser



Dry Etching Techniques for Optoelectronic Devices

Methods

- Chemically Assisted Ion Beam Etching
- Reactive Ion Beam Etching
- Reactive Ion Etching

Applications

- Integrated lasers no cleaved mirrors
- Other integrated devices
  - lenses
  - mirrors
  - modulators

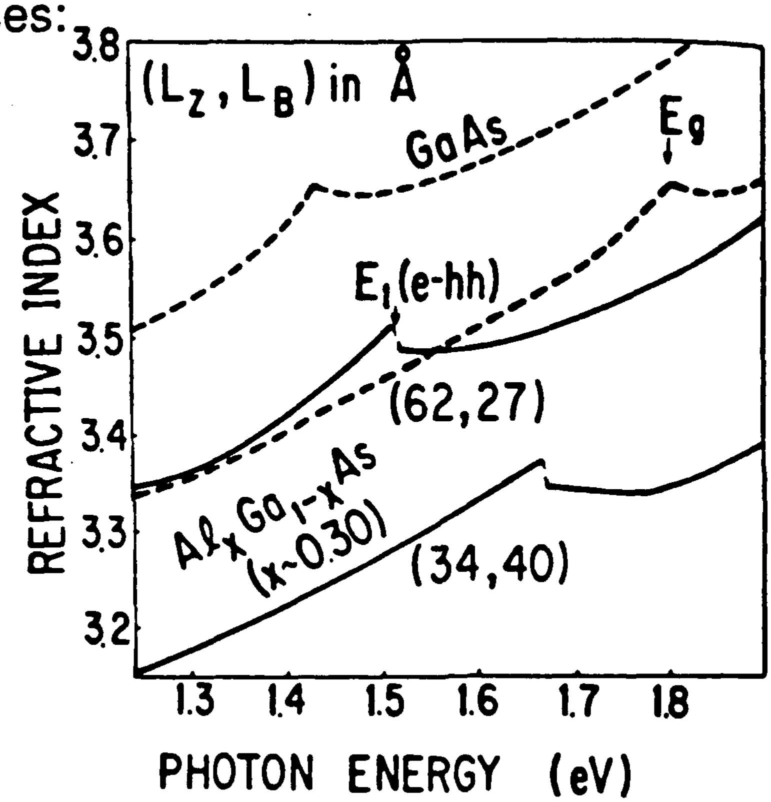
CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

SUPERLATTICE DISORDERING

Experimental:

ref: Y. Suzuki and H. Okamoto, J. Elec. Mats. 12, 397 (1983)

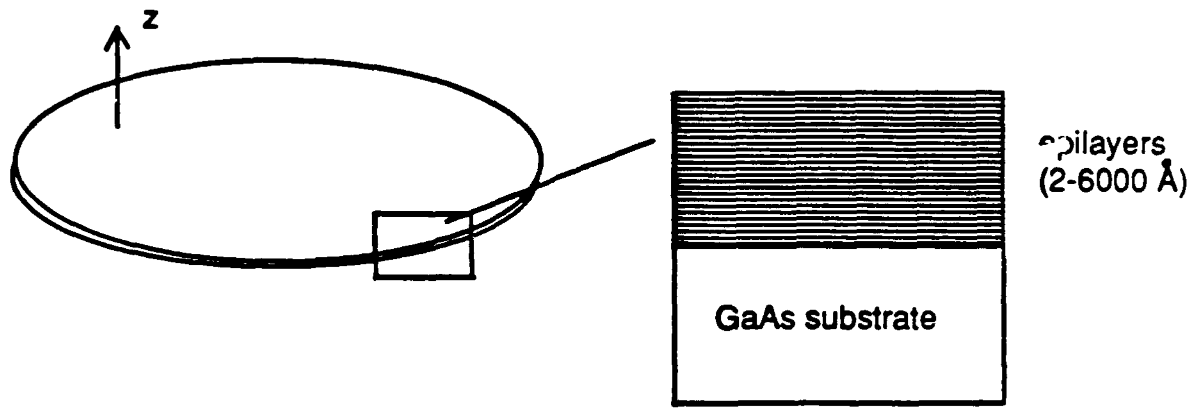
Compare refractive index (dispersion) of bulk $Al_{0.30}Ga_{0.70}As$ to GaAs/AlAs SL's with various barrier thicknesses:



Note: for a fixed average alloy composition, one can make large changes in refractive index by tailoring heterostructure dimensions.

>>useful degrees of freedom in device design
- lasers
- waveguides, lenses, modulators
- detectors

Heterostructures are grown epitaxially
molecular beam epitaxy
metallorganic chemical vapor deposition



INTEGRATION: grow one structure, use same base material for all components

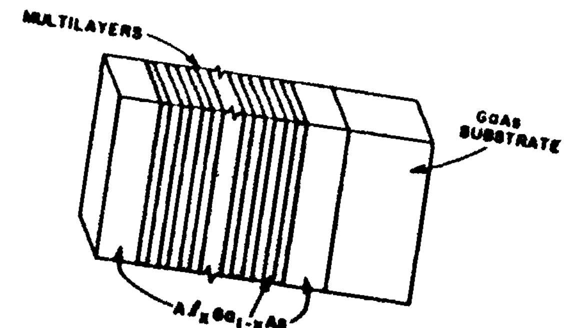
define components(e.g. ridge waveguides, heterostructure lasers) by removing surrounding material (ion beam etching, cleaving, etc.)

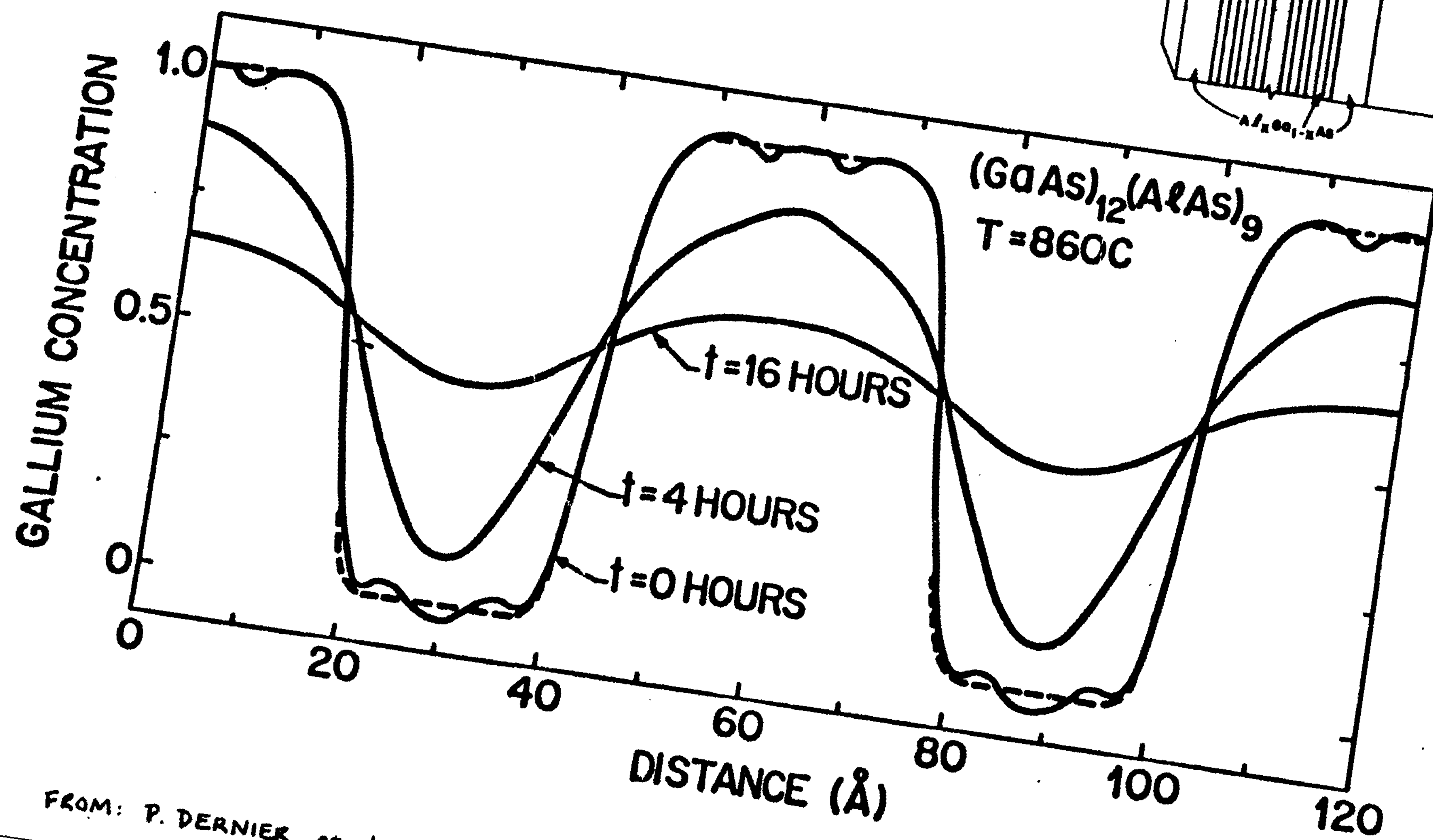
Disadvantage:
scattering, band bending, not planar, etc.

Objective: change bandgap and refractive index locally to define components

New Method: smooth abruptness of heterostructures locally

SL's are stable at moderate temperatures



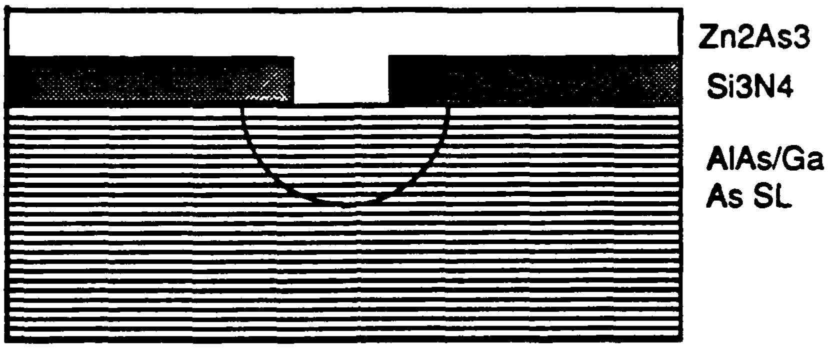


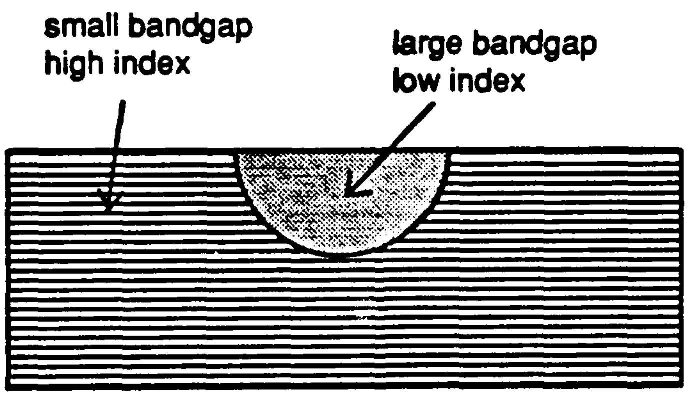
FROM: P. DERNIER, et al, Bull. Amer. Phys. Soc. 22, 293 (1977).

Mixing is enhanced by impurity transport

ref: W.D. Laidig, et al, Appl. Phys. Lett. 38, 776 (1981)

MASKED Zn DIFFUSION INTO SL

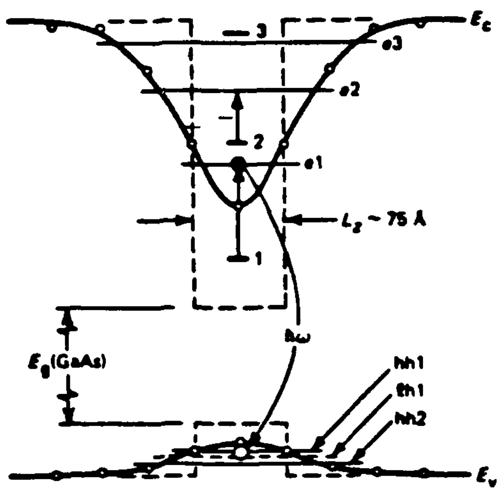




Lasers:

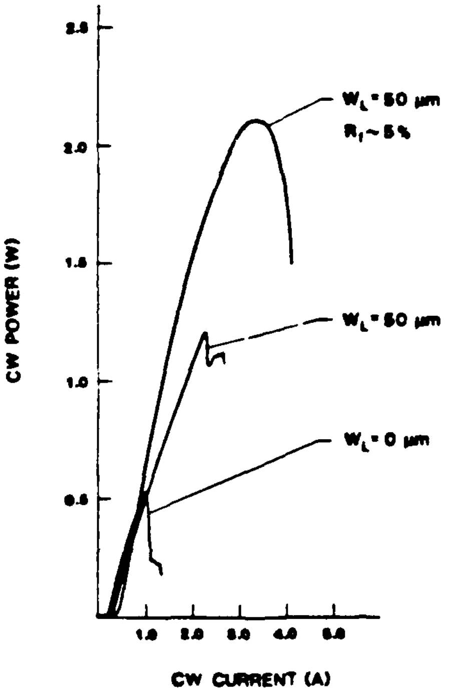
Use layer mixing to:
1.) tune emission wavelength

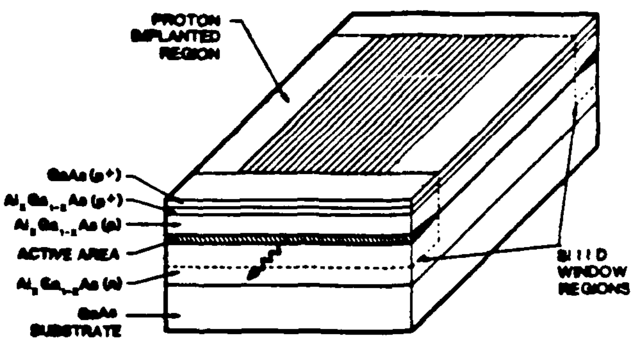
ref.: M. Camras, et al, Appl. Phys. Lett., 54, 5637 (1983).



2.) reduce facet damage by increasing E_g at output windows

ref.: R. Thornton, et al, Appl. Phys. Lett., 49, 1572 (1986).





THIS WORK:

IID involves electrically active species
>>use applied electric field

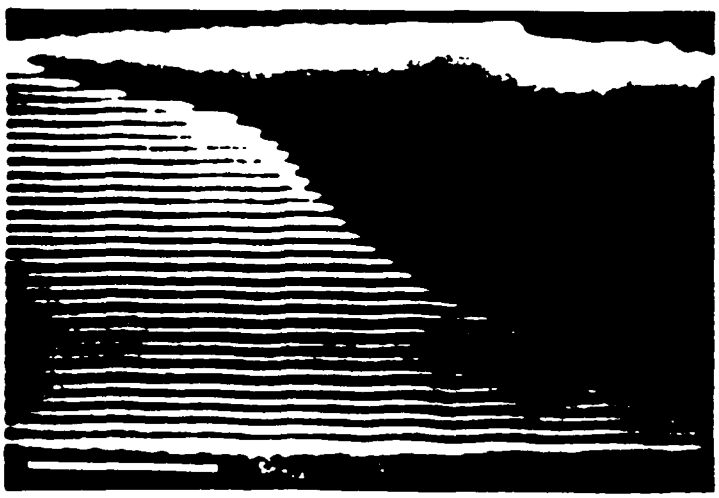
>>more accurate diffusion coefficient measurements

>>improved lateral resolution for component definition

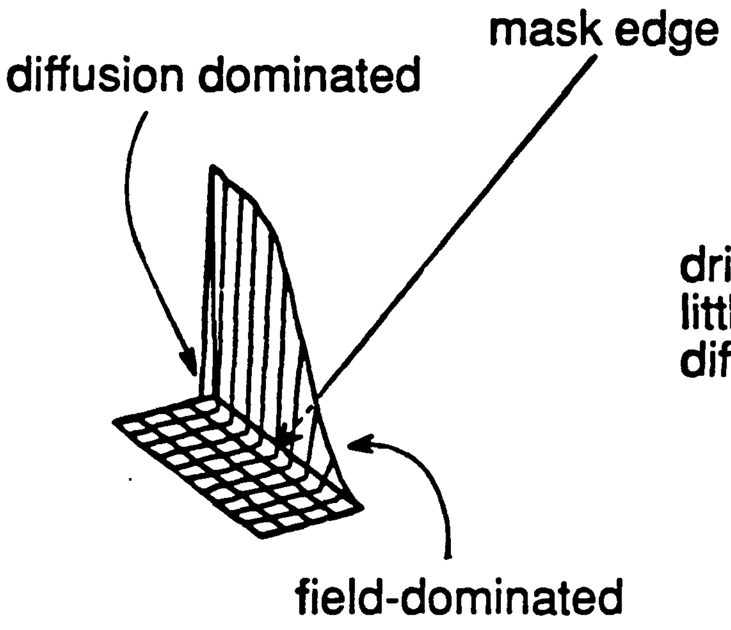
Zn diffusion

1μm

Si diffusion

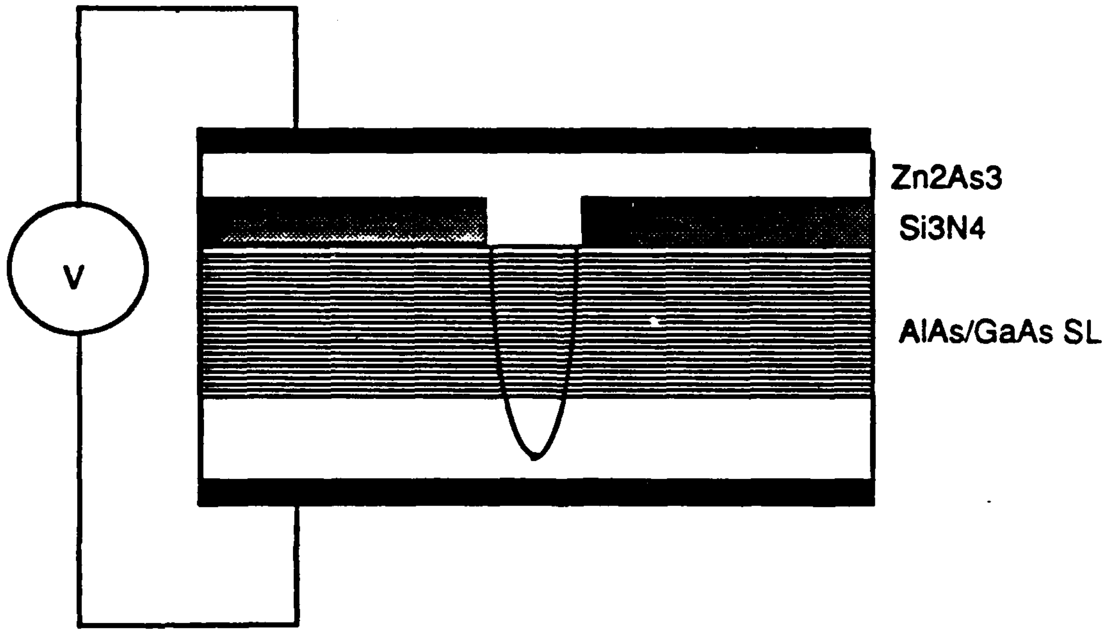


1μm



drive in mixing profile; little time for sideways diffusion.

Use evaporated source or gettering layer:



Use to study IID mechanism, fabricate components.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

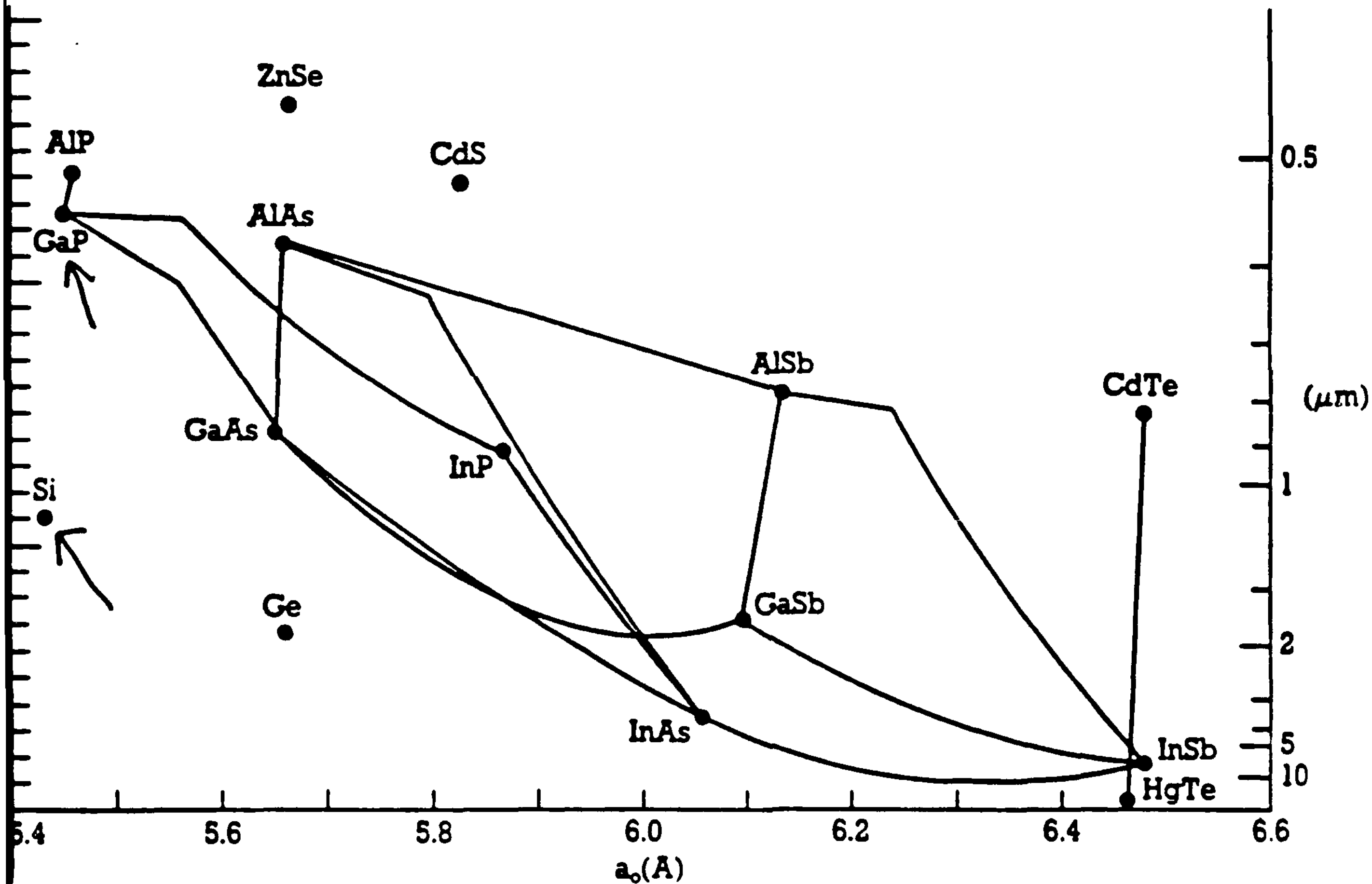
OPTICAL INTERACTIONS IN INDIRECT BANDGAP: III-V SEMICONDUCTORS AND SILICON

OPTICAL INTERACTIONS IN INDIRECT BANDGAP

III-V SEMICONDUCTORS AND SILICON

- Gallium Phosphide, GaP
  - Optical Emission
- Silicon
  - Optical Emission
  - Waveguides

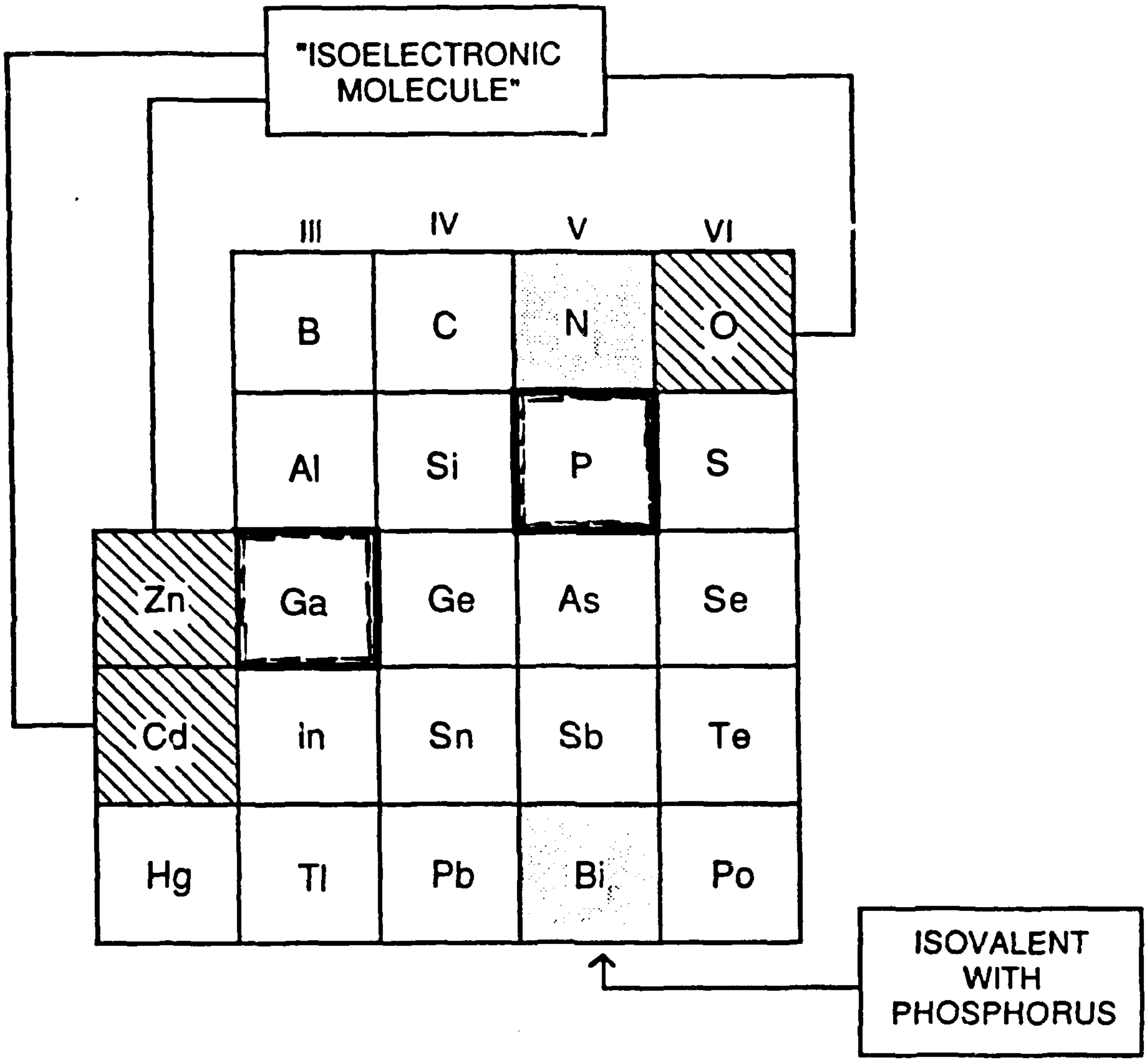
ENERGY GAP (in eV and μm) VERSUS LATTICE CONSTANT AT 300K FOR COMPOUND SEMICONDUCTORS



GALLIUM PHOSPHIDE, GaP

INDIRECT GAP: ~ 2.27 eV AT T = 300K.

IMPURITY - RELATED LUMINESCENCE



ISOVALENT (ISOELECTRONIC) IMPURITY

GaP: N or GaP:Bi

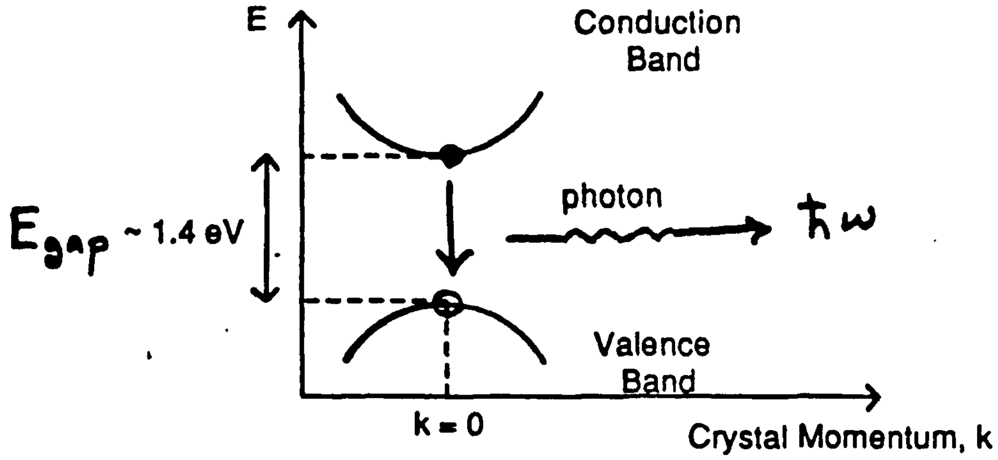
ISOVALENT (ISOELECTRONIC) MOLECULE

GaP:Zn - O or GaP:Cd - O

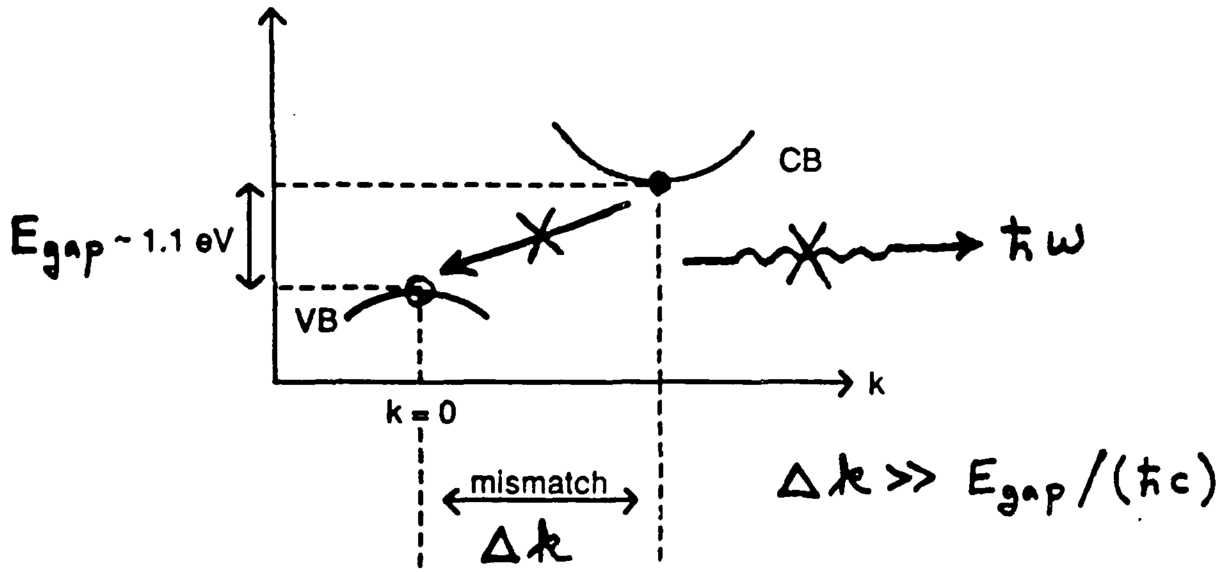
(Nearest-Neighbor Donor-Acceptor Pair)

ENERGY BAND STRUCTURE

GaAs - DIRECT ENERGY GAP



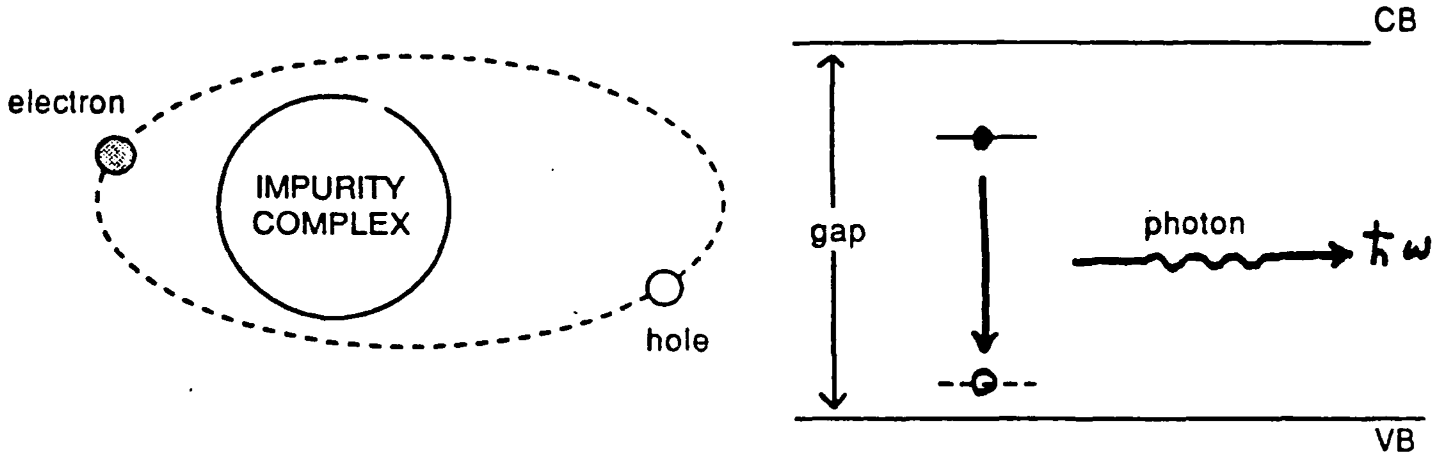
Silicon - INDIRECT ENERGY GAP



k - CONSERVATION SELECTION RULE

- UNASSISTED, BAND - TO - BAND, RADIATIVE RECOMBINATION OF ELECTRONS AND HOLES IS FORBIDDEN.
- PHONON - ASSISTED RADIATIVE TRANSITIONS CAN AND DO OCCUR.

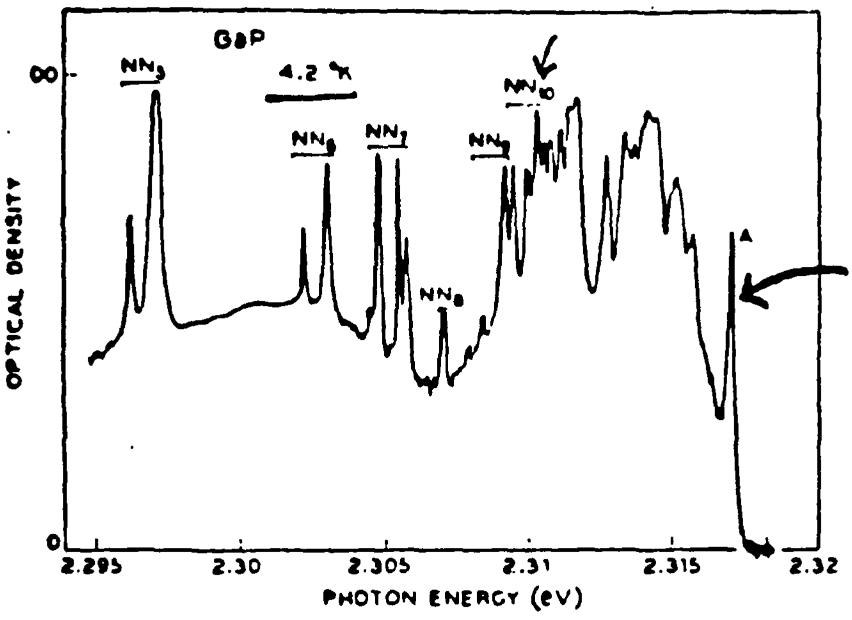
EXCITONS BOUND TO ISOELECTRONIC IMPURITIES



PROBABILITY OF NONRADIATIVE AUGER RECOMBINATION IS LOW.

PROBABILITY OF RADIATIVE RECOMBINATION IS HIGH.

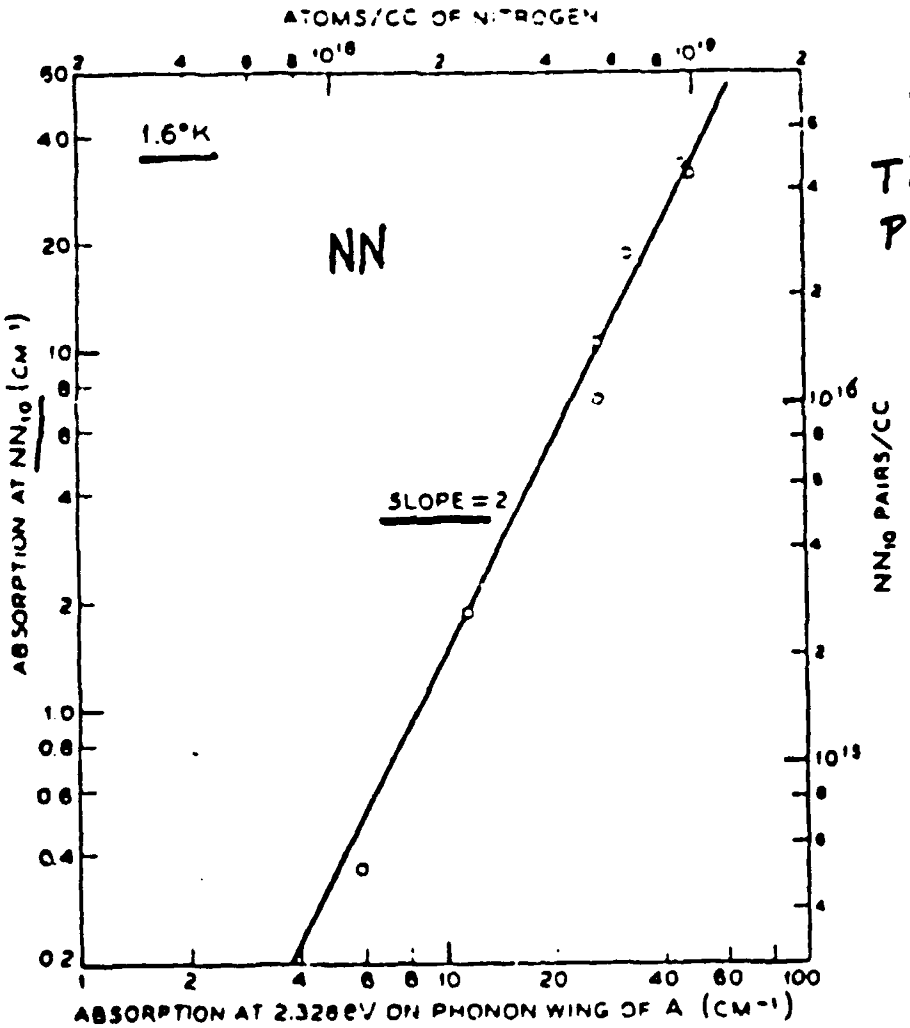
GaP:N



EXCITONS BOUND TO

A → SINGLE N IMPURITY

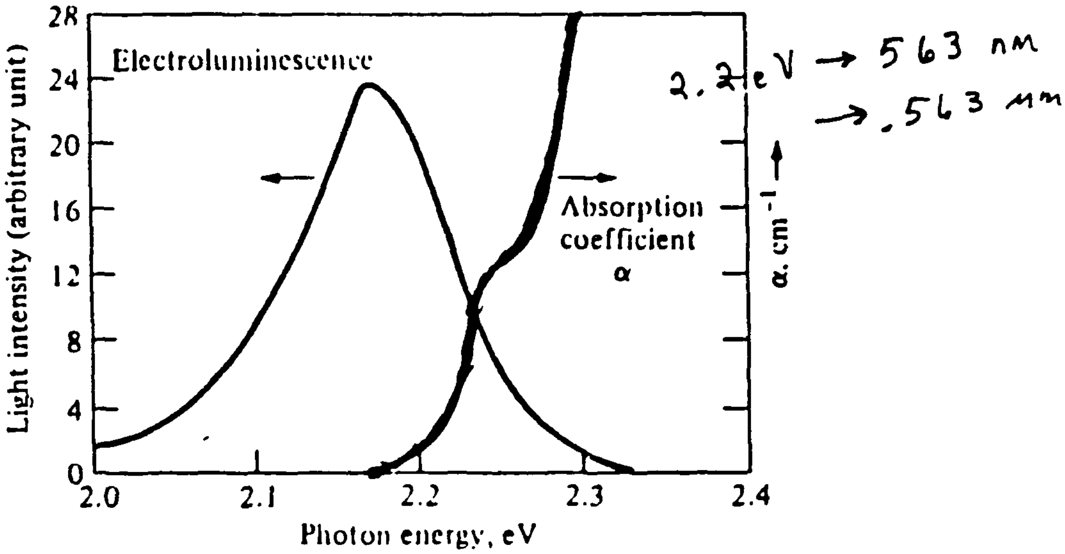
NN → PAIRS OF N IMPs



From:
Thomas and Hopfield, Phys. Rev. 150, 680 (1966).

GaP: N

Green LED



LASER ACTION

U.S. Patent 3,761,837 (1973)

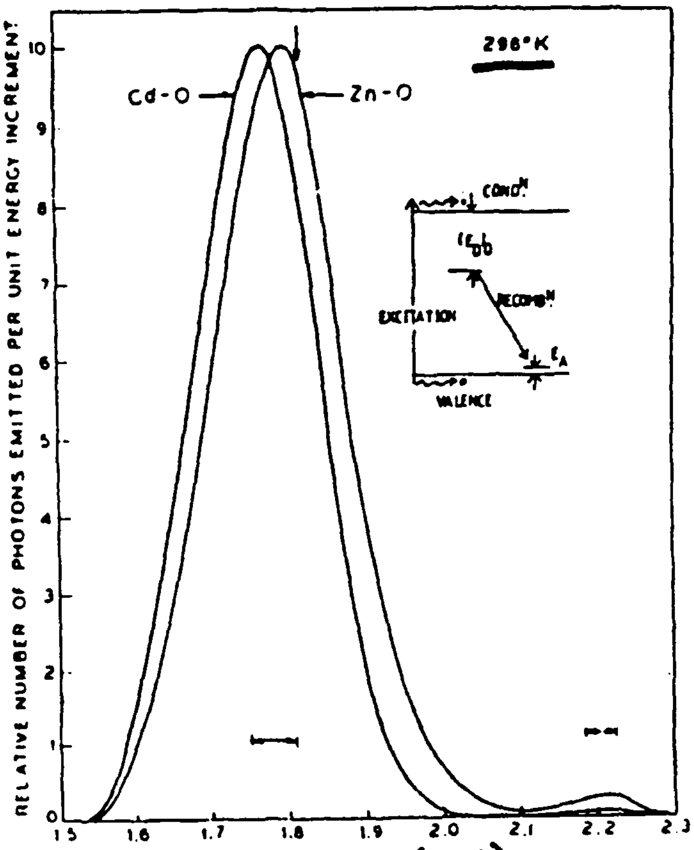
Leheny, Logan, Nahory, and Shaklee

"Lasers in Indirect-Bandgap Semiconductive Crystals Doped with Isoelectronic Traps"

Gain in GaP:N ⇒ 200 cm^{-1} at T=300°K

Gain in GaP:Bi ⇒ observed

ROOM TEMPERATURE

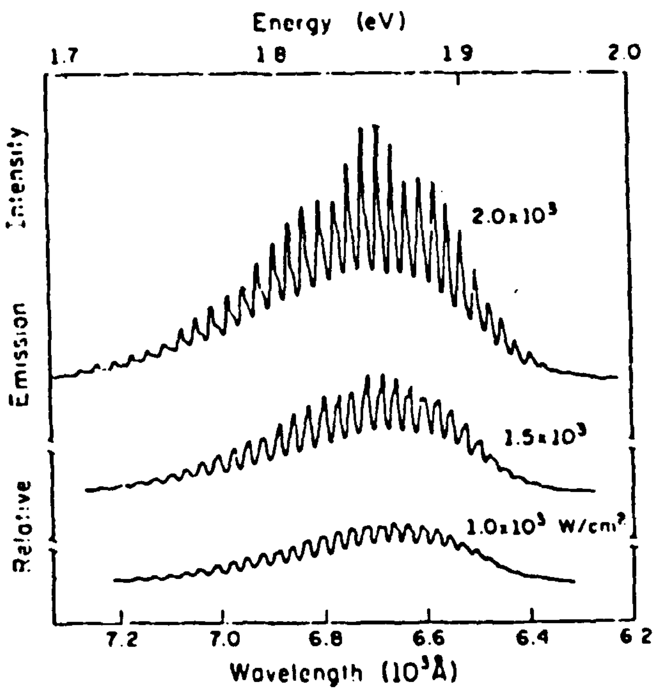


GaP: Zn−O

GaP: Cd−O

M. Gershenzon et al, J. Appl. Phys. 37, 483 (1966).

$1\% < \eta_{ext} < 10\%$



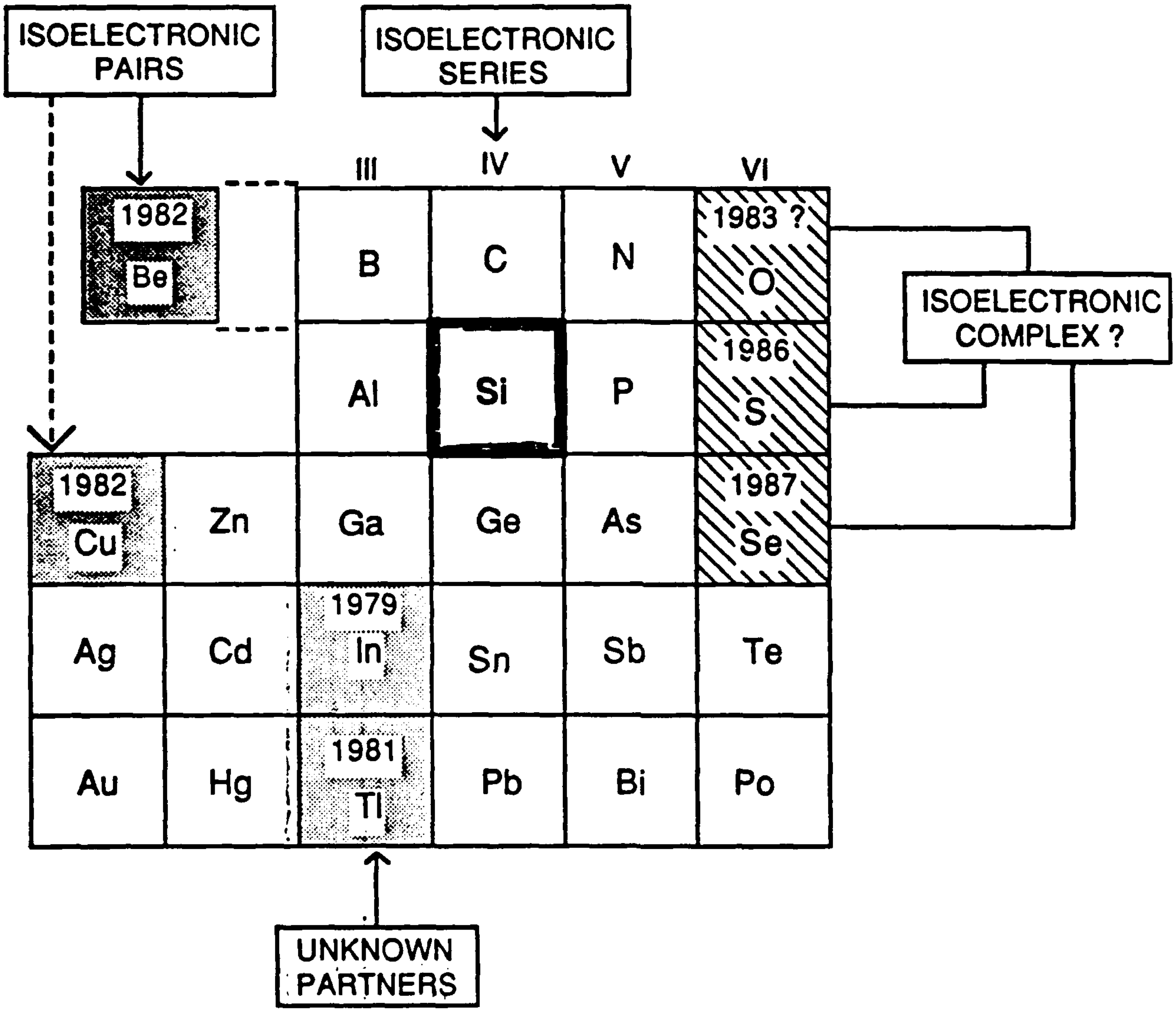
"Stimulated Emission and Laser Operation (cw, 77°K) Associated with Deep Isoelectronic Traps in Indirect Semiconductors"

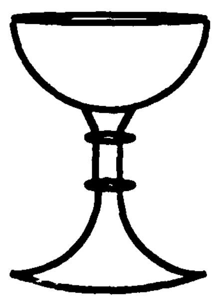
N. Holonyak + 7 authors, Phys. Rev. Lett. 28, 230 (1972).

"The role of this "trap-assisted absorption" has been neglected in arriving at the pessimistic conclusions that have appeared in the literature concerning stimulated emission in indirect semiconductors."

controversial

WHAT ABOUT SILICON ?





W. P. DUMKE
IBM, YORKTOWN HEIGHTS

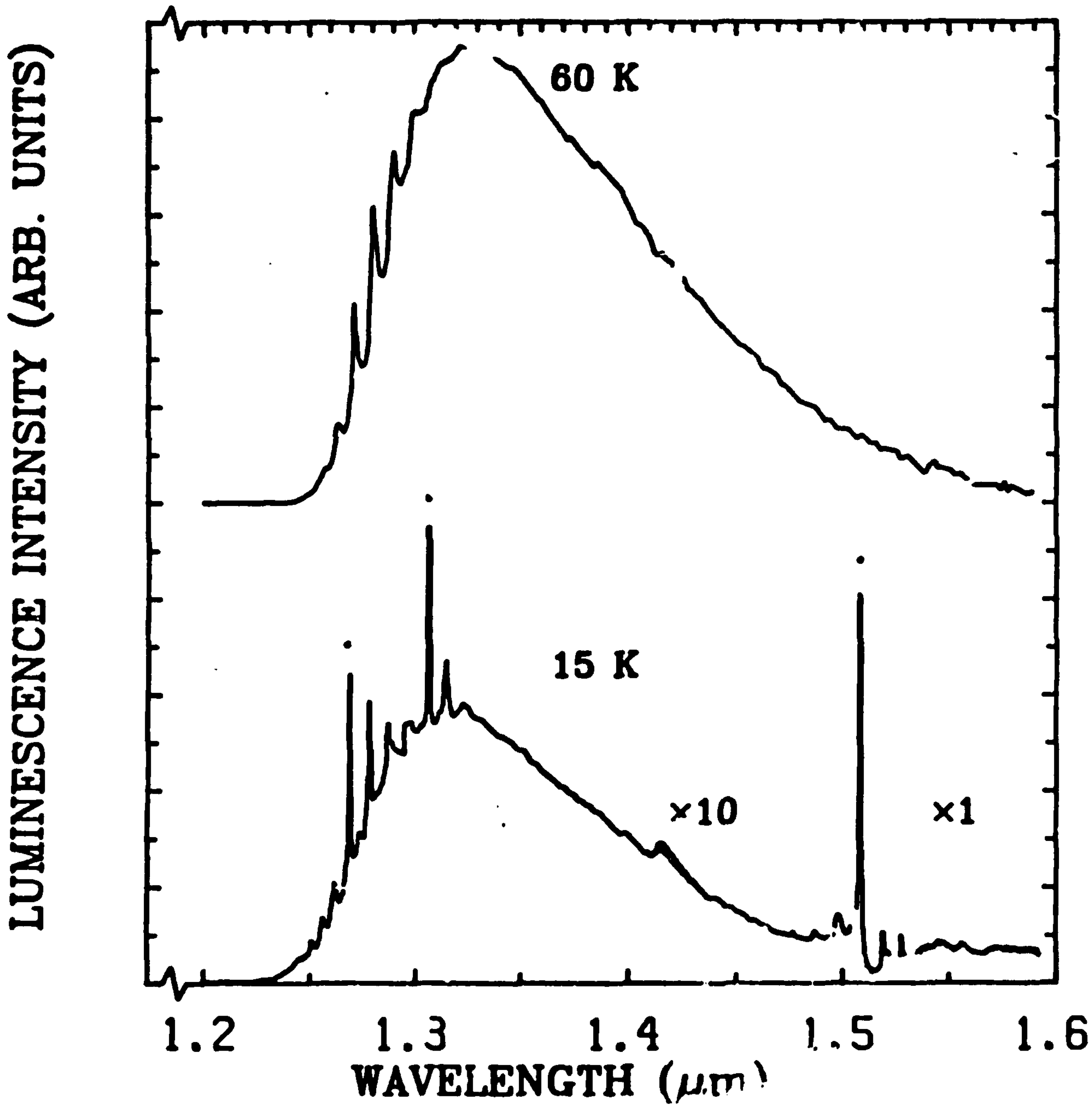
"INTERBAND TRANSITIONS AND MASER ACTION"
PHYS. REV. 127, 1559 (1962).

FIRST LINE OF THE PAPER

Since the initial operation of the ruby maser, there has been considerable speculation concerning the possibility of observing maser action in semiconductors such as Ge and Si.

ABSTRACT OF THE PAPER

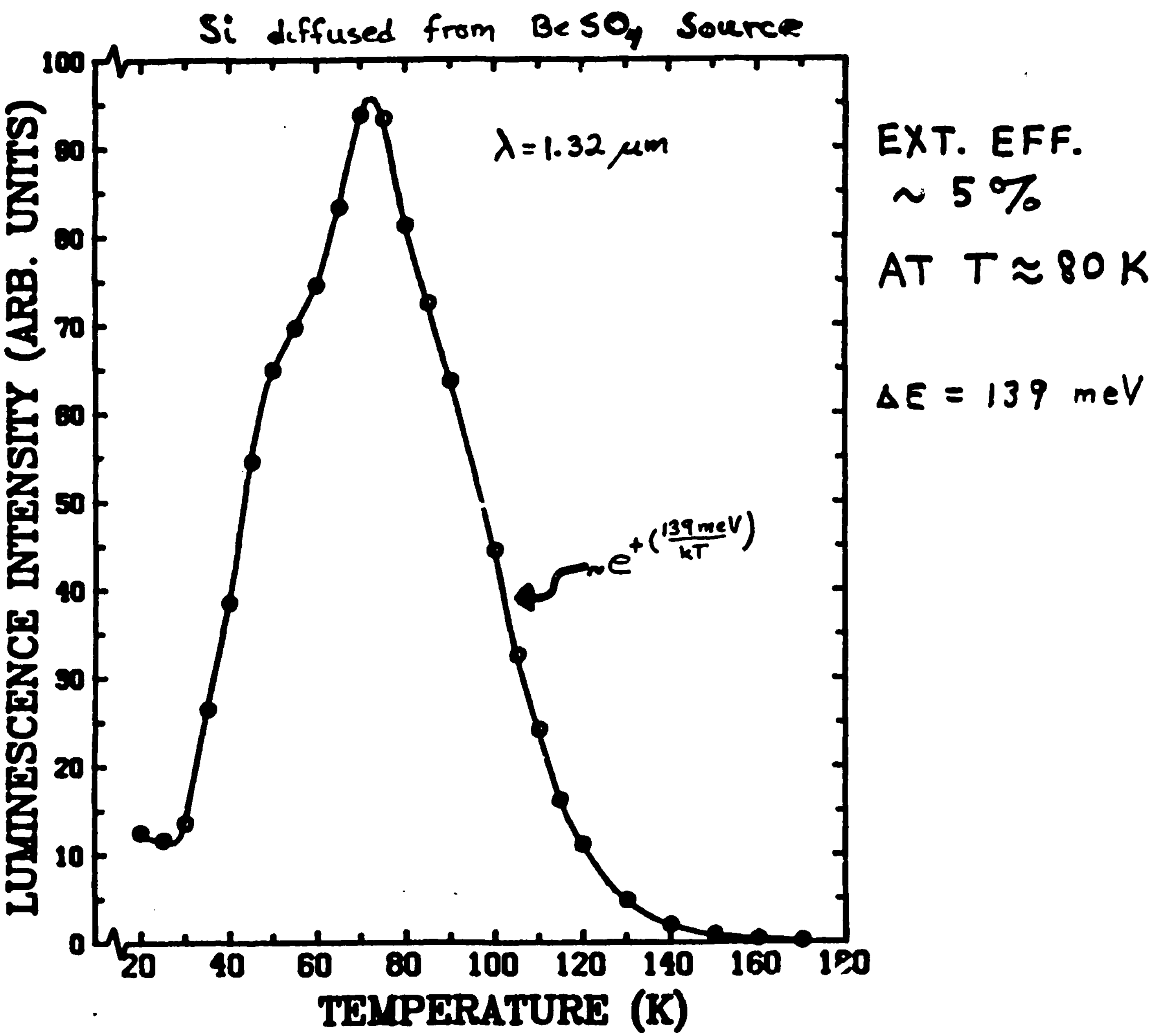
The possibility of using interband transitions to achieve maser action is considered. The criterion for maser action is presented in a way which allows the most direct use of optical absorption data. The absorption constant for interband transitions, which is negative corresponding to induced emission when a population inversion exists, is related to the normal absorption constant for direct, indirect, and indirect exciton transitions. **Using available absorption data, it is shown that in Ge (Si) maser action, using either the indirect or indirect exciton transitions, would be prevented by absorption due to free carriers. In GaAs, or other materials with a direct gap, however, it is entirely possible that maser action could be achieved.**



$\eta_{ext} \sim 5\%$ {edge emission

$T \sim 77°K$ for I_{max}

T. G. Brown and D. G. Hall
Appl. Phys. Lett. 49, 245
August 4, 1986



Si diffused from BeSO4 Source
λ=1.32 μm
~e+(139 meV/kT)
LUMINESCENCE INTENSITY (ARB. UNITS)
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
120
140
160
180
TEMPERATURE (K)
EXT. EFF.
~ 5 %
AT T ≈ 80 K
ΔE = 139 meV

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
III-V OPTOELECTRONICS FOR OPTICAL COMMUNICATIONS

III-V OPTOELECTRONICS FOR OPTICAL COMMUNICATIONS

1. Overview: Communications Systems

2. Overview: Modulation/Demodulation Schemes

3. Source Stability Requirements for Advanced Optical Communications

4. Methods of Source Stabilization

Historical Perspective:

Free Space Optical Communications	Ancient Greeks
Morse Telegraph	1840's
Bell Telephone	1870's
Marconi's Wireless Telegraph . . . Radio	1900
Coherent Carrier Modulation/Demodulation	1940's
Phased Locked Receivers	1950's
First Optical Mixing Observed	1955
Semiconductor Laser Invented	1963
Low Loss Optical Fiber	1970
Free-Space Optical Heterodyne Systems	1970's
High speed, low loss single-mode fiber links	1980's
Coherent Optical Fiber Communications proposed	1980's

Communications Systems:

Free Space

Optical Fiber

Telecommunications   Data Transfer

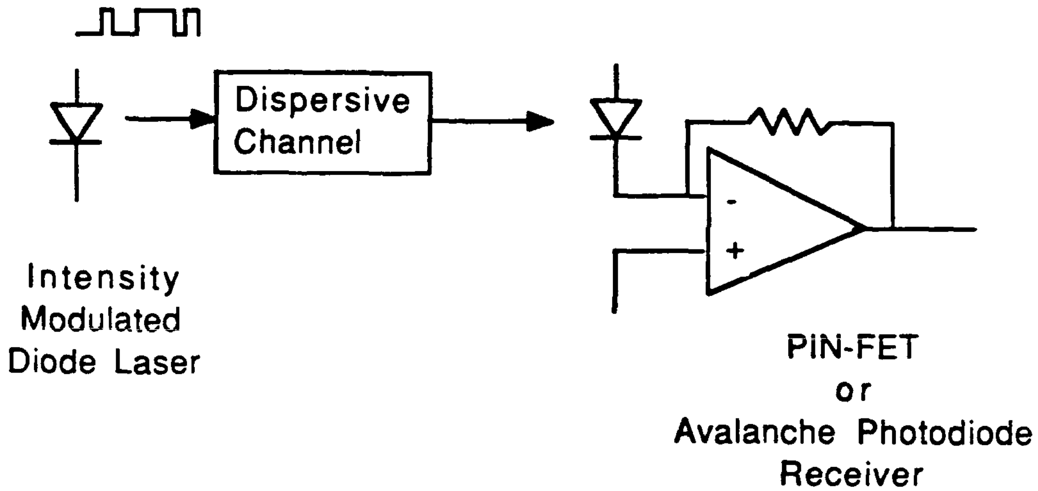
Trunk   Local Area Network   Subscriber

There is current interest in:

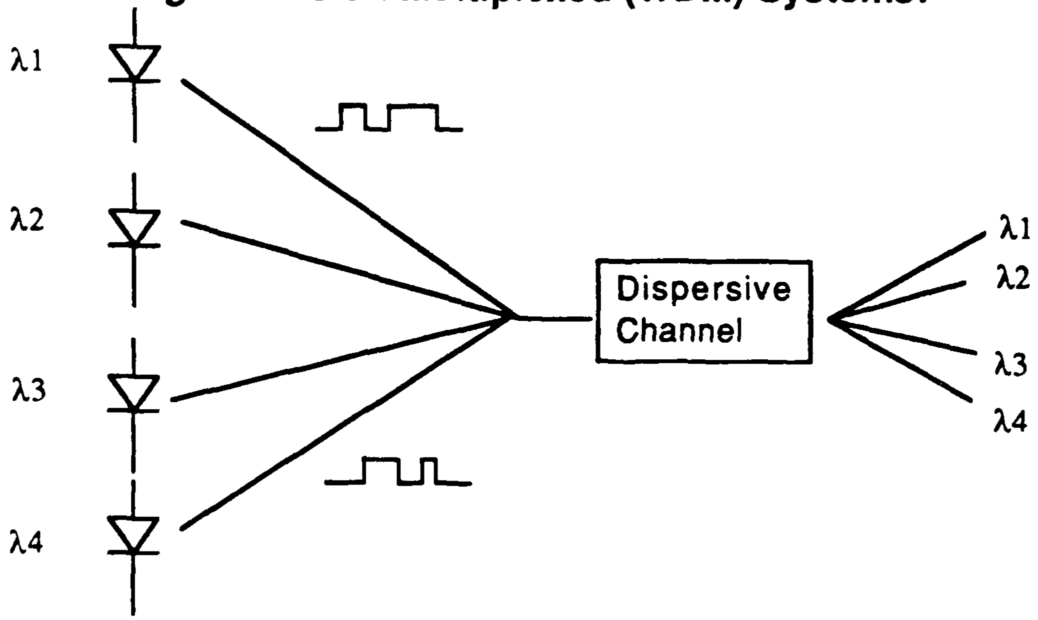
Long repeaterless links.
Extremely high capacity links.
Wide area distribution.

Direct Detection Systems

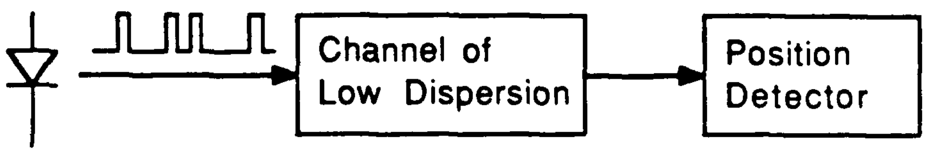
Traditional:



Wavelength-Division Multiplexed (WDM) Systems:

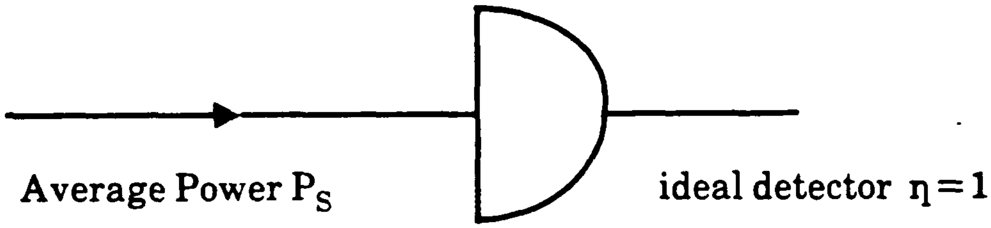


Pulse-Position Modulation (PPM) Systems:



(lowest fundamental limit)

- Direct Detection Systems



Average # of photons per time slot:

$$N_S = \frac{P_S T_B}{\hbar \omega}$$

Photo-electron statistics:

$$p(n) = \frac{{N_S}^n}{n!} e^{-N_S}$$ poisson process

Ideal photon counting: (no dark count)

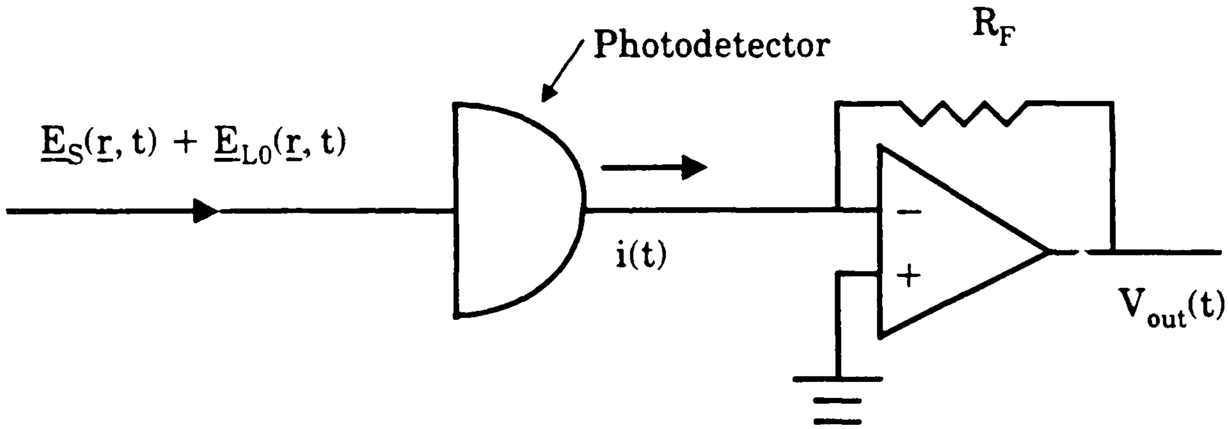
prob. of error $= P_E = \text{prob}(n=0)$

$$= e^{-N_S}$$

$N_S = 20.7$ for $P_E = 10^{-9}$

The Ideal System: Receiver Sensitivity

- Heterodyne/Homodyne Systems
  - No phase noise, perfect phase matching
  - $\left\{ \begin{array}{l} \text{Coherent (Phase-estimation)} \\ \text{Incoherent (Envelope)} \end{array} \right\}$ Demod.



$$i(t) = r\,|\underline{E}_S(\underline{r}, t) + \underline{E}_{L0}(\underline{r}, t)|^2$$

$$\Downarrow$$

$$i(t) = (\eta\, e/\hbar\omega)\{P_S + P_{L0} + 2\sqrt{P_S P_{L0}}\ \mathrm{Cos}(\omega_{if} t + \phi(t))\}$$

ASK

representation: (Binary)

$$\begin{cases} a(t) = 1 \text{ "mark"} \\ a(t) = 0 \text{ "space"} \end{cases}$$

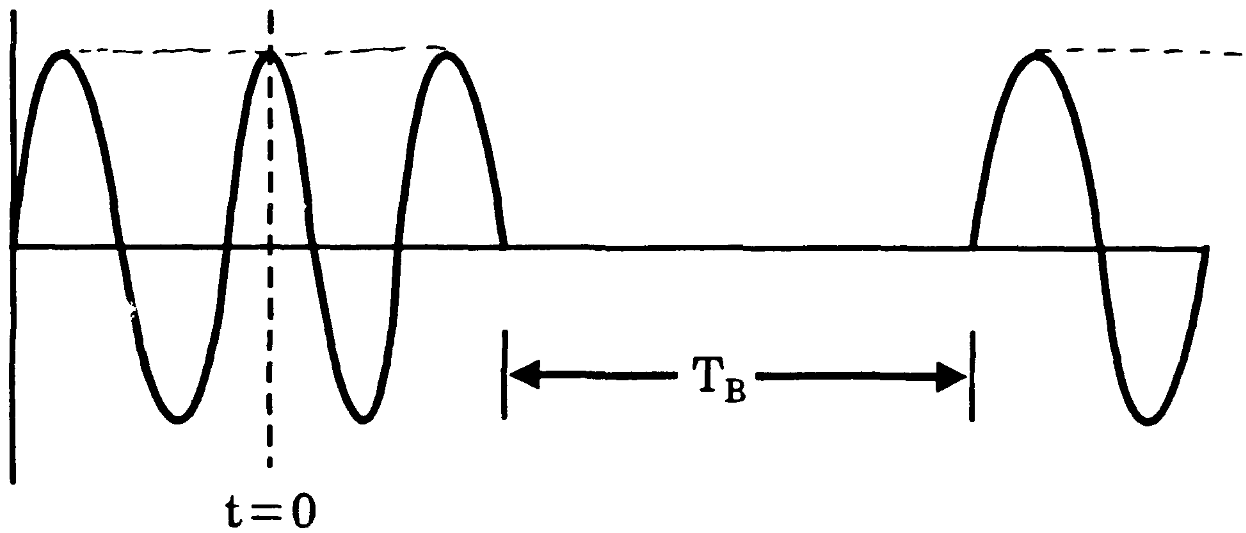
representation: (Quaternary)

$$\begin{cases} a(t) = 1 \\ a(t) = .67 \\ a(t) = .33 \\ a(t) = 0 \end{cases}$$

↓

Analog limit (minimum bandwidth)

- We are not interested in bandwidth compression, so use binary.



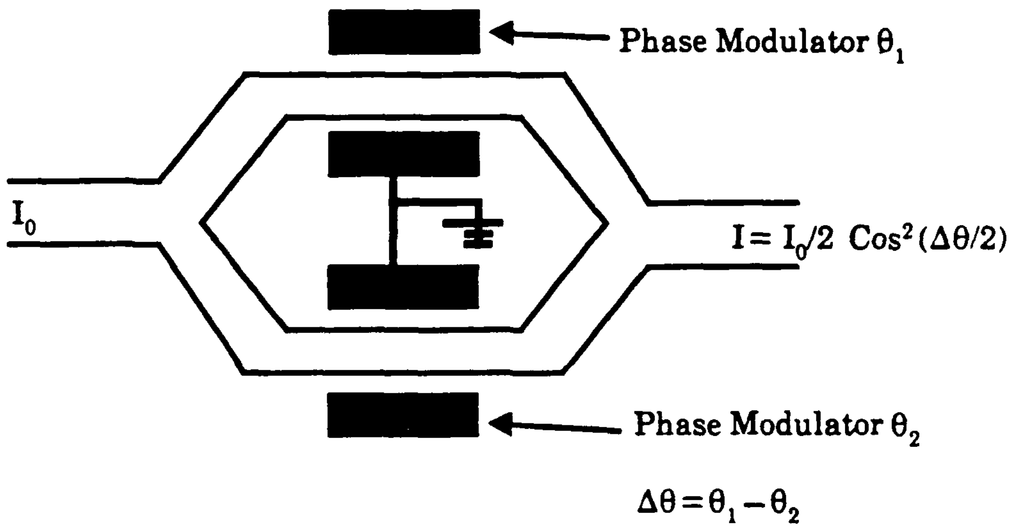
ASK IMPLEMENTATION

- Same modulator technology as direct detection systems.

- External modulators only, since direct modulation of semiconductor lasers results in frequency modulation. (GHz/mA)

- Easy detection (in analogy to RF systems)

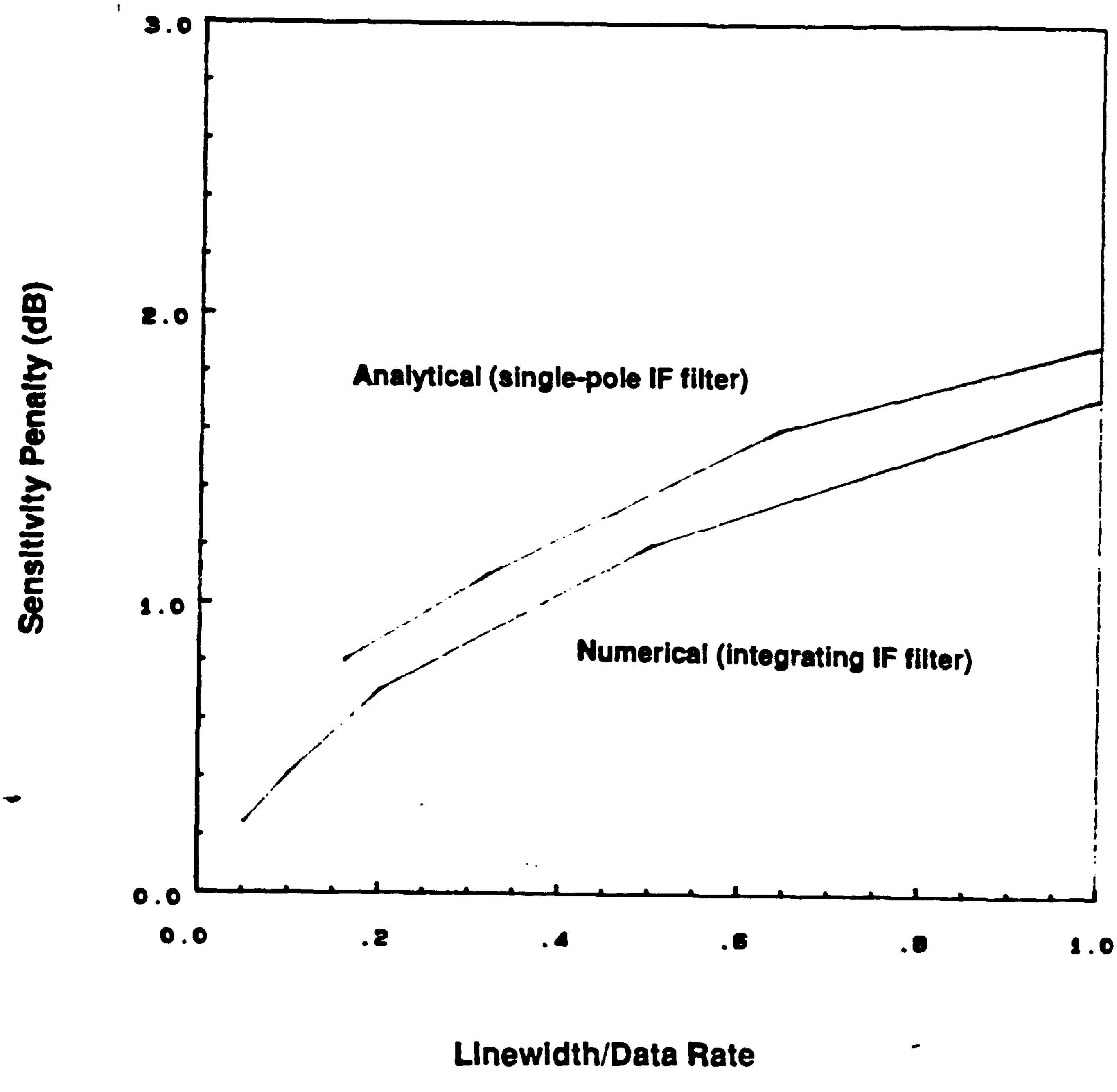
MACH-ZEHNDER INTERFEROMETRIC MODULATOR



- Identical waveguides, equal path lengths yield constructive interference.
- Relative phase shift $\Delta\theta$ causes destructive interference for $\Delta\theta = \pi$
- Practical design considerations require tuning for "on" and "off" states.
- Top speed >17 GHz

[Ref. Gee and Thurmond OFC'84
R. C. Alferness, IEEE JQE 17, 946 (1981)]

Receiver Sensitivity Penalty
ASK Envelope Detection with
Optimized Post-detection Filtering



PSK

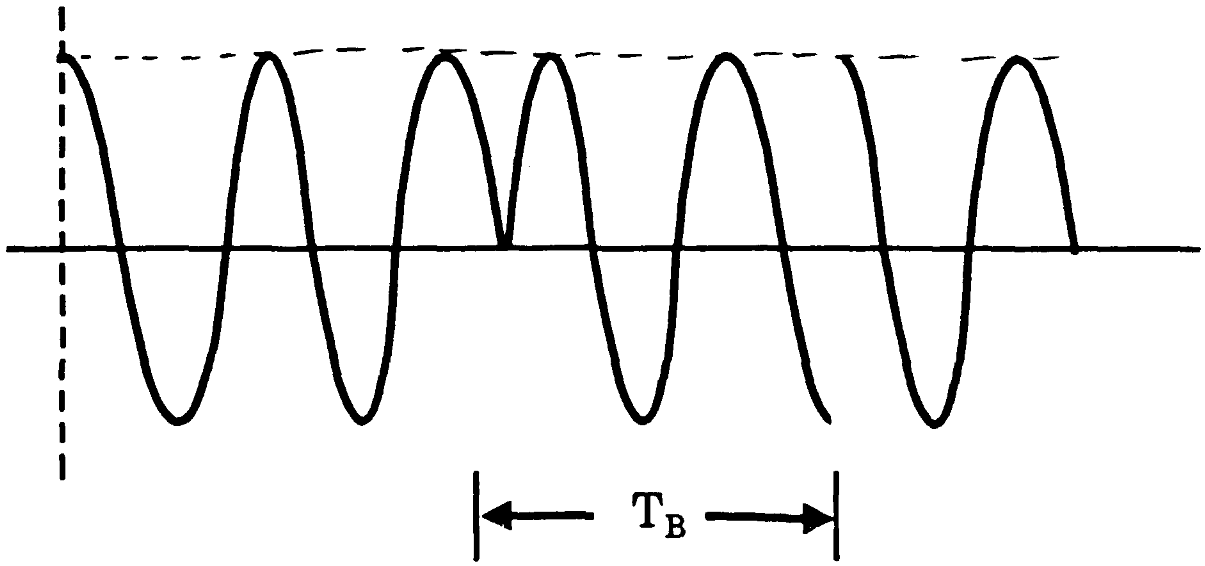
representation: (Binary)
$$\begin{cases} a(t) = 1 \text{ "mark"} \\ a(t) = -1 \text{ "space"} \end{cases}$$

representation: (Quaternary)
$$\left\{ \begin{array}{l} a(t) = 1 \\ a(t) = i \\ a(t) = -1 \\ a(t) = -i \end{array} \right\} \text{4 Levels}$$

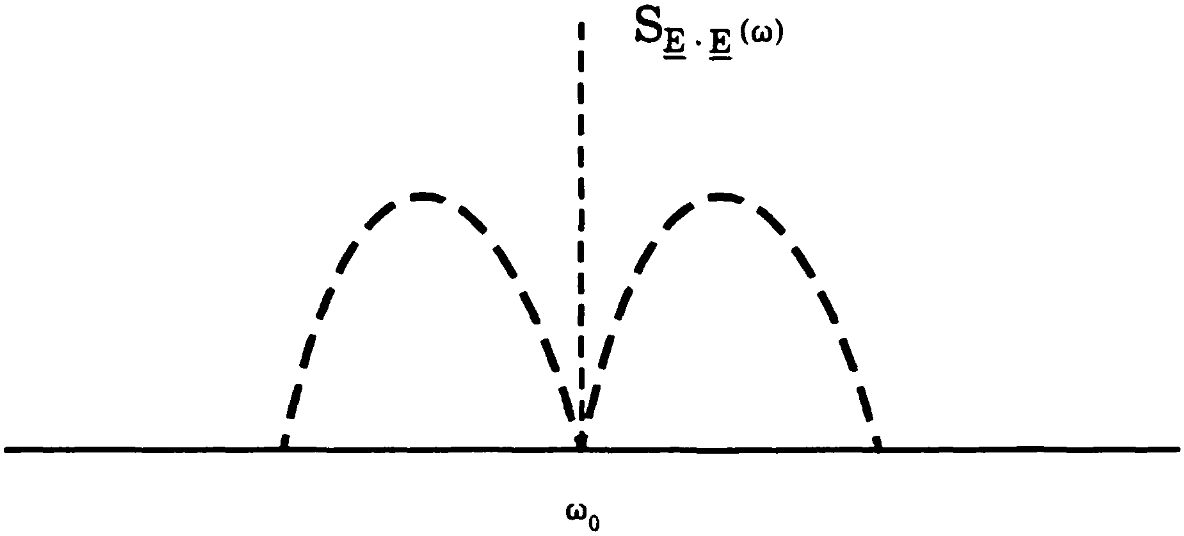
↓

Analog limit (minimum bandwidth)

- Once again, use binary.



- PSK is a suppressed carrier modulation technique

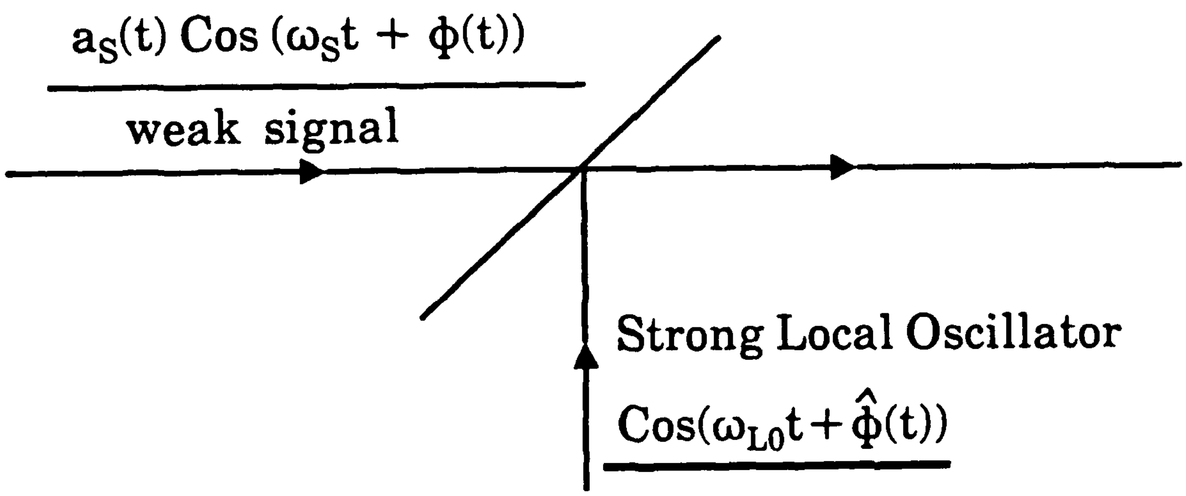


- No energy at $\omega = \omega_0$

- Requires nonlinear phase recovery scheme.

PSK Implementation:

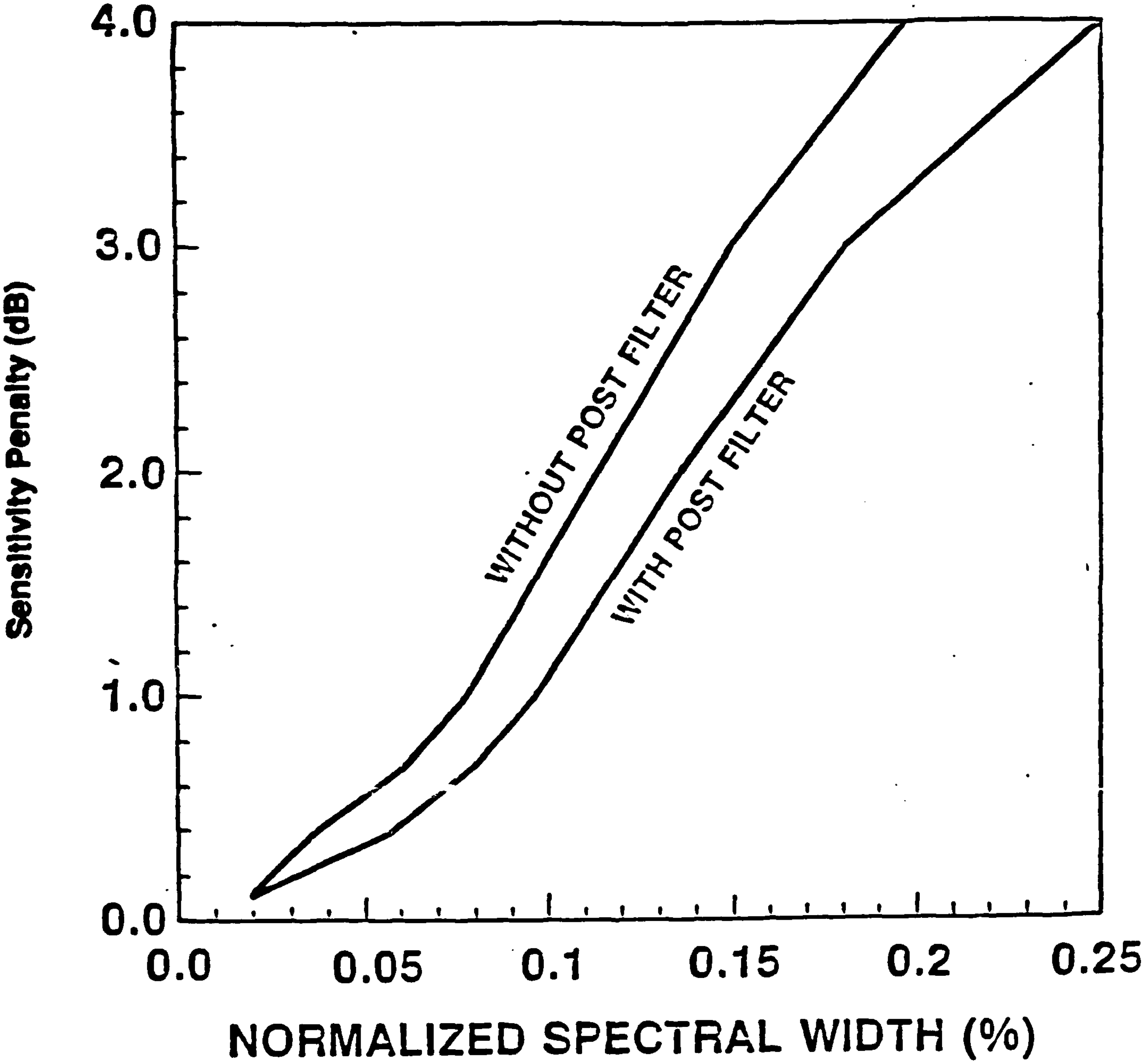
- Simplest possible modulator configuration.
  - Electro-optic (Pockels) effect
  - Free carrier effect (semiconductors)
- External modulators only
- Detection is difficult



for error-free detection,

$\phi(t) = \hat{\phi}(t)$

PSK HETERODYNE DETECTION



FSK

Binary Representation:

ω_c = channel spacing

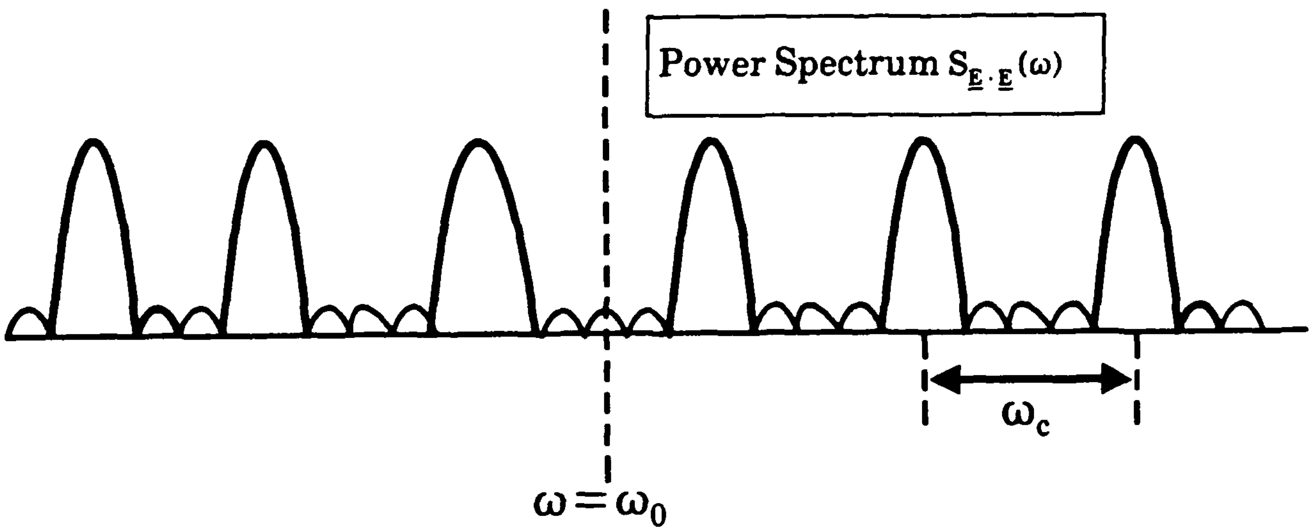
$$\begin{cases} a(t) = e^{i\omega_c t/2} & \text{"mark"} \\ a(t) = e^{-i\omega_c t/2} & \text{"space"} \end{cases}$$

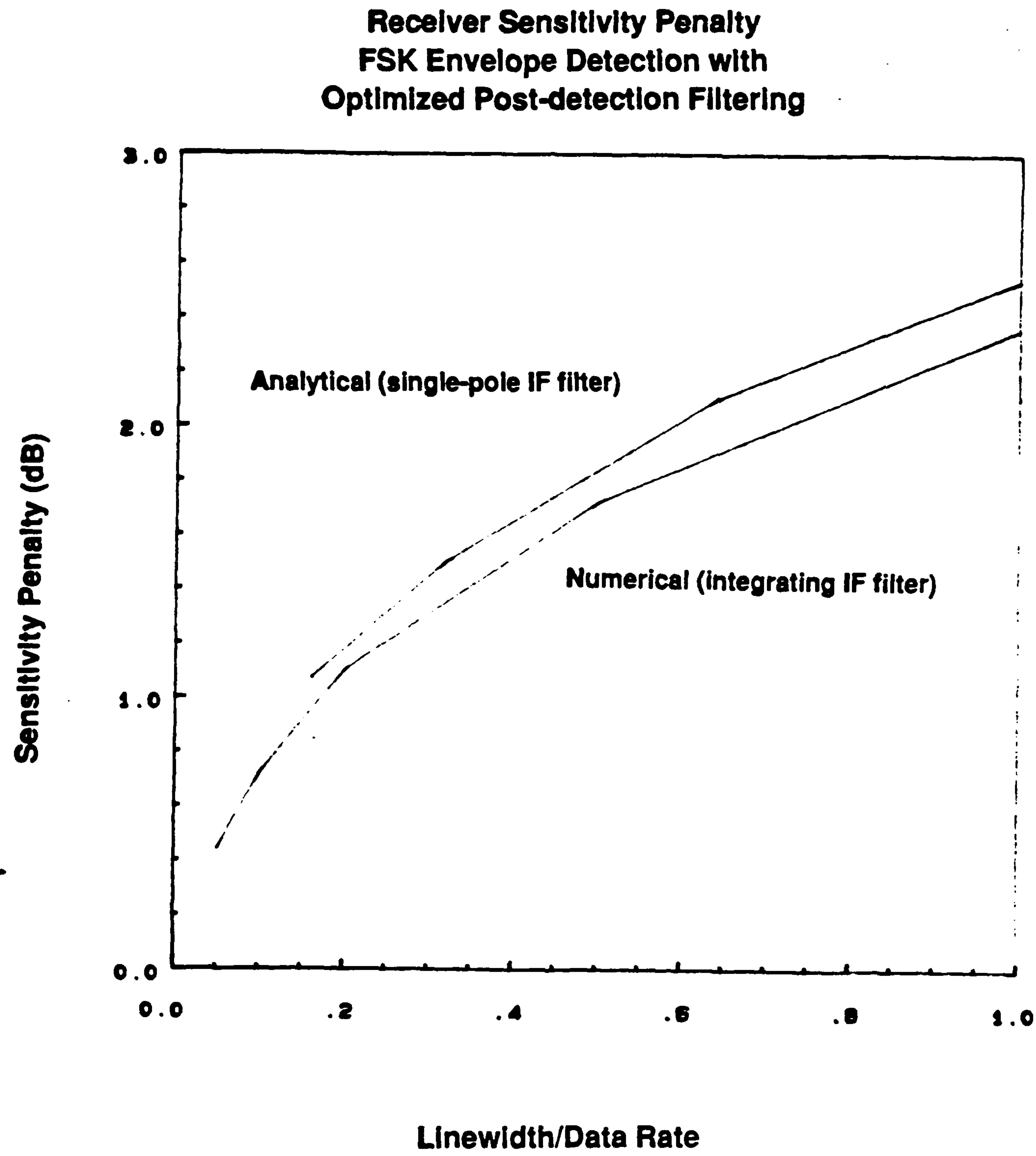
M-ary representation

#Channels $M = 2m$

$$\begin{cases} a(t) = e^{i(m+\frac{1}{2})\omega_c t} \\ \vdots \\ a(t) = e^{i\frac{1}{2}\omega_c t} \\ \vdots \\ a(t) = e^{-i(m+\frac{1}{2})\omega_c t} \end{cases}$$

→ Bandwidth Expansion technique




Receiver Sensitivity Penalty
FSK Envelope Detection with
Optimized Post-detection Filtering
Analytical (single-pole IF filter)
Numerical (integrating IF filter)
Sensitivity Penalty (dB)
Linewidth/Data Rate
0.0
1.0
2.0
3.0
.2
.4
.6
.8
1.0

III-V Optoelectronic Devices: Limitations to System Performance

Semiconductor Lasers:

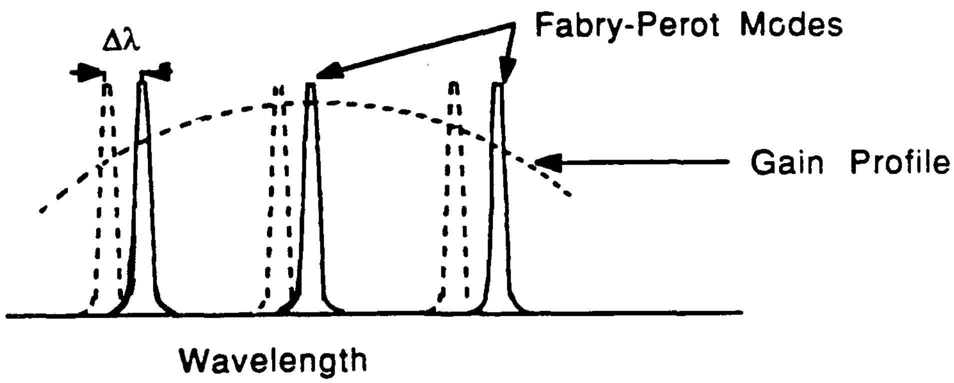
Mode Partitioning
(Direct Detection)

Phase Fluctuations/Line Broadening
(Coherent Detection)

Noise Mechanisms

Thermal Instabilities → **Phase Shifts in Optical Signal**
Quantum Fluctuations

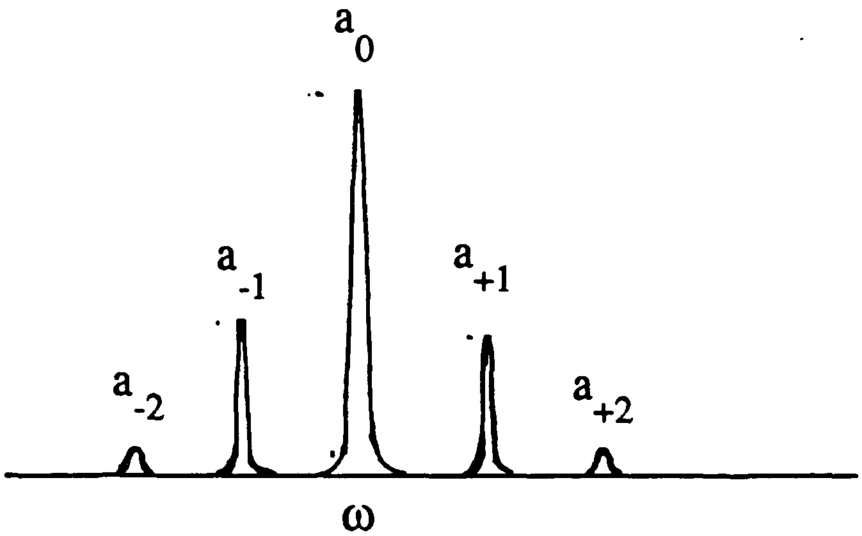
How does this happen?



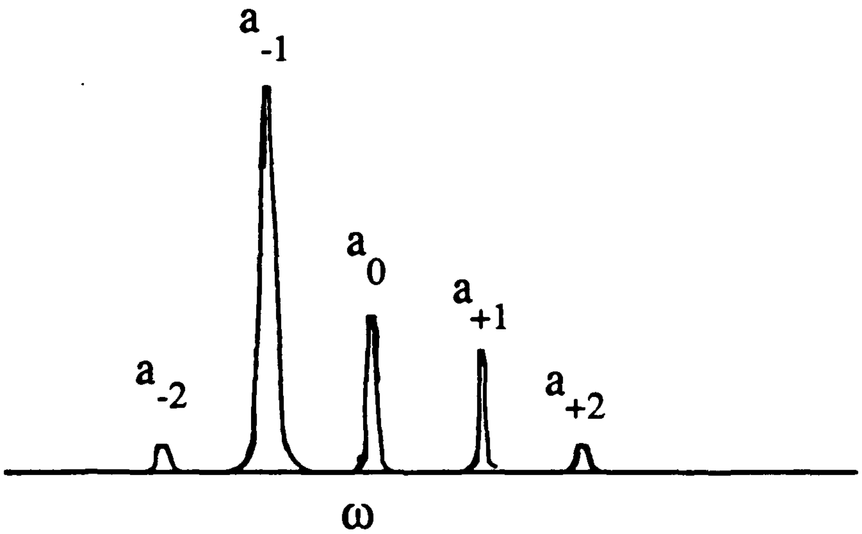
Large changes ------- Mode "partitioning"
Small changes ------- Line Broadening

Mode Partitioning

1) **Time Averaged Laser Spectrum**



2) **"Instantaneous" Measurement**

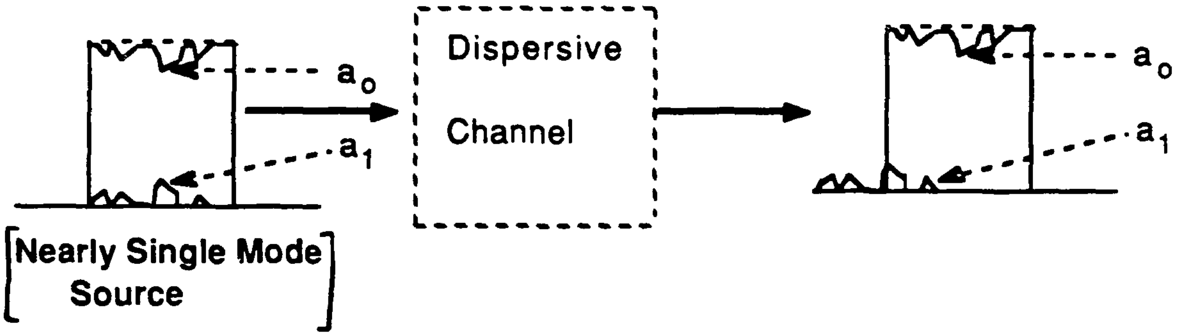


Assuming the population adiabatically follows the quantum fluctuations:

$$\sum_{j=-\infty}^{+\infty} a_j = \text{Constant}$$

Constant flux is dynamically "partitioned" among the modes.

What happens in a dispersive channel?

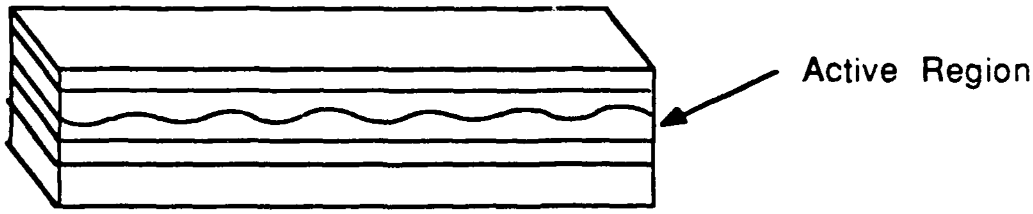


Solutions:

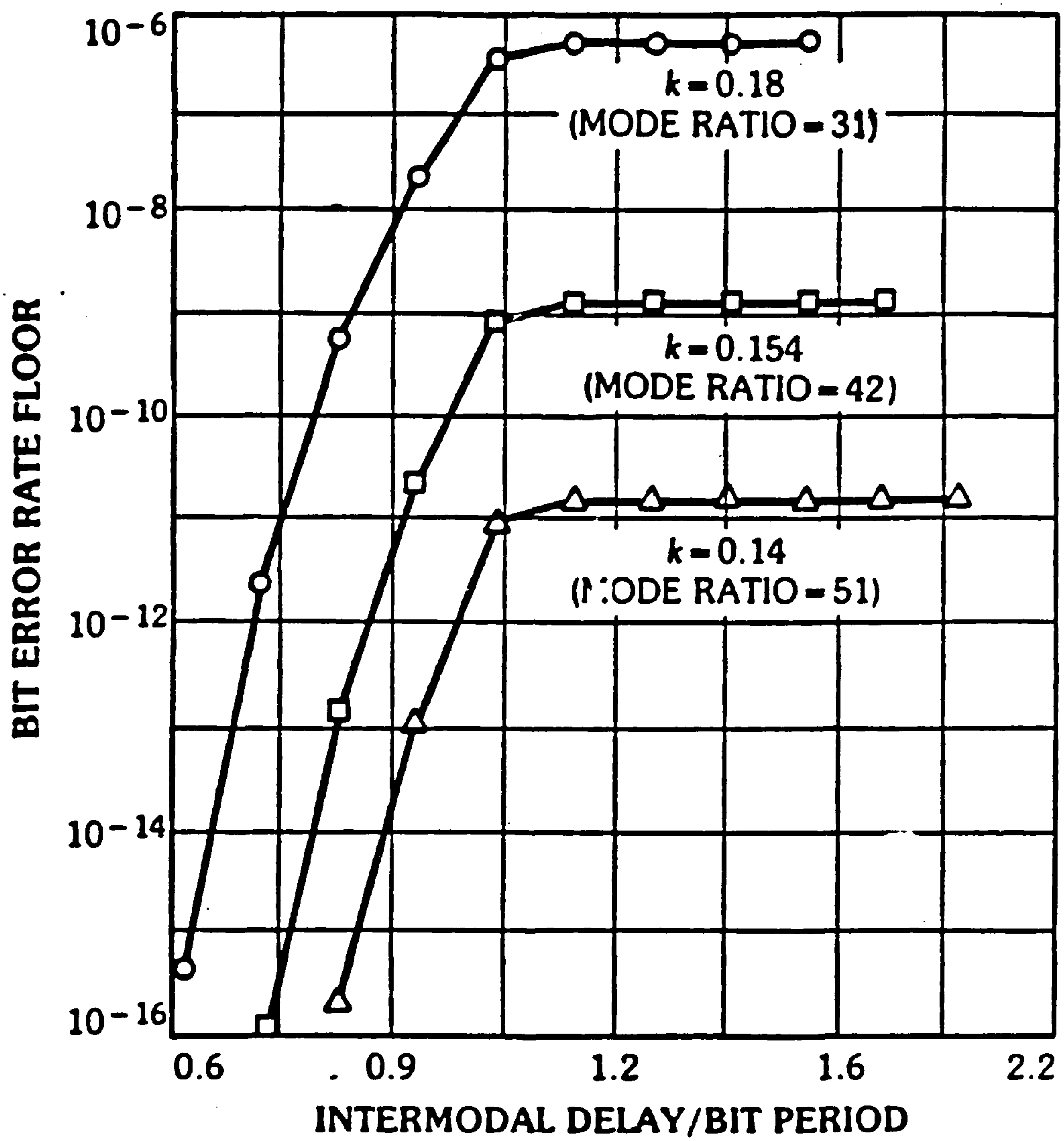
- Use the minimum dispersion point in fiber.
- Stabilize the diode laser:

"Single-mode" lasers require a side mode suppression ratio of about 100:1.

Distributed Feedback (DFB) Lasers provide mode stabilization.



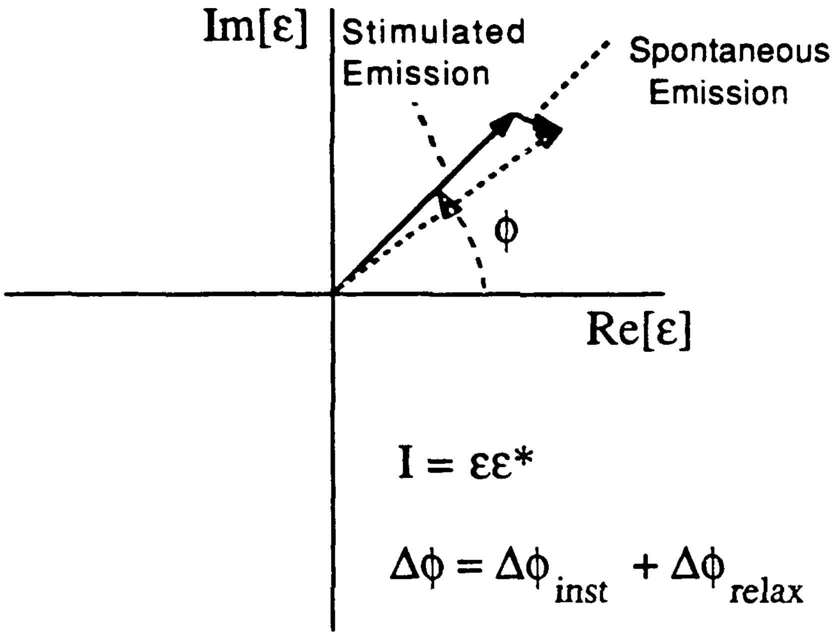
DFB Laser Structure



10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
BIT ERROR RATE FLOOR
$k = 0.18$
(MODE RATIO = 31)
$k = 0.154$
(MODE RATIO = 42)
$k = 0.14$
(MODE RATIO = 51)
0.6
0.9
1.2
1.6
2.2
INTERMODAL DELAY/BIT PERIOD

LINE BROADENING

Take a closer look at what is driving the phase fluctuations:



$$I = \varepsilon\varepsilon^*$$

$$\Delta\phi = \Delta\phi_{inst} + \Delta\phi_{relax}$$

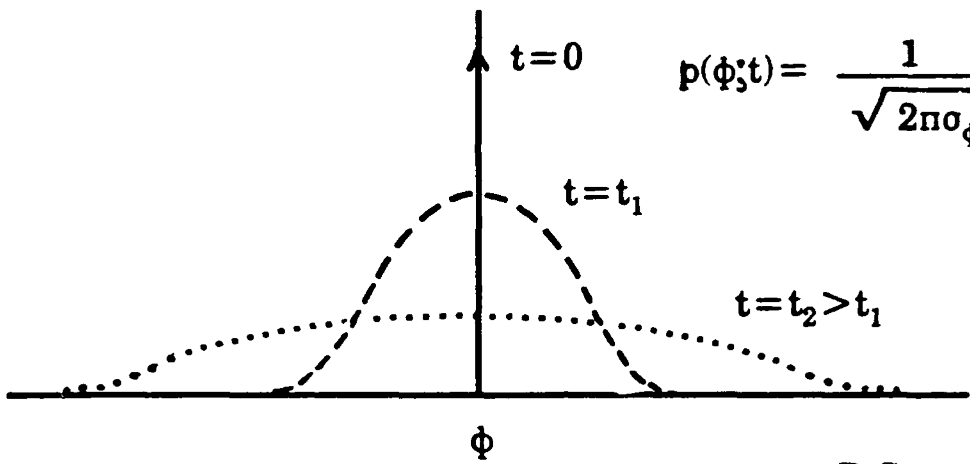
$$\Delta I \rightarrow \mathrm{Im}[\Delta n] \rightarrow \mathrm{Re}[\Delta n] \rightarrow \Delta\phi$$

Figure of (de)merit for Gain medium:

$$\alpha = \frac{\mathrm{Re}[\Delta n]}{\mathrm{Im}[\Delta n]} \cong 5 \quad \text{for GaInAs}$$

- ϕ exhibits a "random walk"

$$\sigma_\phi^2 = Dt$$



$$p(\phi;t) = \frac{1}{\sqrt{2\pi\sigma_\phi^2}}\, e^{-\phi^2/2\sigma_\phi^2}$$

$$D = (1+\alpha^2)\, R/2I$$

R-Sp. emission rate

α increases σ_ϕ^2 by ~25 to 50.

$$\boxed{\Delta\nu = D/2\pi}$$

- Solutions

  DFB Lasers (MHz)

  External Cavities (10-100 KHz)

How do we narrow the laser linewidth?

In an ideal system, we can:

- Increase the pump power (% above threshold).

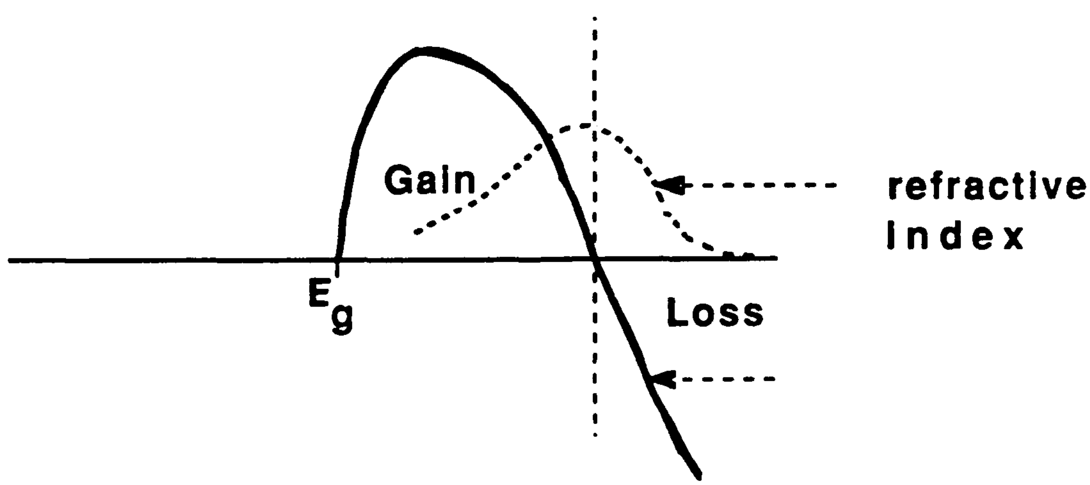
- Decrease the spontaneous emission rate. (External/Coupled Cavities)

- Introduce active stabilization.

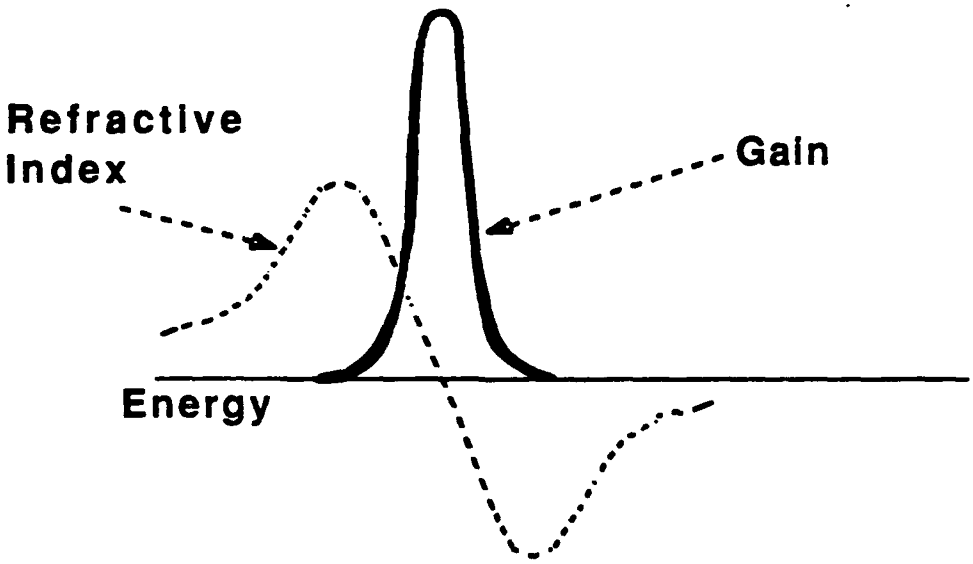
- Decrease α

How can α be reduced?

Bulk III-V Gain Medium



Discrete Transitions (Multiple Quantum Well)



Reducing the strong amplitude-phase coupling can improve linewidths by 25 - 50.

Options for discrete transitions:

- Multiple Quantum Well (MQW) diode lasers.

- Rare-earth resonant diode lasers.

Modulation Technique	Sensitivity (Photons/bit)	Linewidth Requirements	Laser of choice
Direct Detection	400-4000	100:1 side mode	Good FP or DFB
ASK Het.	80	0.1 x Data Rate	DFB
FSK Het.	40	0.1 x Data Rate	DFB
PSK Het.	18	10^{-3} x Data Rate	?
PSK Hom.	9	10^{-4} x Data Rate	?