USPAS Course on Photocathode Physics

John Smedley, BNL and Matt Poelker, TJNAF

Lecture 3

Austin, TX January 16-20, 2011

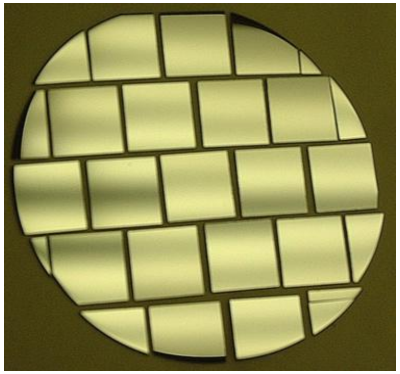
Lecture 3 Outline:

- First results from bulk GaAs
- Breaking the 50% barrier
- Review of growth techniques
- Properties of GaAs

Polarized Electron Source “Musts”

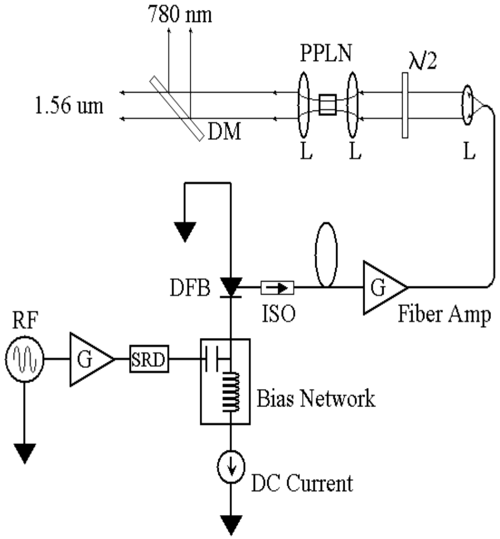
Good Photocathode

- High Polarization
- Many electrons/photon
- Fast response time
- Long lifetime



Good Laser

- “Headroom”
- Suitable pulse structure
- Low jitter



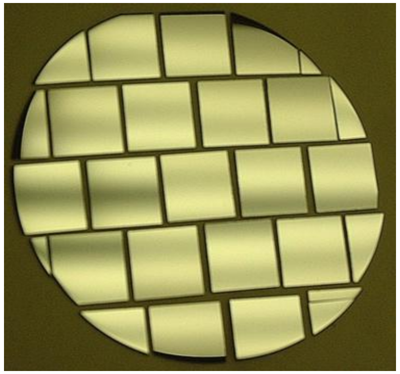
Good Electron Gun

- Ultrahigh vacuum
- No field emission
- Maintenance-free

Define "Good Photocathode"

Good Photocathode

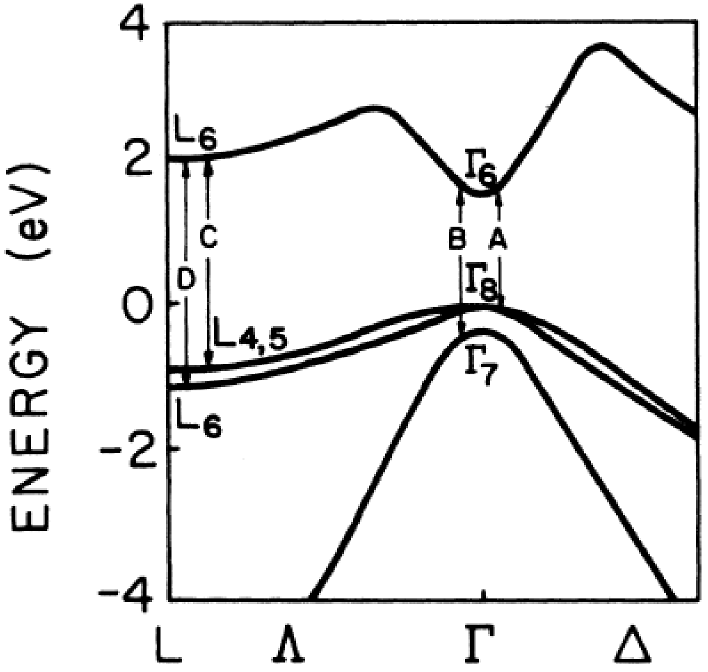
- High Polarization
- Many electrons/photon
- Fast response time
- Long lifetime

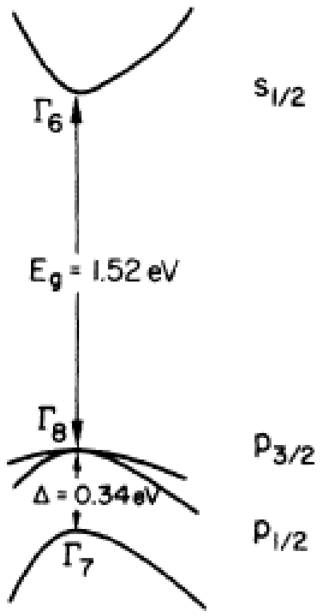


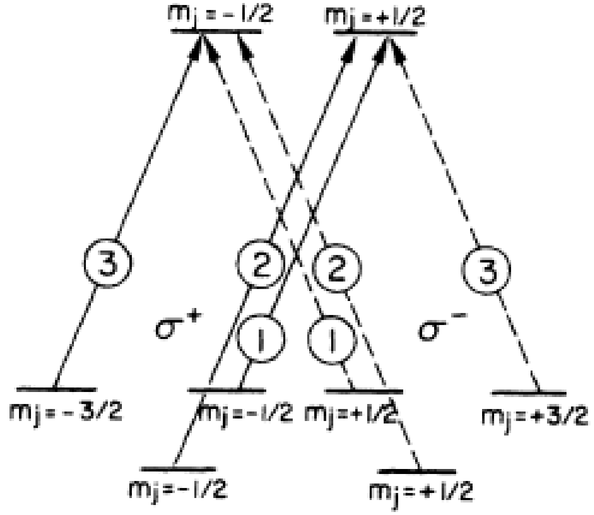
1) High Polarization
   - Bulk GaAs
   - Strained layer
   - Strained superlattice
2) High quantum efficiency (QE, yield)
   - Growth method
   - Clean surface
   - Thickness
   - Dopant
   - How you activate it
3) Response Time
   - NEA vs PEA
4) Long lifetime
   - dark lifetime
   - while you run beam

GaAs Energy Levels

First proposed by Garwin, Pierce, Siegmann and Lampel and Weisbuch







$$P_e = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{3-1}{3+1} = 50\%$$

- Energy versus momentum
- GaAs is a “Direct” transition semiconductor
- Valence band P-state split due to spin-orbit coupling
- m_j quantum numbers describe electron’s spin and orbital angular momentum
- Quantum mechanical selection rules dictate Δm_j=+/-1 for absorption of circularly polarized light
- Clebsch-Gordon coefficients indicate the relative likelihood of transitions between states

First Observation of Polarization

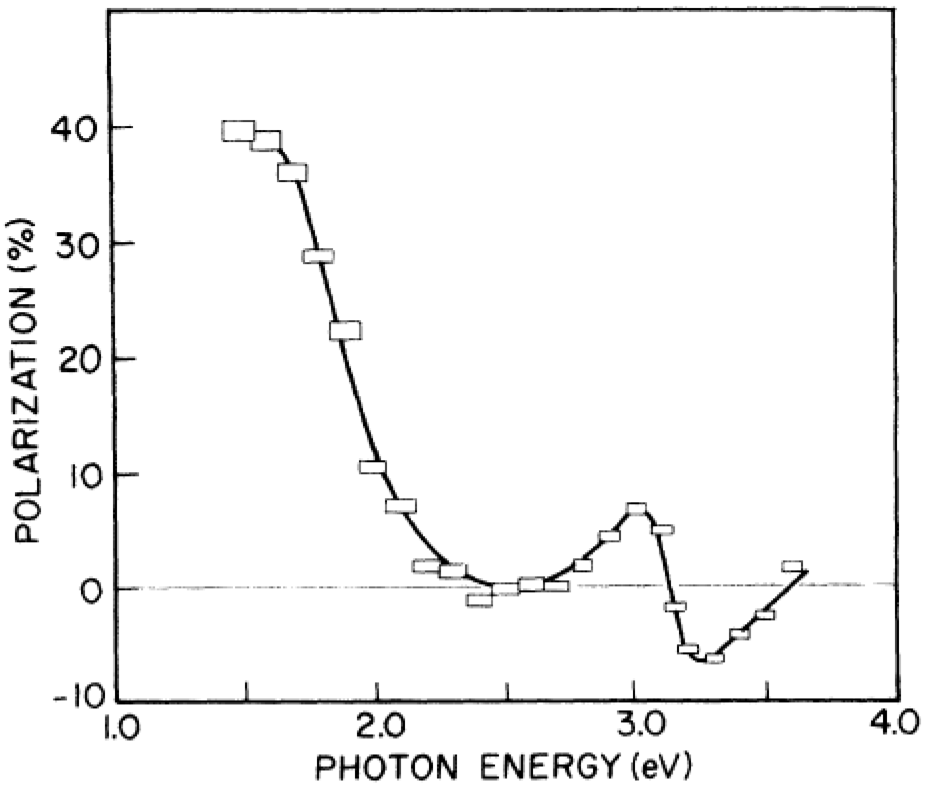
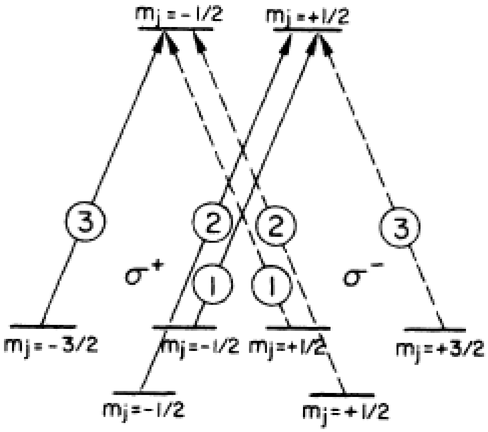


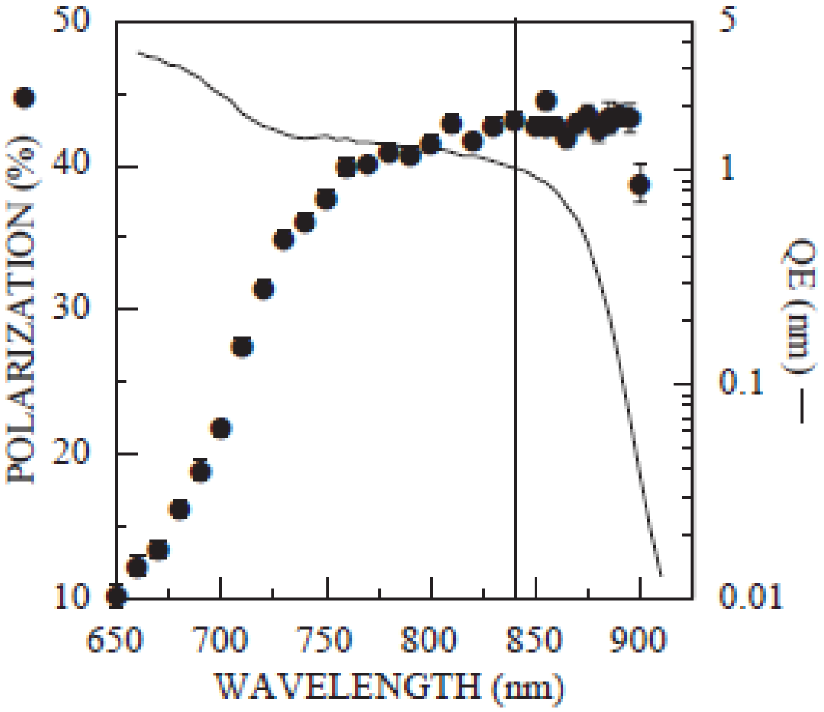
FIG. 6. Spectrum of spin polarization from GaAs + CsOCs at $T \leq 10$ K [the same sample and conditions as curve (a) of Fig. 5]. Note the high value of $P = 40\%$ at threshold ($\hbar\omega \sim 1.5$ eV) and positive and negative peaks at $\hbar\omega = 3.0$ and 3.2 eV.

Pierce and Meier, Phys. Rev. B, **13**, 5484 (1976)

- Maximum polarization not 50%
- Note interesting non-zero polarization sub-peaks at 3.0eV and 3.2eV
- Flip the sign of polarization by flipping the polarity of the light



Typical bulk GaAs Result



- QE at bandgap (i.e., where you get highest polarization) can be 10% or more
- We will talk about QE limitations later

Pablo Saez, PhD Thesis, SLAC Report 501, 1997

Depolarization Mechanisms

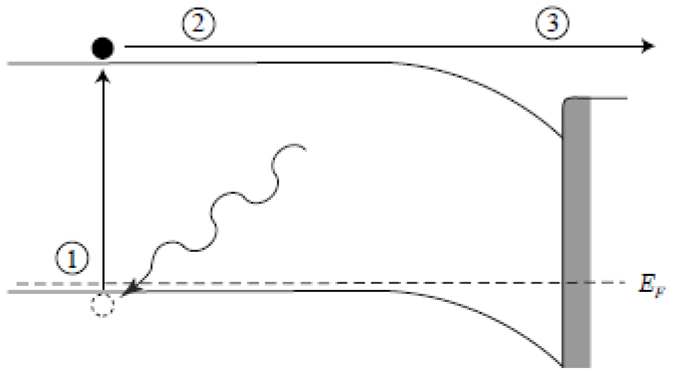
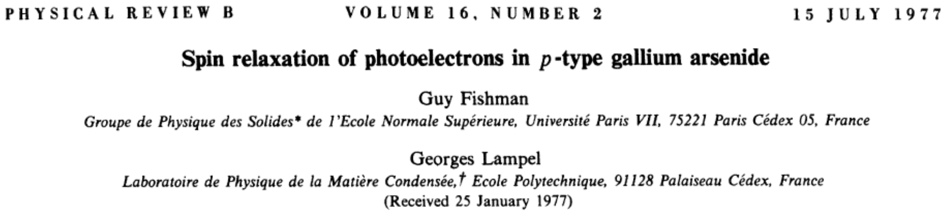


Figure 2.6: Spicer's Three–Step Photoemission Process: 1– photoexcitation of valence electrons into the conduction band (creation of electron–hole pair), 2– transport of electrons to the surface, 3– emission of electrons into the vacuum.

Time scales for these depolarization processes are roughly equal to the lifetime of the electron in the conduction band, ~ 200ps. Therefore, it is very important to get the polarized electrons out of the material as quickly as possible

- BAP Process: the exchange interaction between electrons and holes (after G. L. Bir, A. G. Aronov and G. E. Picus)
- DP Process: the dynamic narrowing of the magnetic resonance in spin–orbit split–off conduction bands (after M. I. Dyakonov and V. I. Perel)
- EY process in which the spin–orbit interaction generates non–pure spin states in the conduction band (after R. J. Elliot and Y. Yafet)
- Radiation Trapping, where recombination radiation is re-absorbed producing unpolarized photoemission



PHYSICAL REVIEW B VOLUME 16, NUMBER 2 15 JULY 1977

Spin relaxation of photoelectrons in *p*-type gallium arsenide

Guy Fishman
Groupe de Physique des Solides de l'Ecole Normale Supérieure, Université Paris VII, 75221 Paris Cédex 05, France*

Georges Lampel
Laboratoire de Physique de la Matière Condensée,† Ecole Polytechnique, 91128 Palaiseau Cédex, France
(Received 25 January 1977)

Photoemission: a three step process

old

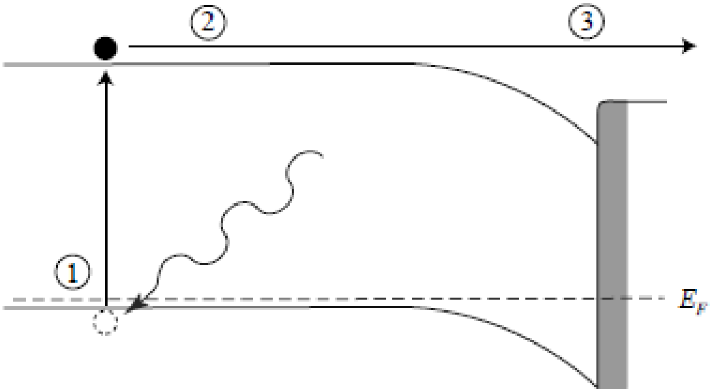
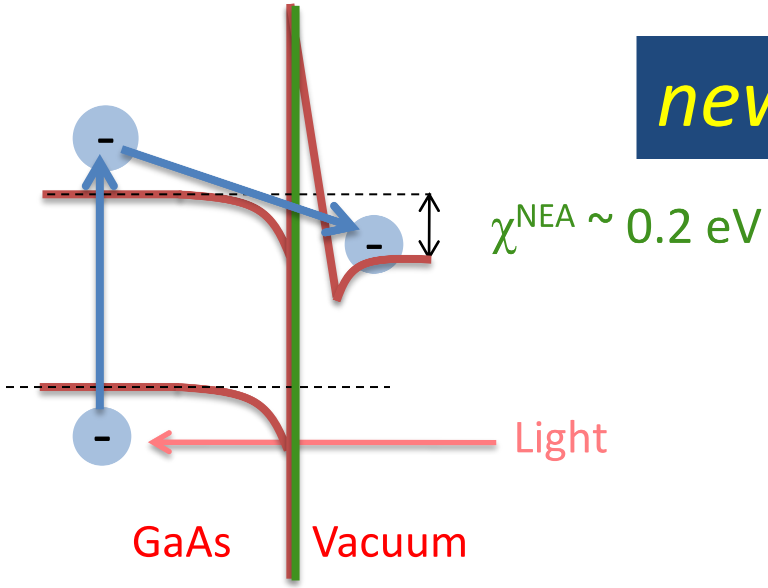


Figure 2.6: Spicer's Three–Step Photoemission Process: 1– photoexcitation of valence electrons into the conduction band (creation of electron–hole pair), 2– transport of electrons to the surface, 3– emission of electrons into the vacuum.

new

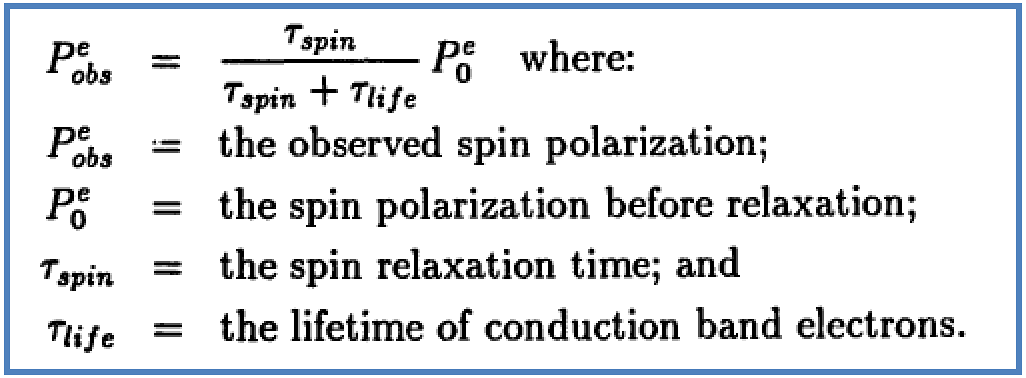


Step 1: Electrons are excited to conduction band by absorbing light

Step 2: (some) Electrons diffuse to the surface

Step 3: (some) Electrons leave material (by tunneling through thin barrier)

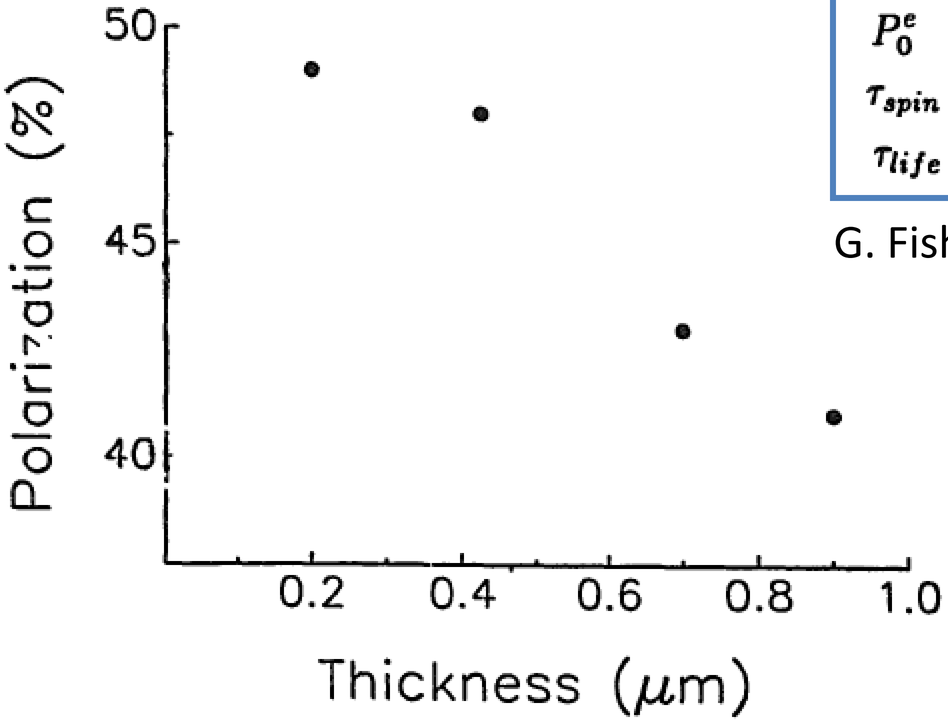
What limits polarization?



$$P^e_{obs} = \frac{\tau_{spin}}{\tau_{spin} + \tau_{life}} P^e_0 \quad \text{where:}$$

P^e_{obs} = the observed spin polarization;
P^e_0 = the spin polarization before relaxation;
τ_{spin} = the spin relaxation time; and
τ_{life} = the lifetime of conduction band electrons.

G. Fishman and G. Lampel, Phys Rev. B16, 820 (1977)



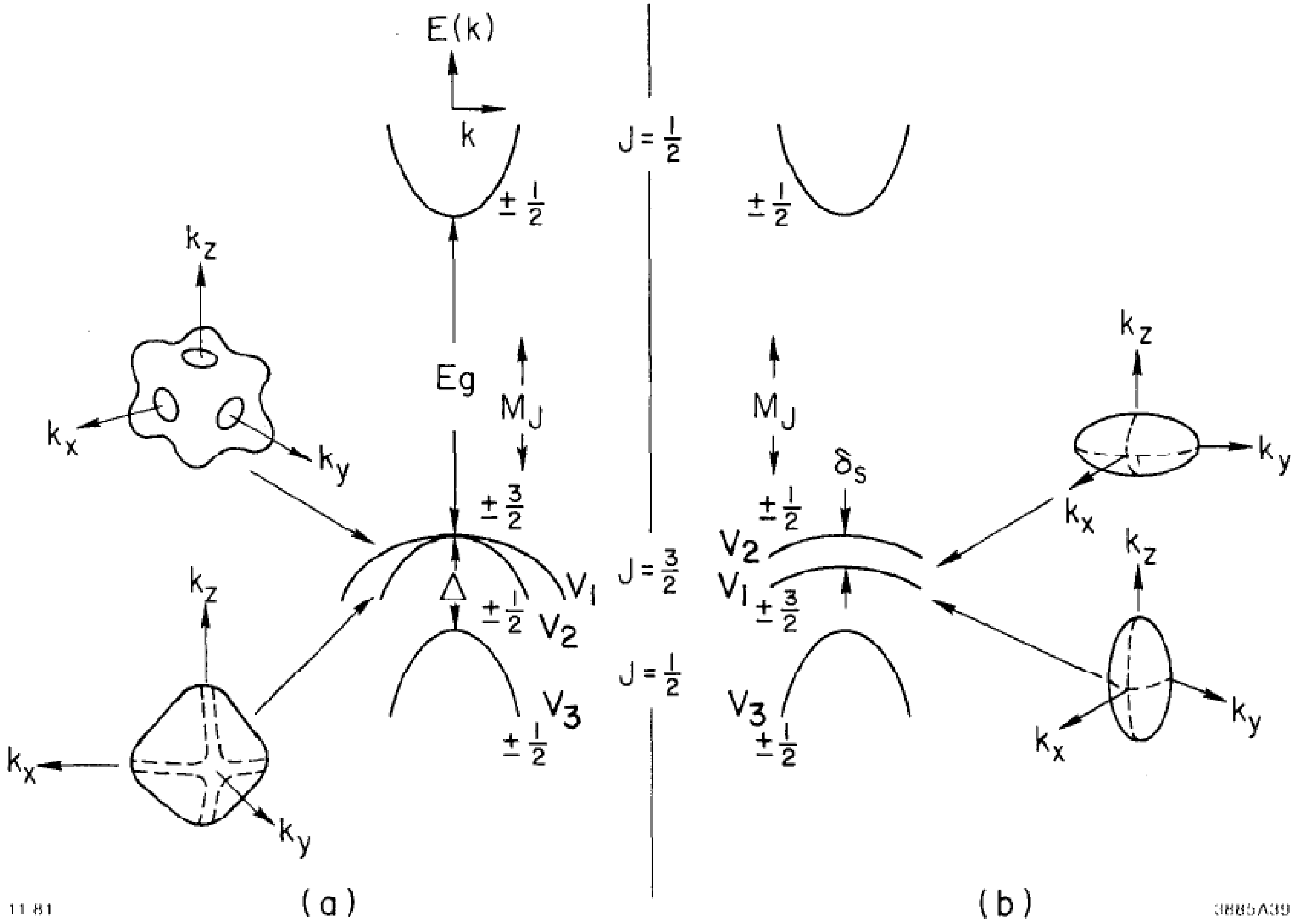
Maruyama et al., Appl. Phys. Lett., 55, 1686 (1989)

Absorption depth ~ 1um in GaAs

Polarization lost as electrons diffuse to the surface: thin samples provide higher polarization, at expense of QE

Breaking the 50% barrier

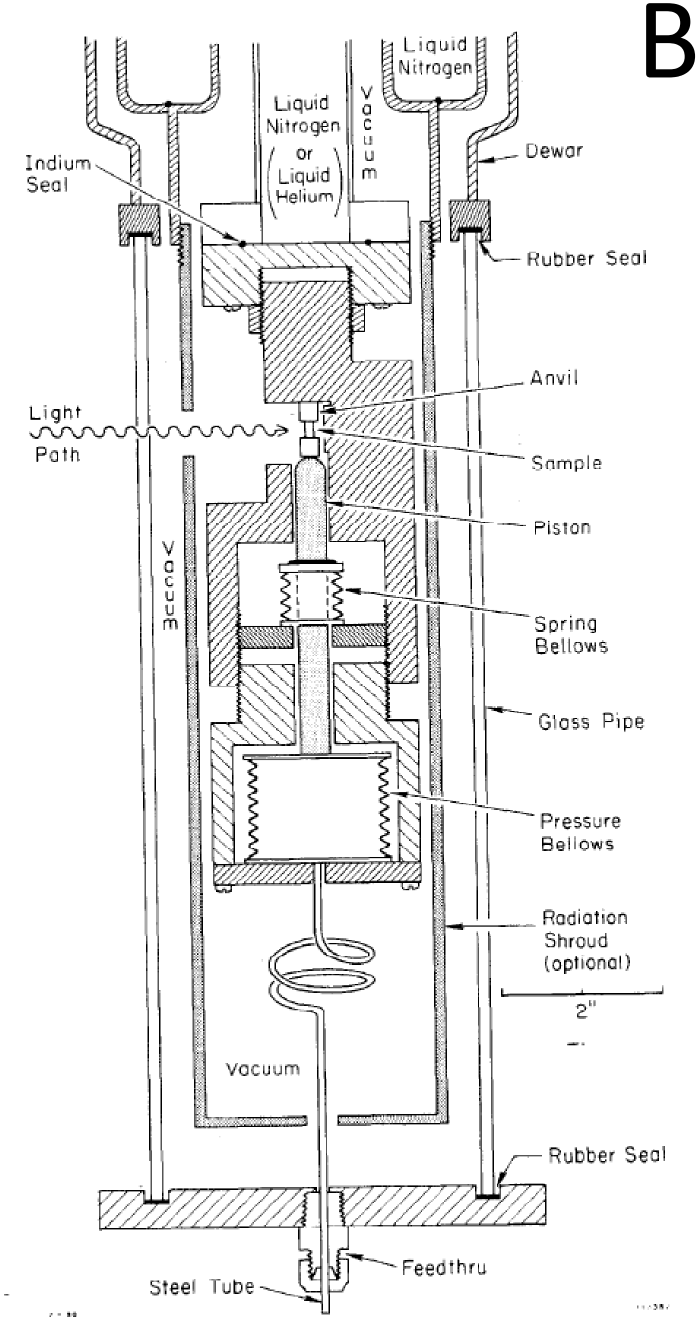
PhD thesis, Paul Zorabedian, SLAC Report 248, 1982



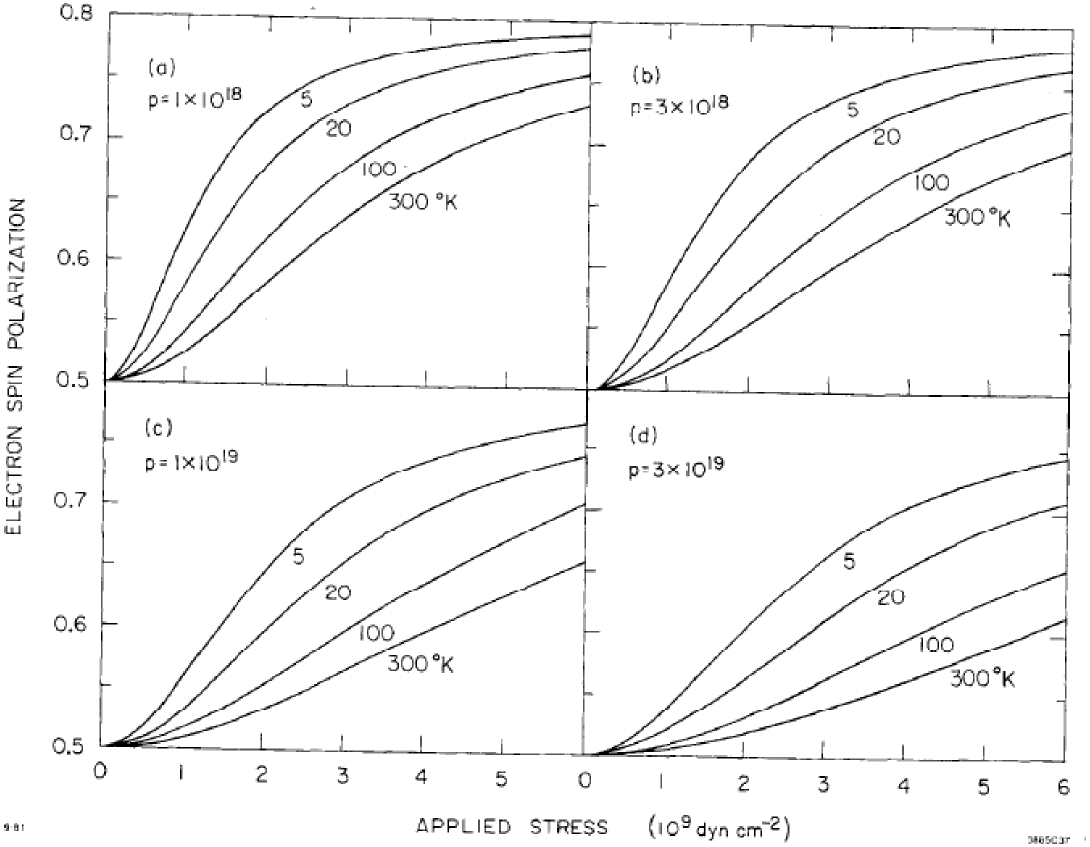
Application of a uniaxial strain removes the degeneracy of the $P_{3/2}$ state

Breaking the 50% barrier

PhD thesis, Paul Zorabedian, SLAC Report 248, 1982



Electron polarization inferred from photoluminescence measurements



Compress the GaAs crystal in hydraulic press!

Hard to keep the GaAs sample from shattering

Eliminate degeneracy of $P_{3/2}$ state via "Interface Stress Method"

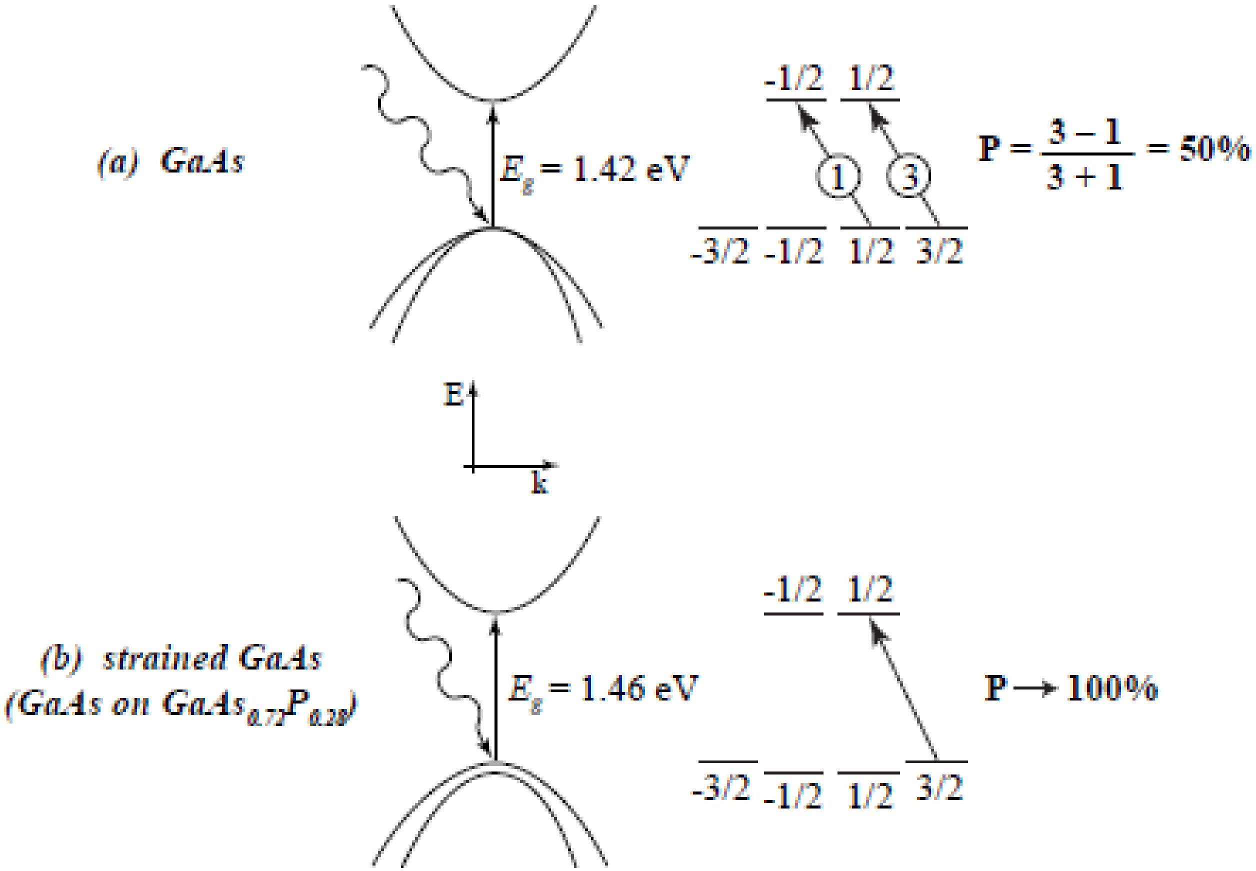
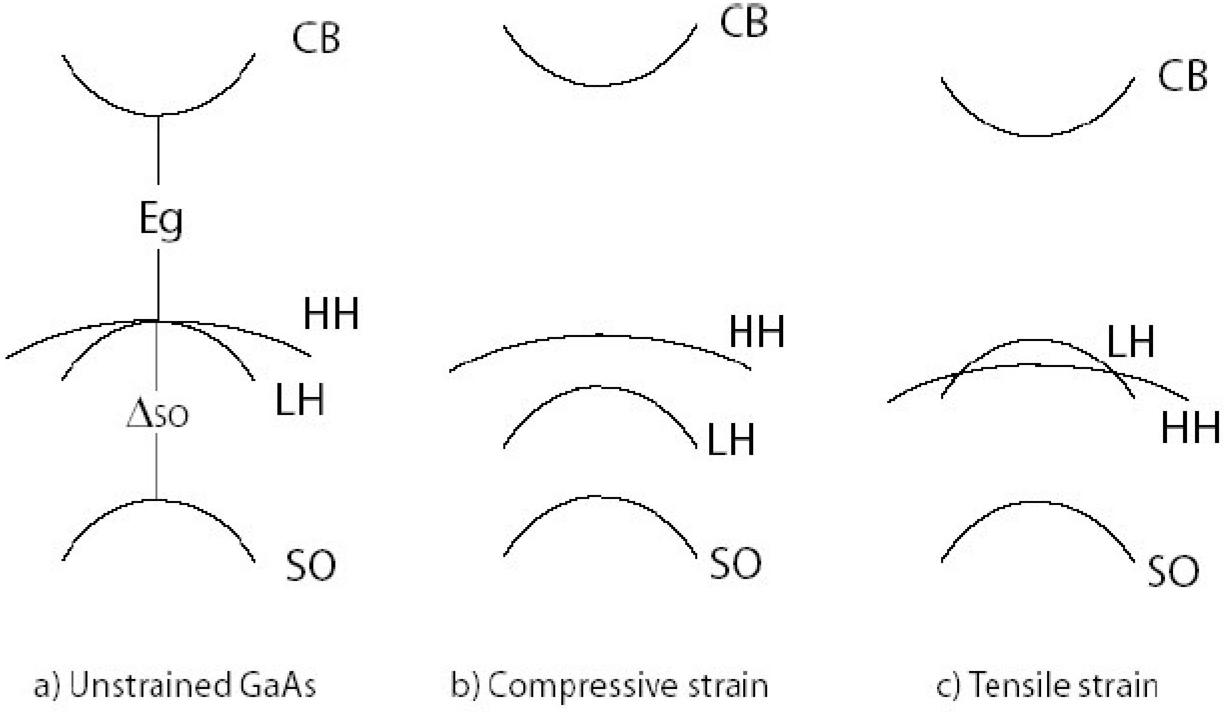
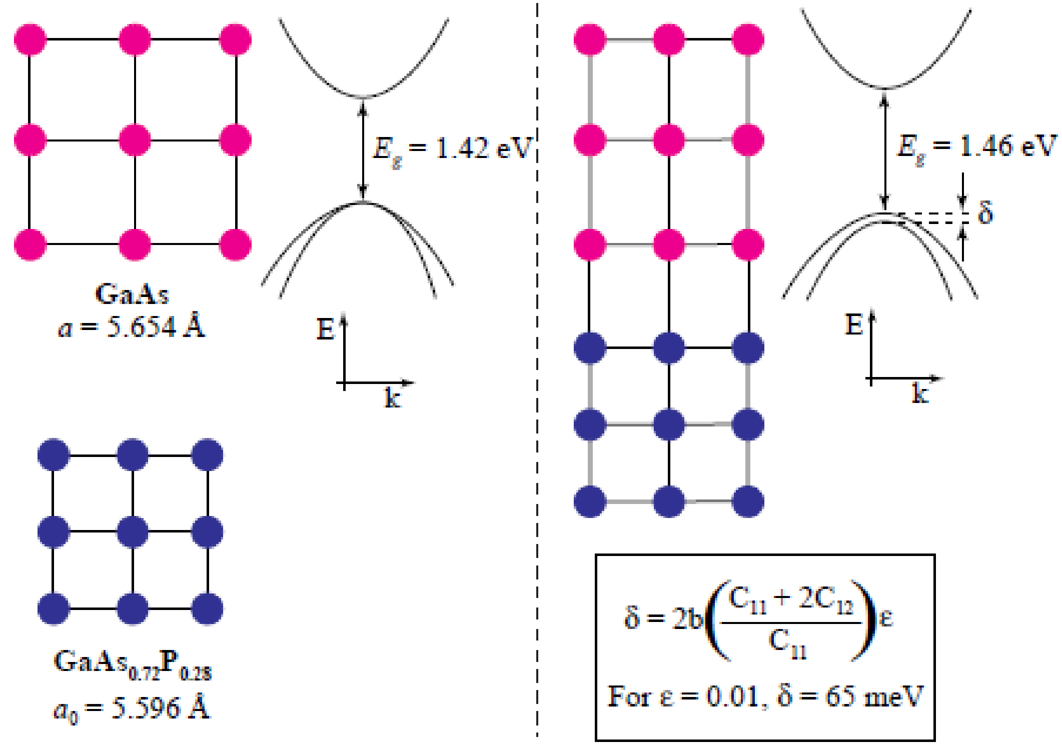


Image from Pablo Saez, PhD Thesis, Stanford University, SLAC Report 501, 1997

Compressive vs Tensile Strain?



Lattice mismatch provides stress



$$\delta = 2b\left(\frac{C_{11} + 2C_{12}}{C_{11}}\right)\varepsilon$$

For $\varepsilon = 0.01$, $\delta = 65$ meV

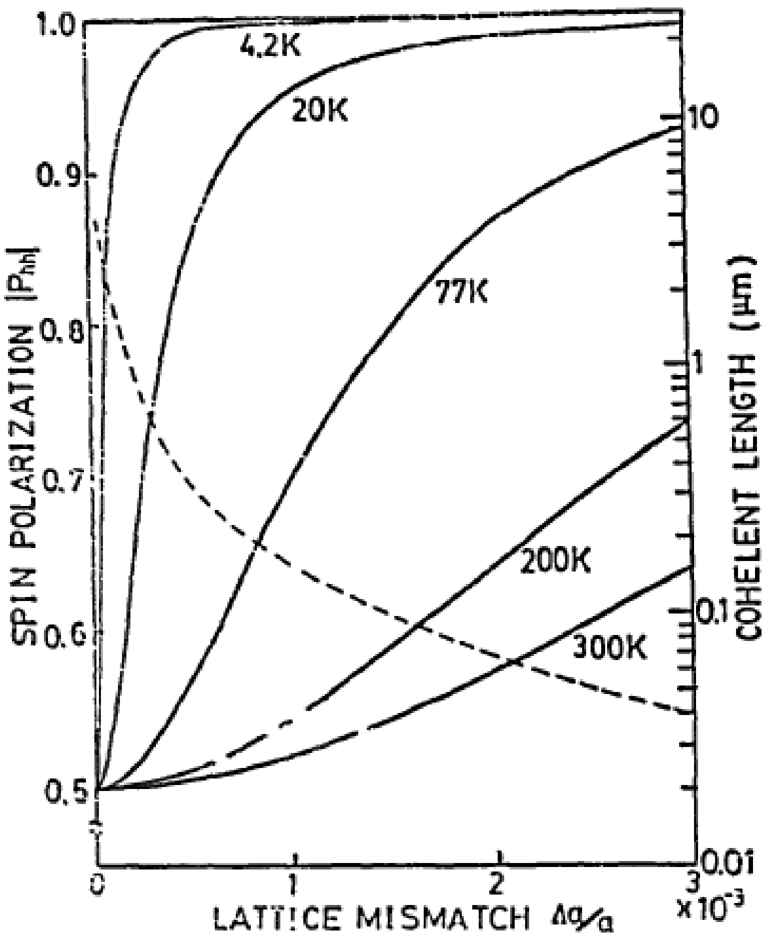
Pablo Saez, PhD Thesis, SLAC Report 501, 1997

- The band gap of the substrate layer must be larger than surface layer
- Lattice constants must differ enough to introduce suitable strain
- Adjust lattice constant of substrate by varying concentration of third element

$$\delta_s = 6.5\left(\frac{\Delta a}{a_0}\right)\ (eV)$$

1% lattice mismatch provides equivalent force as hydraulic press!

Lattice mismatch provides stress



$$\delta_s = 6.5\left(\frac{\Delta a}{a_0}\right)\ (eV)$$

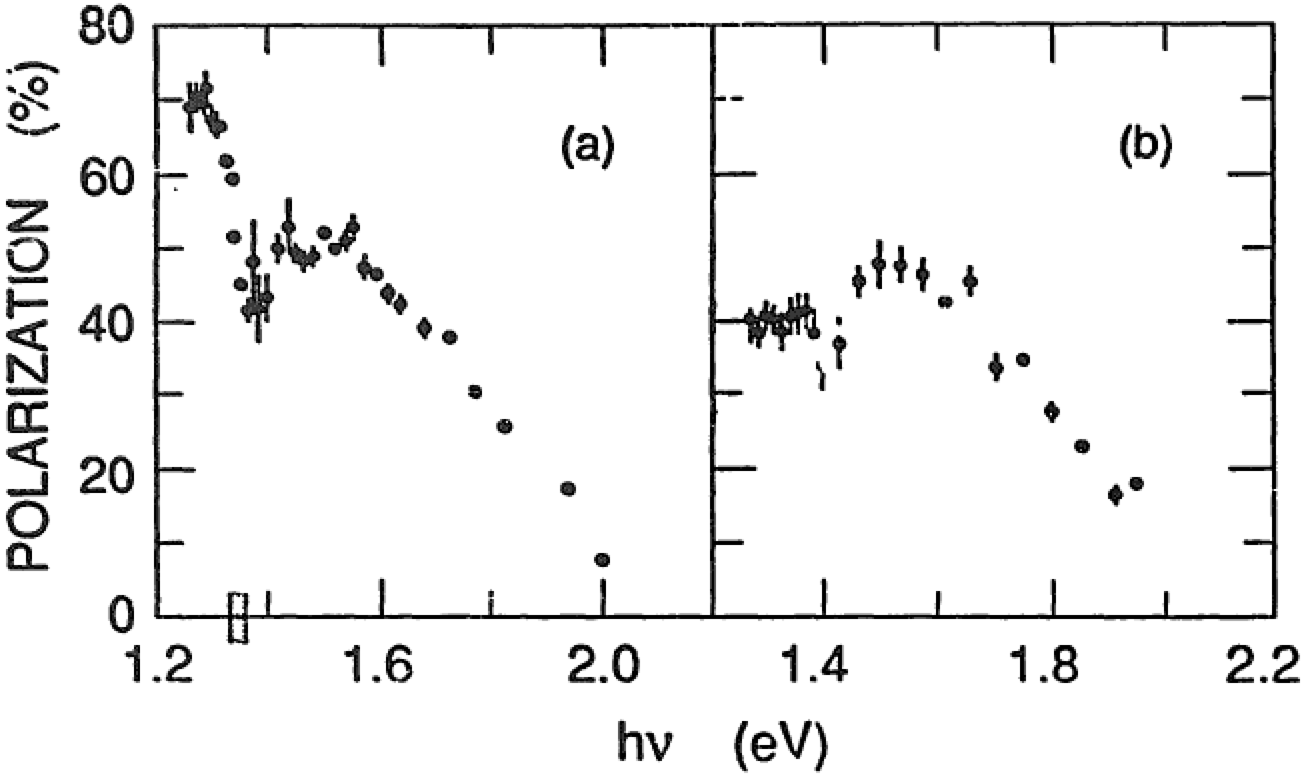
$$t_c = \frac{0.224}{\epsilon}\left[1 + \ln\left(\frac{t_c}{4.00}\right)\right]\ (A)$$

J.W. Mathews and A. E. Blakeslee, J. Cryst. Growth 27, 118 (1974)

Surface layer can’t get too thick, or the strain relaxes

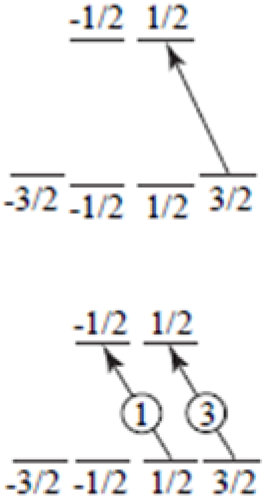
T. Nakanishi et al, Division of Physics Nagoya University, 90-16, unpublished

First Strained GaAs Result



0.1um thick surface layer

1.14um thick surface layer



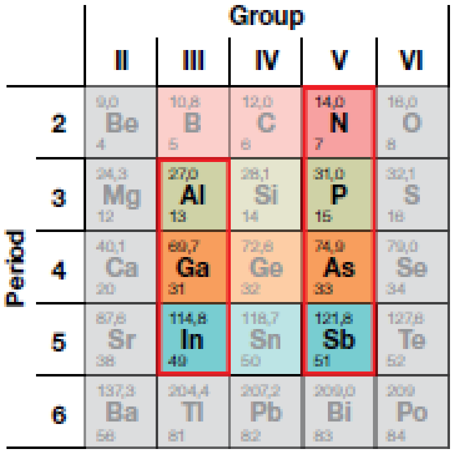
$In_xGa_{1-x}As$ grown on GaAs substrate (x = 0.13)

Maruyama et.al., Phys. Rev. Lett., 66, 2376 (1991)

Getting the Recipe Right

- Choice of Surface layer
- Choice of Substrate layer
- Tensile vs compressive strain?
- What is correct lattice mismatch?
- How thick to make the active layer?

Periodic Table (Detail)



	Group				
Period	II	III	IV	V	VI
2	9,0 Be 4	10,8 B 5	12,0 C 6	14,0 **N** 7	16,0 O 8
3	24,3 Mg 12	27,0 **Al** 13	28,1 Si 14	31,0 **P** 15	32,1 S 16
4	40,1 Ca 20	69,7 **Ga** 31	72,6 Ge 32	74,9 **As** 33	79,0 Se 34
5	87,6 Sr 38	114,8 **In** 49	118,7 Sn 50	121,8 **Sb** 51	127,6 Te 52
6	137,3 Ba 56	204,4 Tl 81	207,2 Pb 82	209,0 Bi 83	209 Po 84

Al = Aluminium
Ga = Gallium
In = Indium
N = Nitrogen
P = Phosphorus
As = Arsenic
Sb = Antimony

Getting the Recipe Right

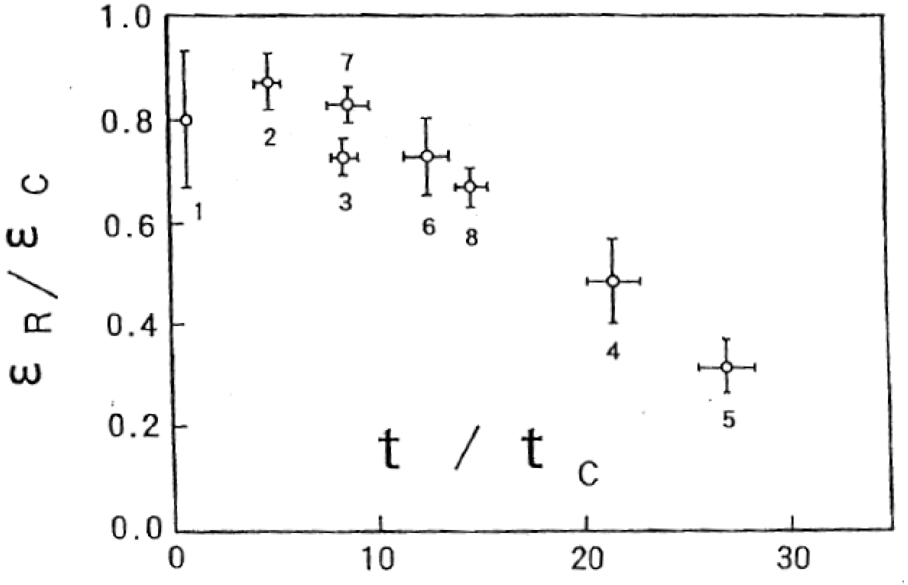
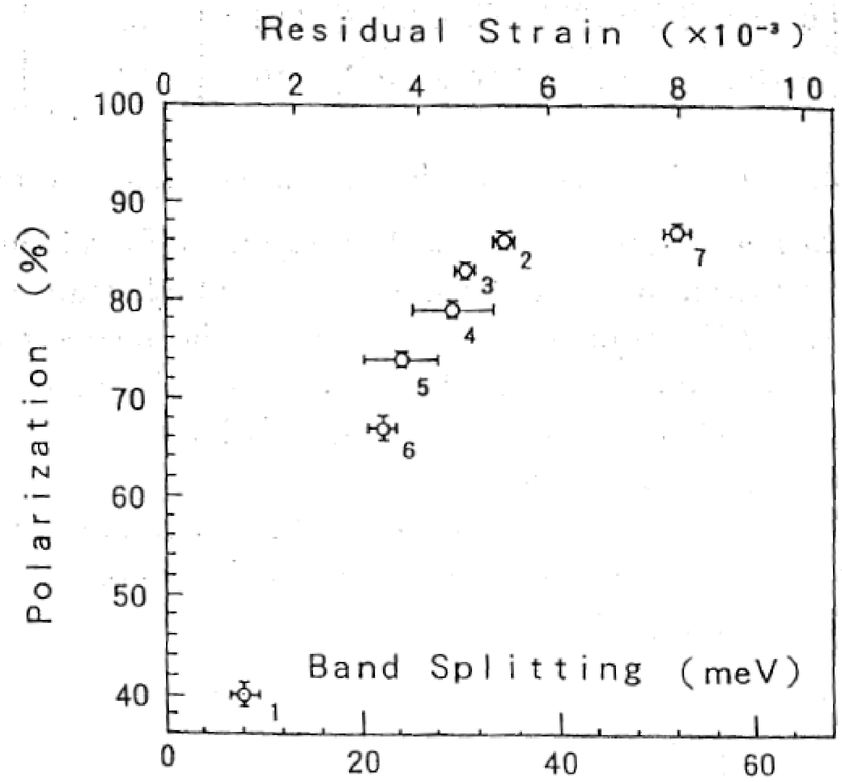


Fig. 1. Strain relaxation in GaAs layers



g. 2. Strain dependence of the maximum polarization

- Thickness can be 10x greater than t_c
- Band splitting needs to be > 30 meV

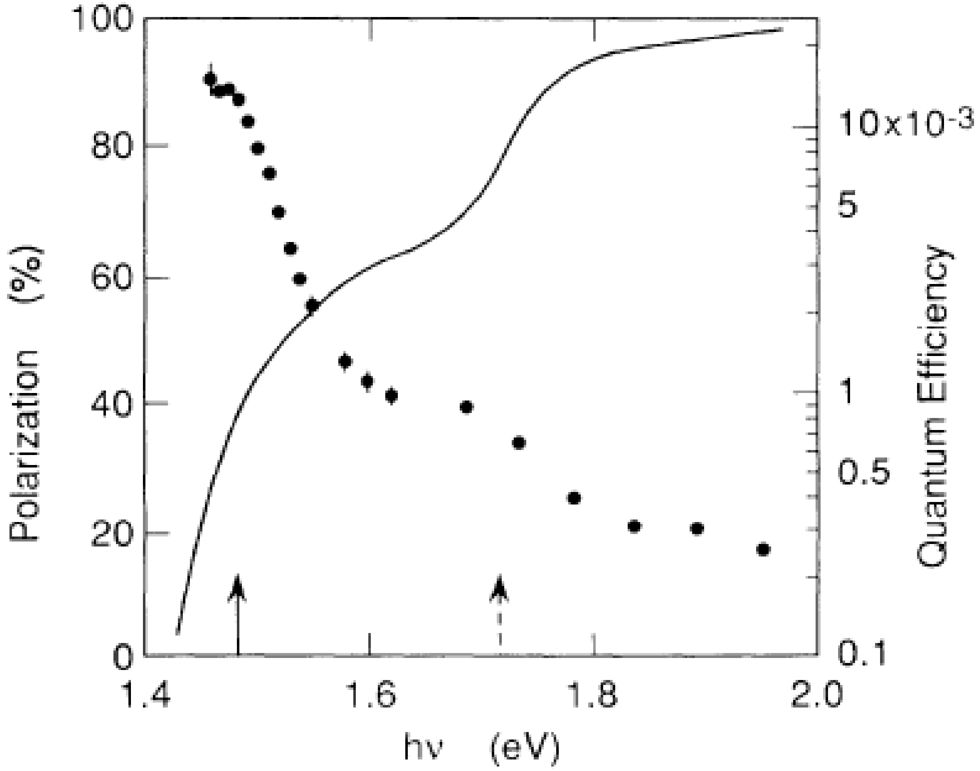
Aoyagi, Nakanishi, et.al., Division of Physics Nagoya University Tech Note 93-14

Higher Polarizations Followed

GaAs grown on top of $GaAs_{1-x}P_x$ substrate

GaAs thickness ~ 0.1 um and x = 0.29, lattice mismatch ~ 1%

This became the standard SPIN Polarizer wafer sold by SPIRE, now Bandwidth Semiconductor

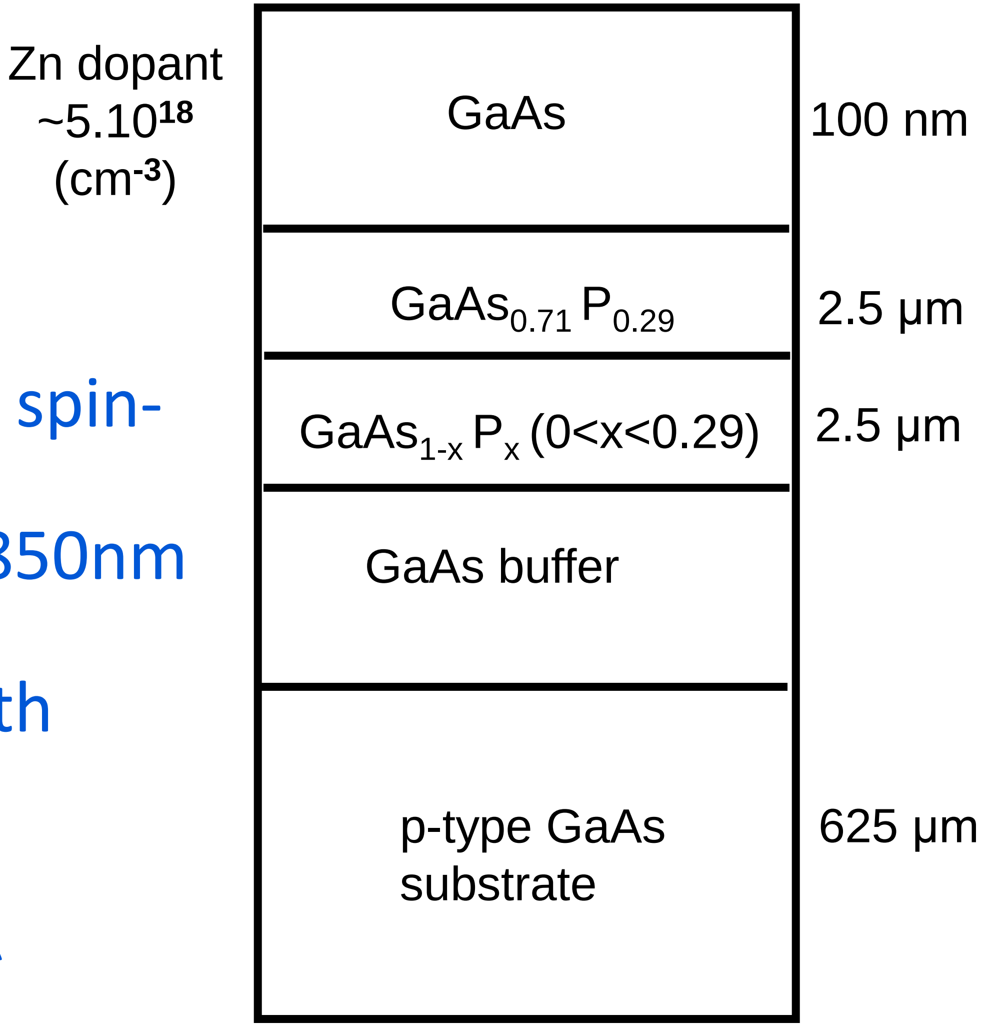


Maruyama et al., Phys. Rev. B., 46, 4261 (1991)

Strained-layer GaAs

More on “dopant” in a few slides

- MOCVD-grown epitaxial spin-polarizer wafer
- Polarization ~ 75% at ~ 850nm
- QE ~ 0.1%
- Available from Bandwidth Semiconductor
- 3” dia. wafer ~ 10k$
- Developed via DOE-SBIR program



Zn dopant ~5.10^{18} (cm^{-3})

Layer	Thickness
GaAs	100 nm
$GaAs_{0.71}P_{0.29}$	2.5 µm
$GaAs_{1-x}P_x$ $(0<x<0.29)$	2.5 µm
GaAs buffer	
p-type GaAs substrate	625 µm

Manufactured by Bandwidth Semiconductor

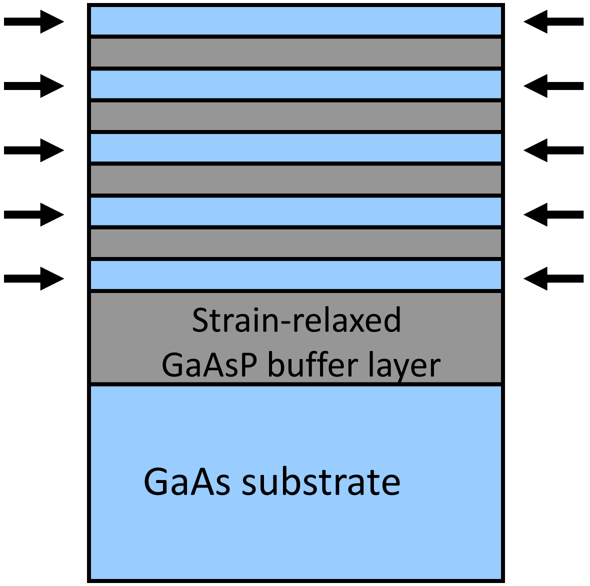
Higher P, Higher QE?

- Problem: Strained layers start relaxing beyond thickness ~10nm. Strained layer practical limit ~100nm
  - Strain relaxation → Lower polarization
  - Thin layer → Lower QE
- So how to get Higher Polarization and Higher QE?
- Solution: Use many thin strained layers – ***Strained Superlattice Photocathode***…

Strained Superlattice Photocathode

Electrons tunnel through very thin buffer layers!!

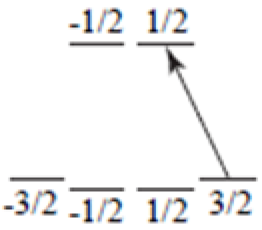
Slide courtesy Toru Ujihara, PESP 2008

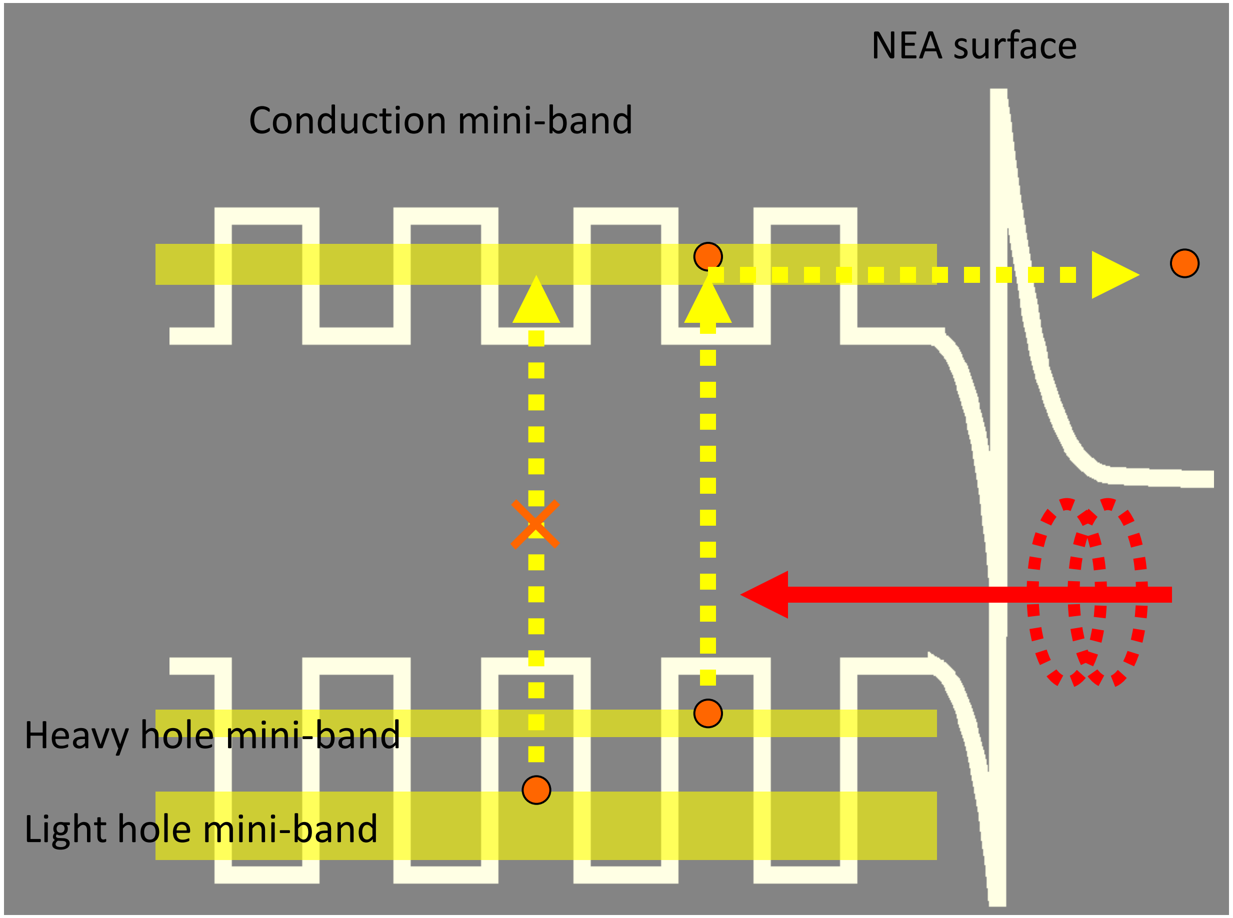


Strain-relaxed GaAsP buffer layer

GaAs substrate

eg., GaAs/GaAsP strained superlattice





NEA surface

Conduction mini-band

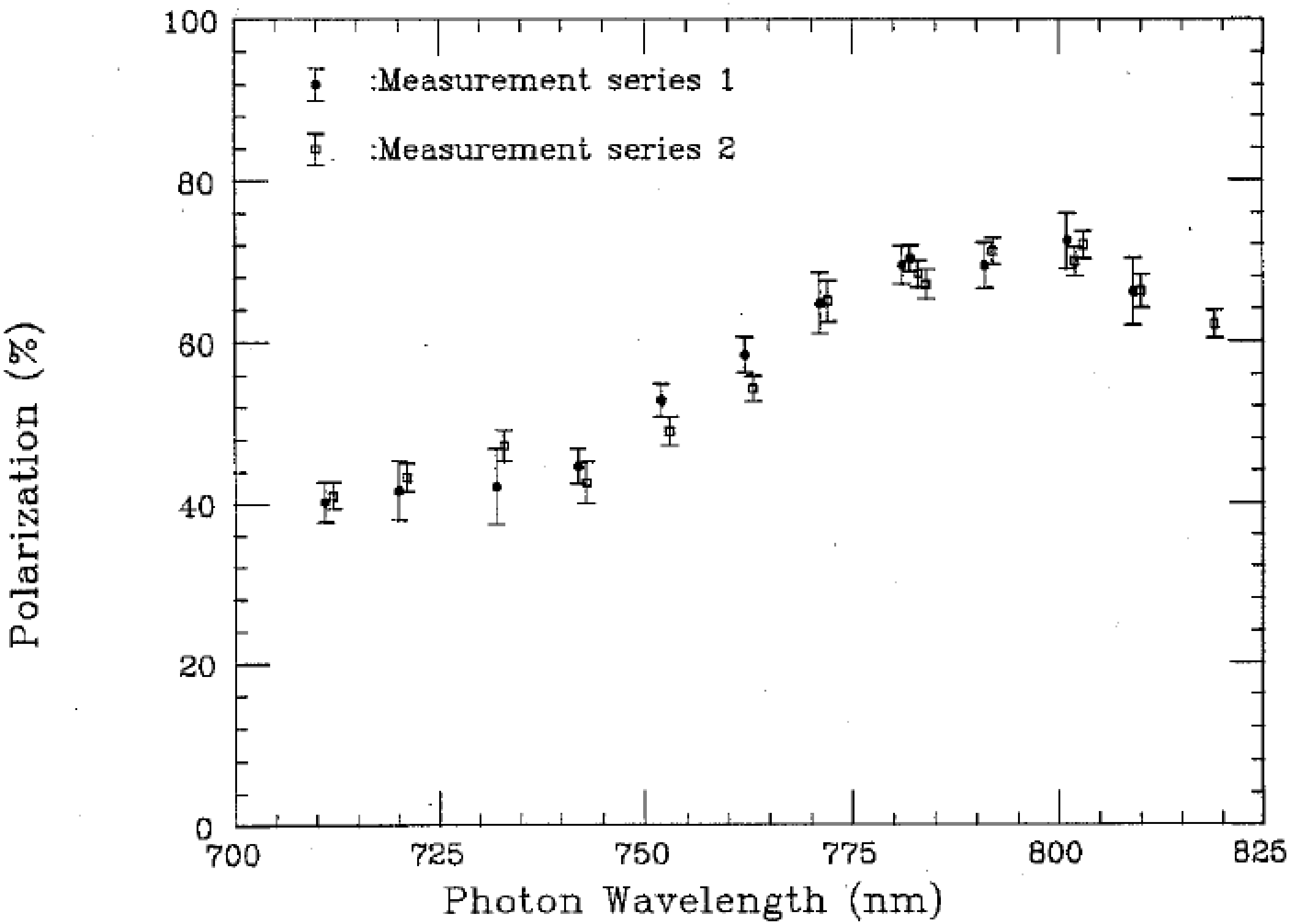
Heavy hole mini-band

Light hole mini-band

It is important that electrons are excited ONLY FROM HEAVY-HOLE MINI-BAND

Strained Superlattice Photocathode

One of the first results…

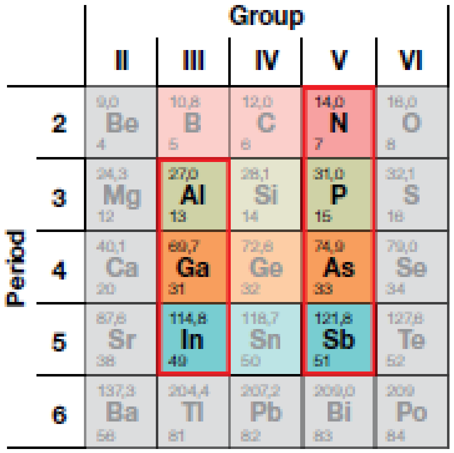


Omori, Kurihara, Nakanishi, et al., DPNU-91-12, KEK Preprint 90-190

Getting the Recipe Right

- *Choice of Surface layer*
- *Choice of Substrate layer*
- *Tensile vs compressive strain?*
- *What is correct lattice mismatch?*
- *How thick to make the active layer?*
- How thick to make the very thin active and buffer layers?

Periodic Table (Detail)



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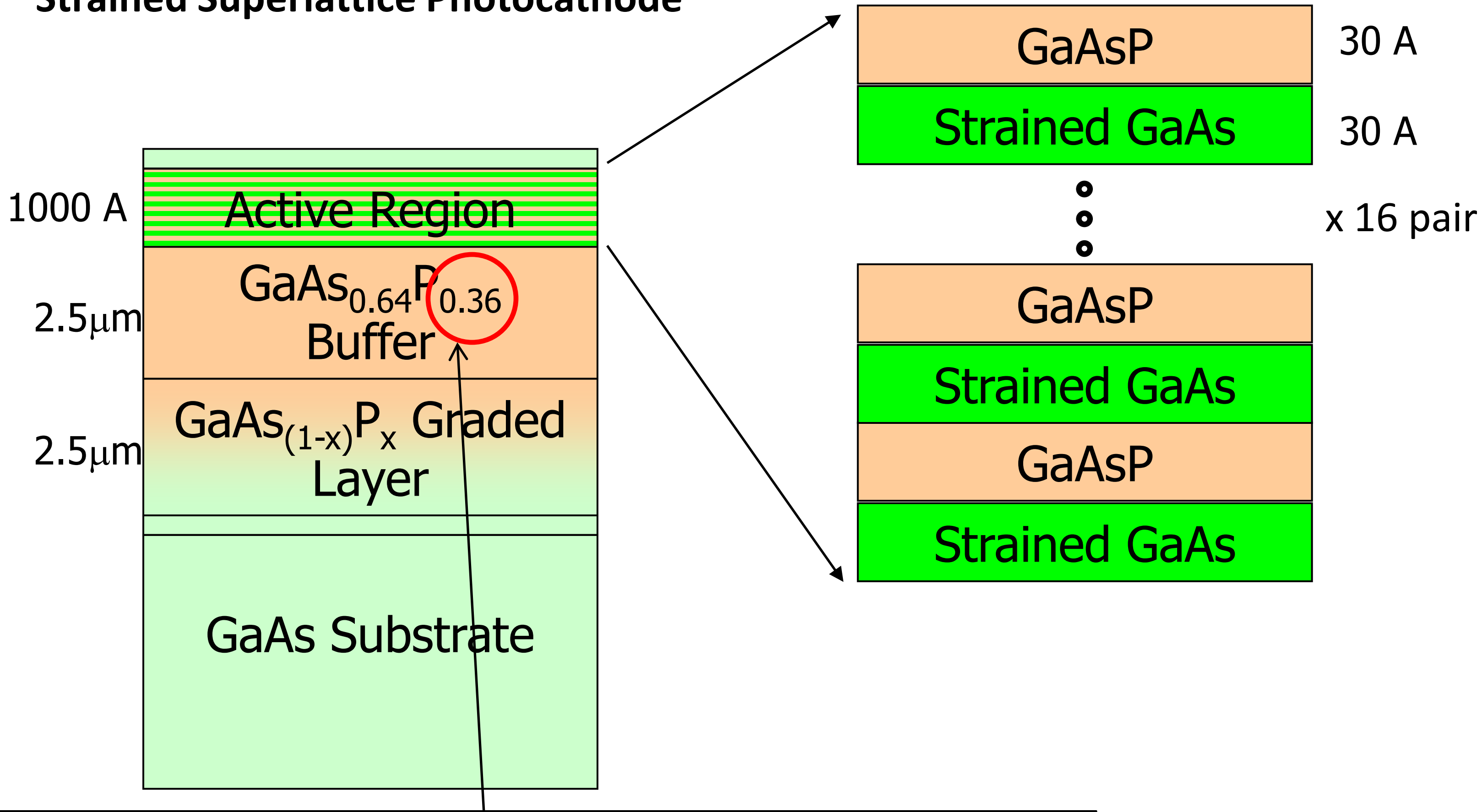
Getting the Recipe Right

Strained Superlattice Photocathode

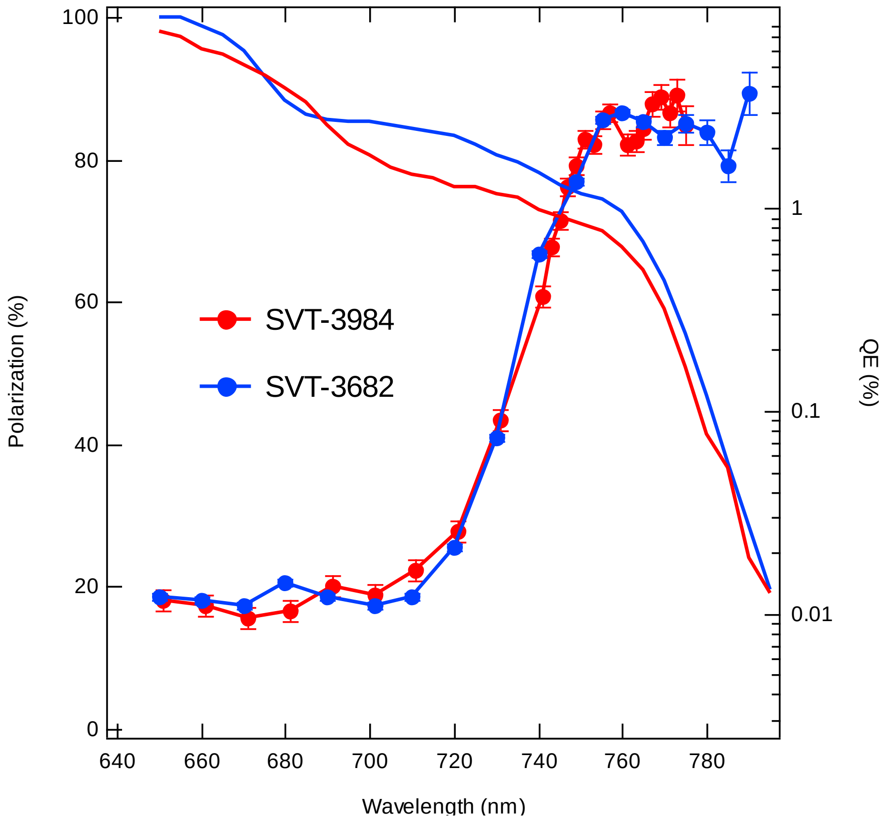


Notice more [P] → more strain, more $P_{3/2}$ state splitting, higher Pol

From Aaron Moy, SVT Assoc and SLAC, PESP2002

Higher Polarization AND Higher QE

- MBE-grown epitaxial spin-polarizer wafer
- Pol ~ 85% at ~ 780nm
- QE ~ 1%
- Available from SVT Associates
- 2" dia. wafer ~ 10k$
- Developed via DOE-SBIR program



D. Luh et al, SLAC, PESP2002

Strained-Superlattice GaAs

Notice“dopant”, will discuss significance

- MBE-grown epitaxial spin-polarizer wafer
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- QE ~ 1%
- Available from SVT Associates
- 2” dia. wafer ~ 10k$
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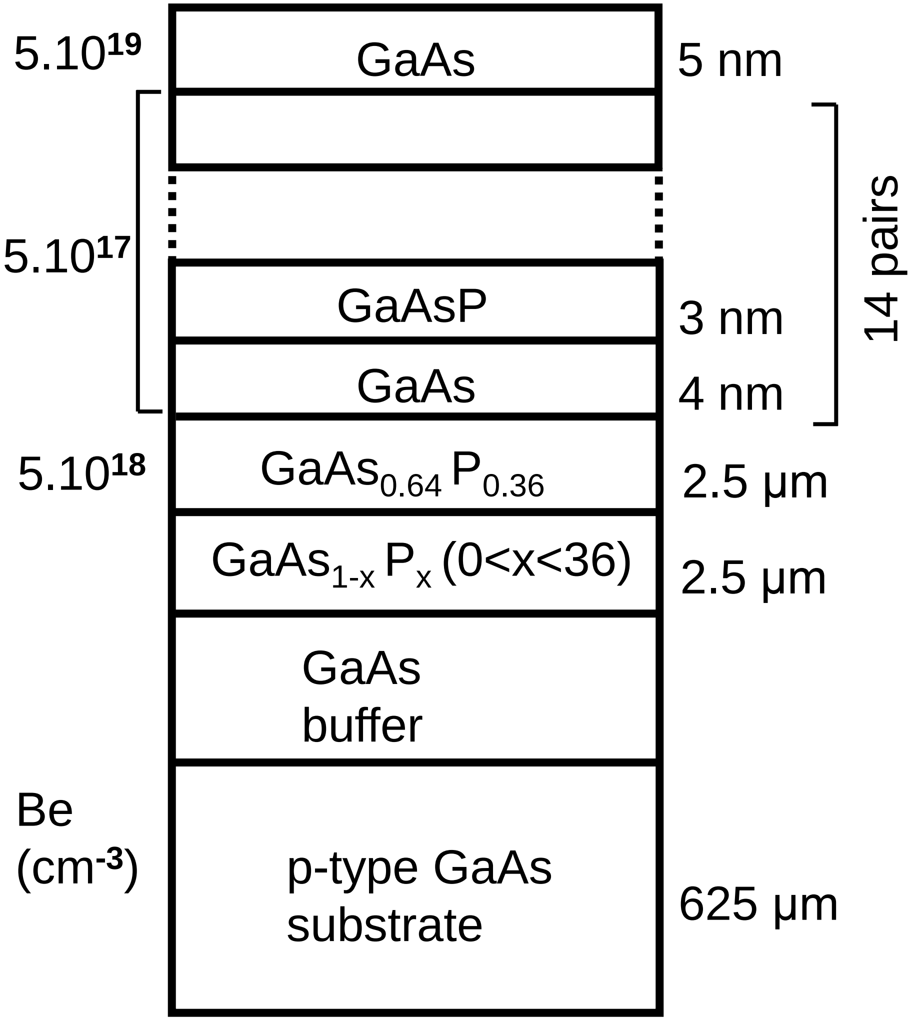


5.10¹⁹ GaAs 5 nm

5.10¹⁷ GaAsP 3 nm, GaAs 4 nm — 14 pairs

5.10¹⁸ $GaAs_{0.64}P_{0.36}$ 2.5 µm

$GaAs_{1-x}P_x$ (0<x<36) 2.5 µm

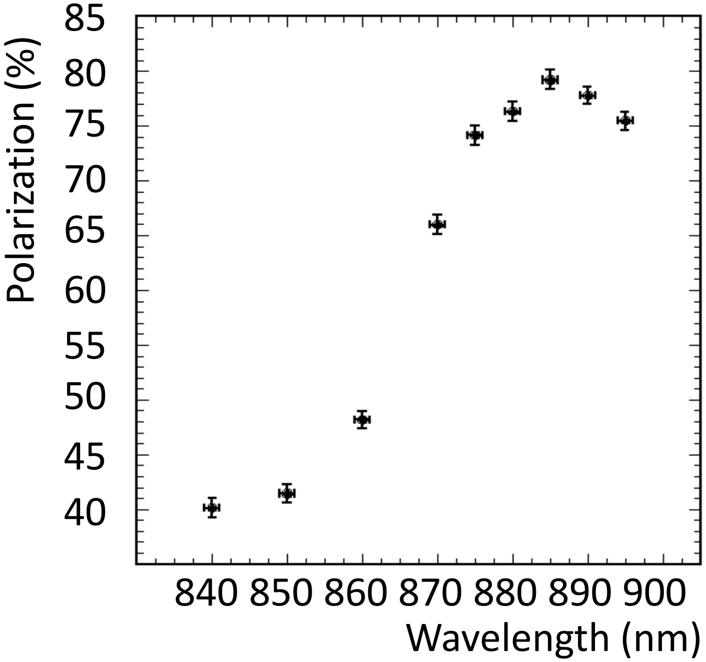
GaAs buffer

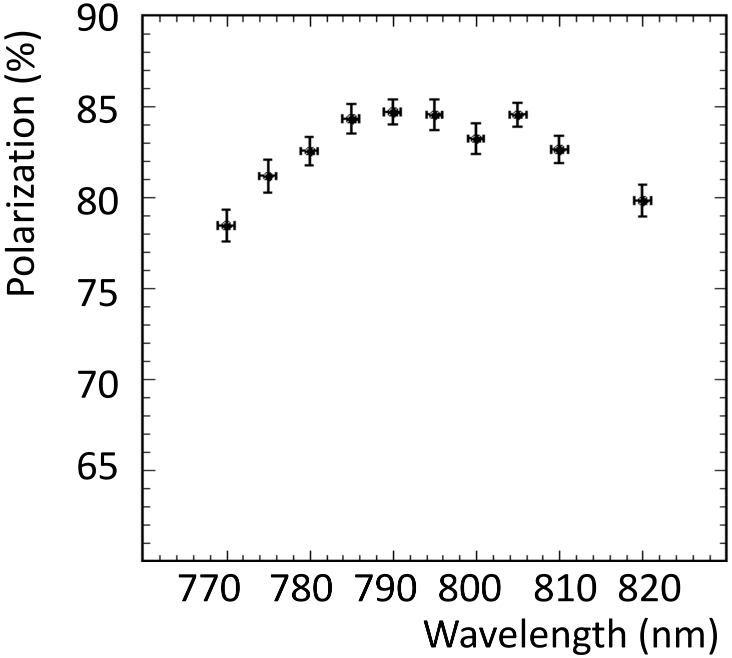
p-type GaAs substrate 625 µm

Be (cm^{-3})

Manufactured by SVT Associates

Typical Results at CEBAF



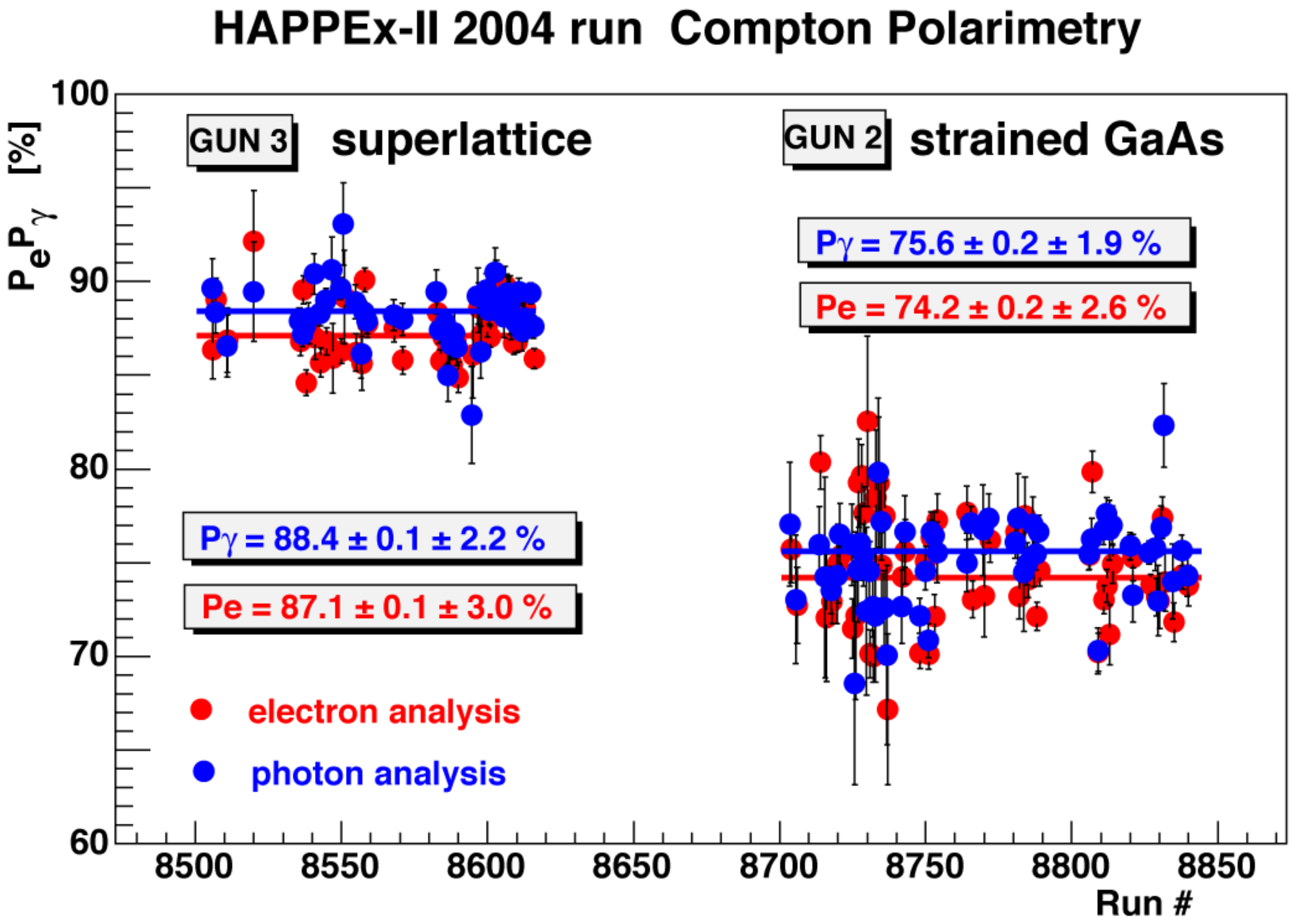


QE at max polarization ~ 0.1%
Narrow Peak
Diode or Ti-Sapphire Laser
12% QE anisotropy

QE at max polarization ~ 1%
Broad Peak
Doubled Fiber laser
5% QE anisotropy

M. Baylac, *et al.*, “Effects of atomic hydrogen and deuterium exposure on high polarization GaAs photocathodes”, *Phys. Rev. ST Accel. Beams*, vol. 8, pp. 123501-1–123501-11, 2005

Significant FOM Improvement

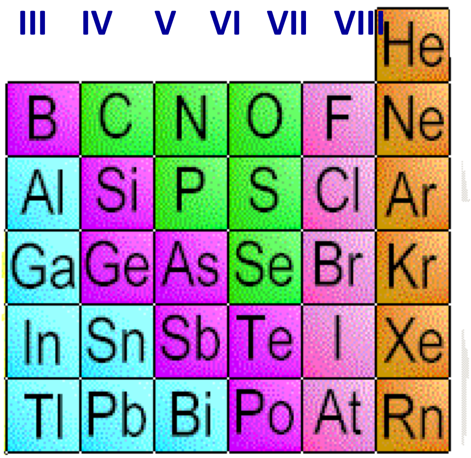


$$FOM\ Improvement = \frac{P_{ssl}^2 I}{P_{sl}^2 I} = 1.38$$

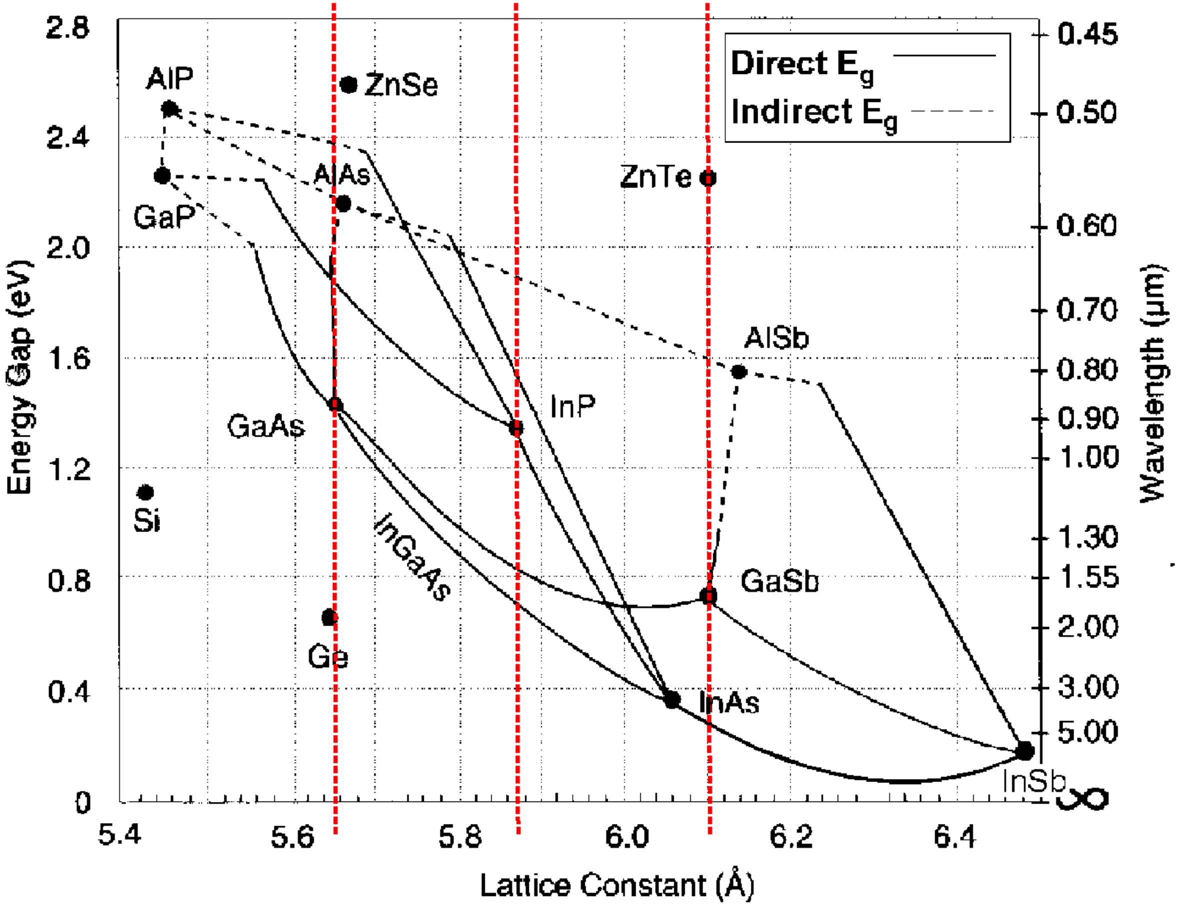
This means it takes less time to do an experiment with same level of statistical accuracy

Still Tweaking the Recipe

III-V Compound Semiconductors



III	IV	V	VI	VII	VIII
					He
B	C	N	O	F	Ne
Al	Si	P	S	Cl	Ar
Ga	Ge	As	Se	Br	Kr
In	Sn	Sb	Te	I	Xe
Tl	Pb	Bi	Po	At	Rn

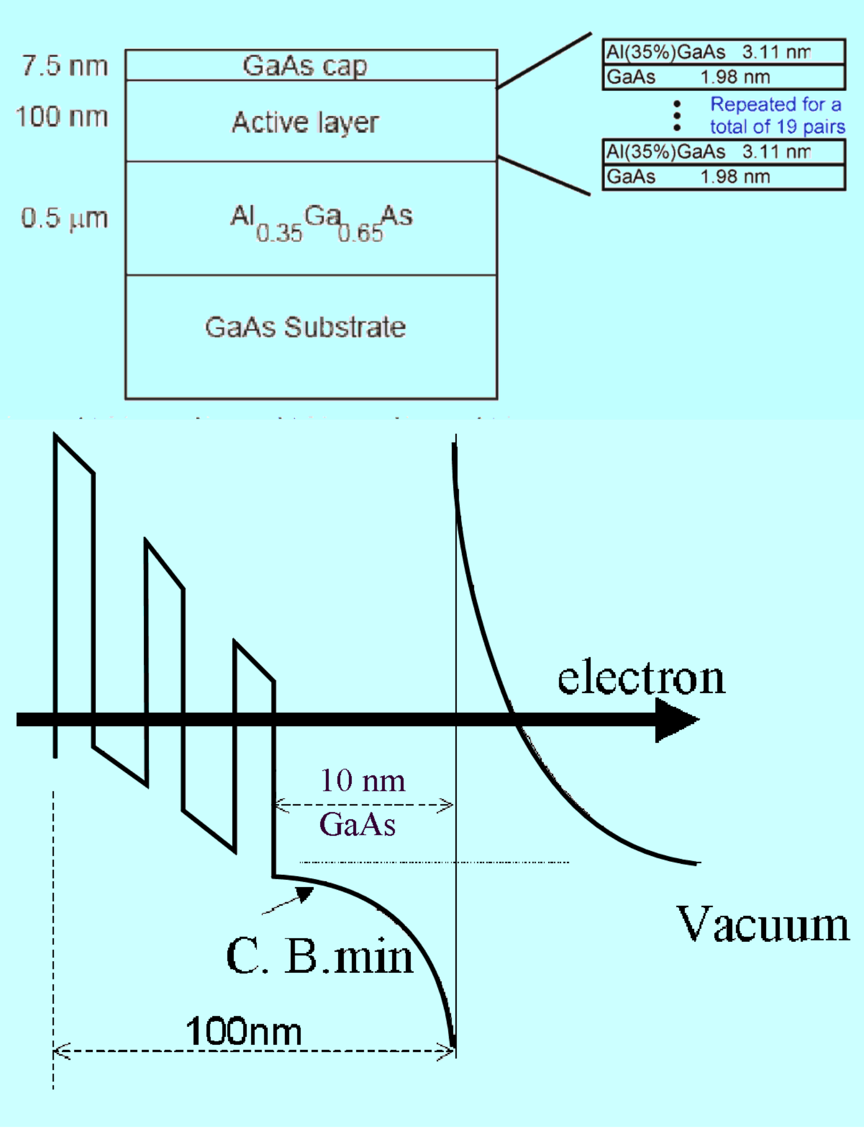


Still looking for combinations that provide Higher Polarization, **Higher QE**, more rugged lifetime

Courtesy Aaron Moy of SVT Associates

Internal Gradient Strained-Superlattice

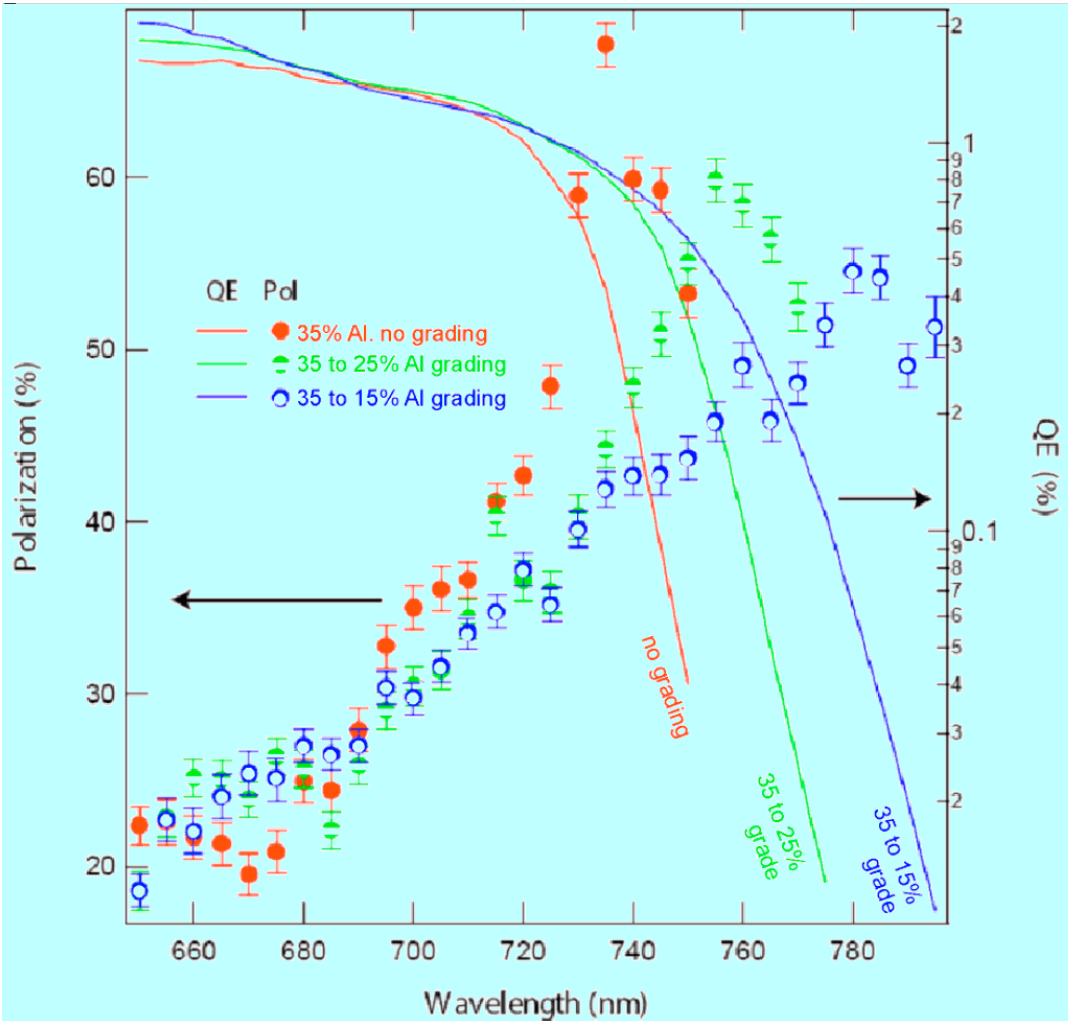
- Photocathode active layers with internal accelerating field
- Internal field enhances electron emission for higher QE
- Less transport time also reduces depolarization mechanisms
- Gradient created by varied alloy composition or dopant profile



Courtesy Aaron Moy of SVT Associates

Internal Gradient GaAs/AlGaAs SLs

- Polarization decreased as aluminum gradient increased
- Due to less low LH-HH splitting at low aluminum %
- QE increased 25% due to internal gradient field
- Peak polarization of 70 % at 740 nm, shorter than 875 nm of GaAs



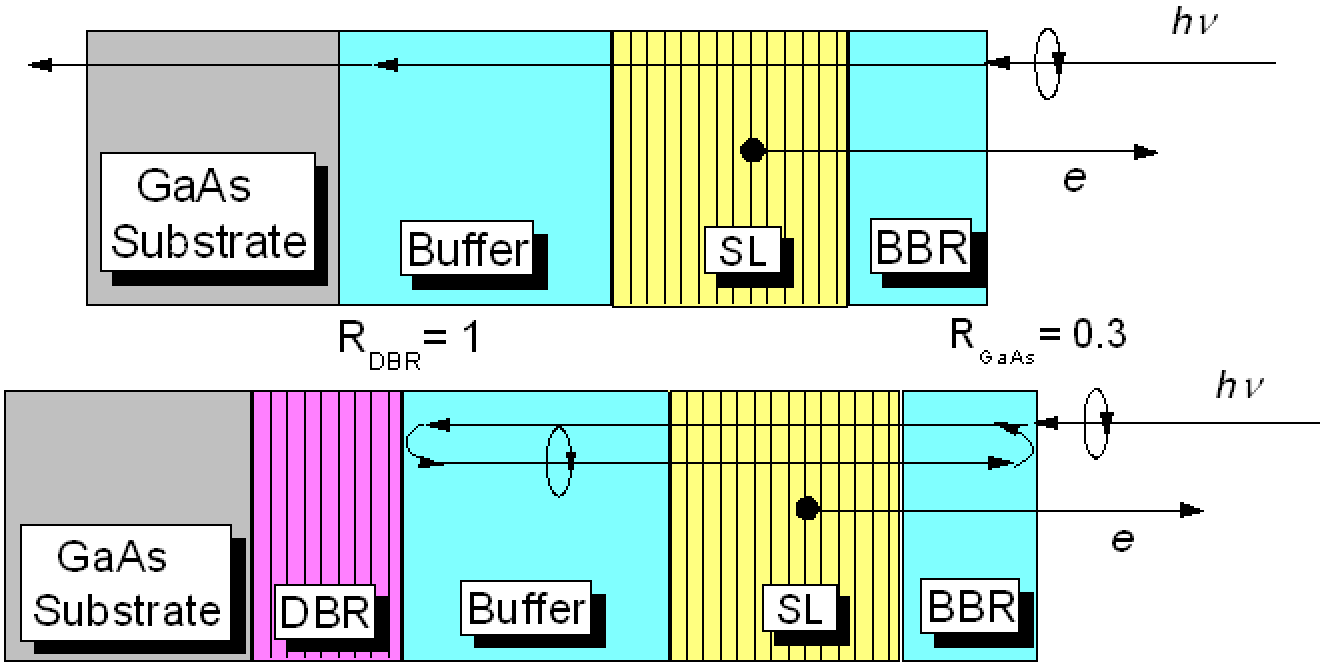
Courtesy Aaron Moy of SVT Associates

DBR – Equipped Crystal

For instance, talk by L. Gerchikov, St. Petersburg, at PESP 2007

“Normal” cathode

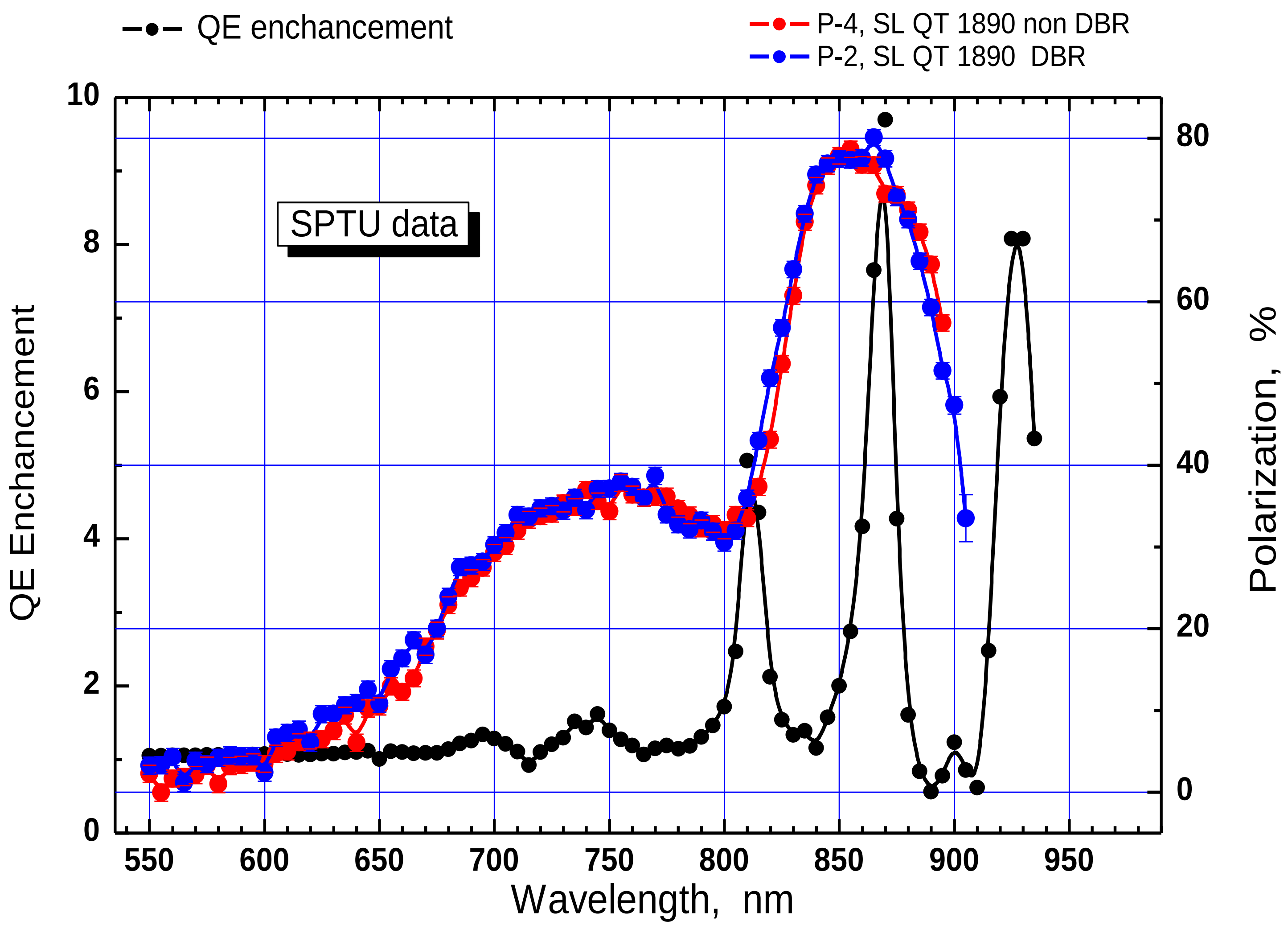
Cathode with Bragg Reflectors



Index of refraction of GaAs is such that, 30% of incident light lost at surface. Not sure we can do anything about that.

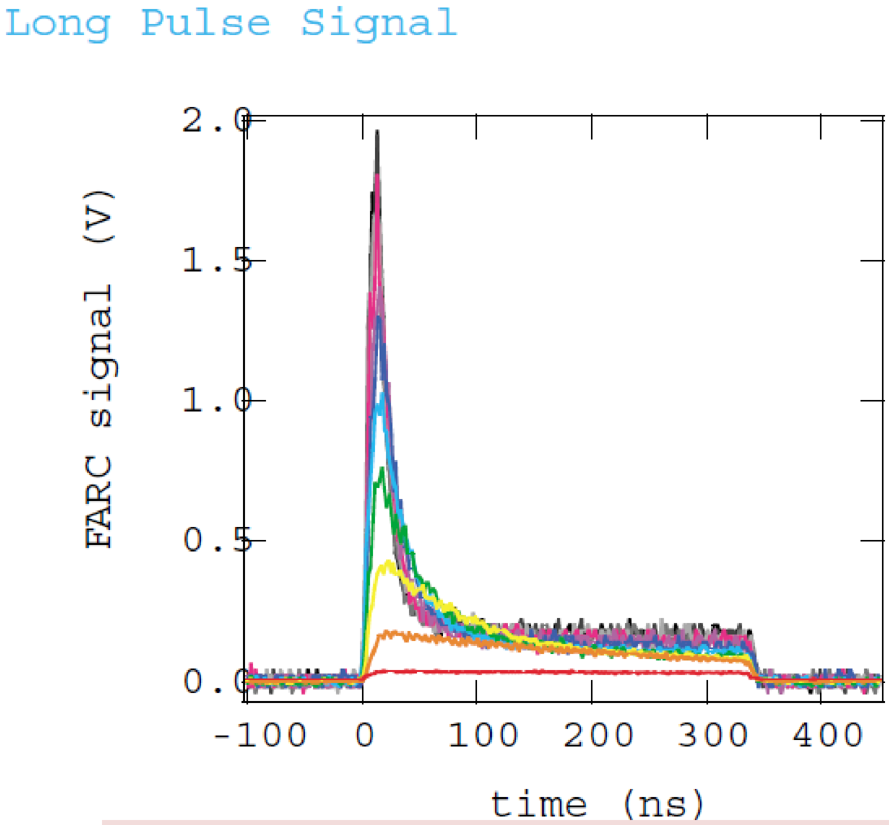
Add a Distributed Bragg Reflector behind photocathode to reflect back the un-absorbed light…

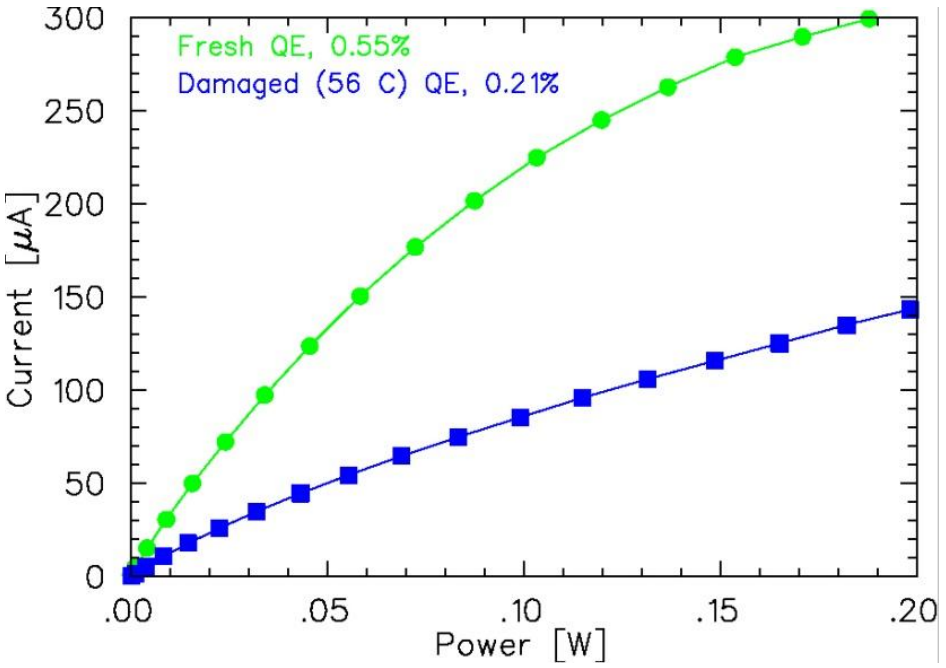
Resonant enhancement of QE



Accepted for publication at Semiconductors, 2008

Surface Charge Limit





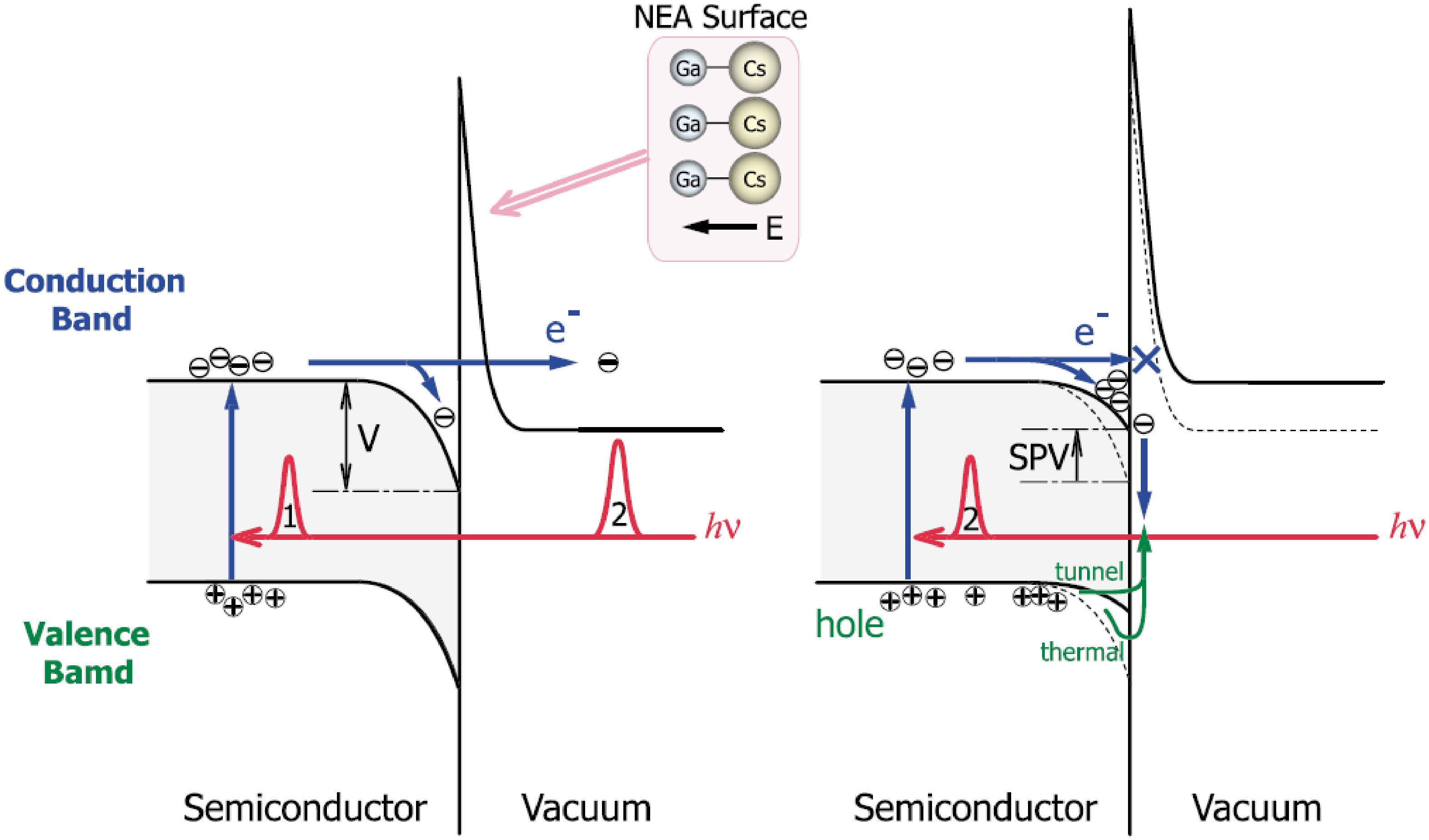
SLAC: can't extract enough electrons (nC bunch charge)

CEBAF: current saturates at higher laser power (pC bunch charge)

Slide info courtesy Takashi Maruyama, SLAC, e.g., his PESP2000 talk

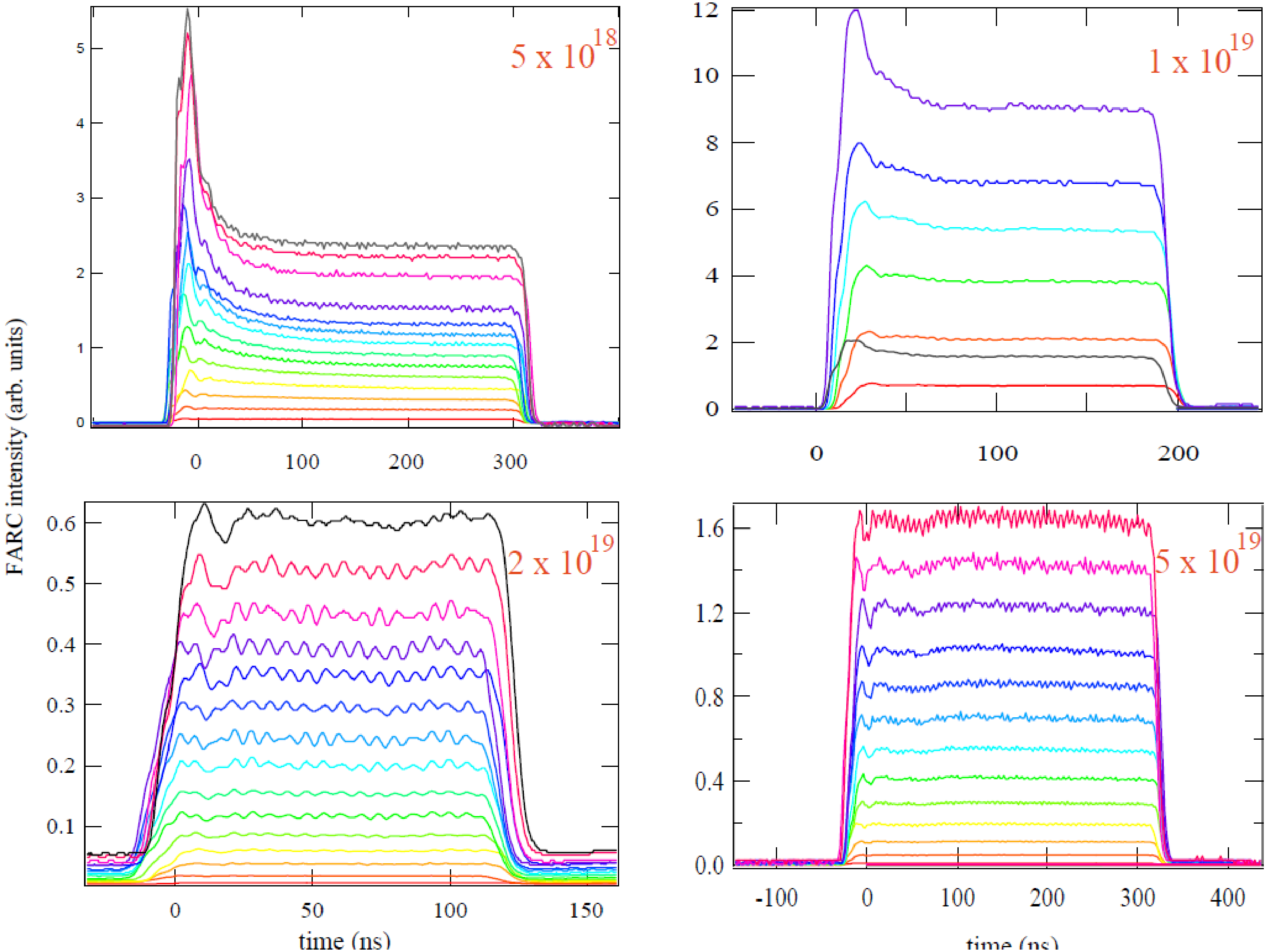
Surface Charge Limit

Bunch beam extraction with high peak current ➔ SCL Problem



From K. Wada, Nagoya university, PESP2002 presentation

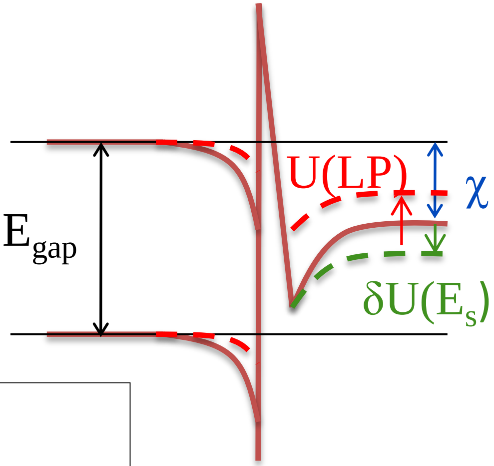
Surface Charge Limit



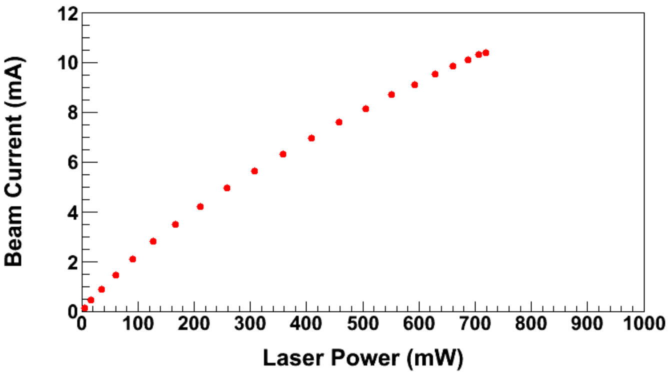
Slide info courtesy Takashi Maruyama, SLAC, e.g., his PESP2000 talk

- Surface Charge Limit, also known as Surface Photovoltage Effect, reduces NEA of GaAs: Photoelectrons trapped near GaAs surface produce opposing field that reduces NEA resulting in QE reduction at high laser power (LP),

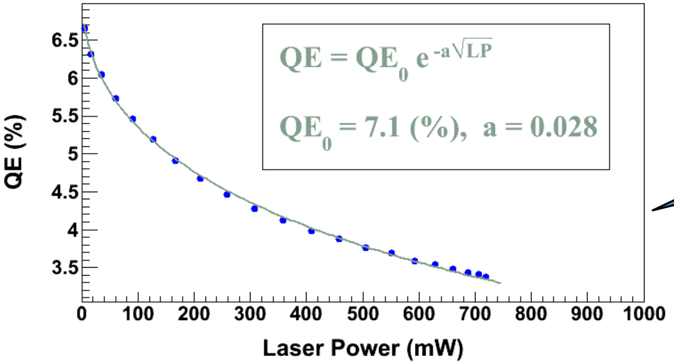
$$QE = QE_0\left(1 - \frac{U(LP)}{\chi + \delta U(E_s)}\right)$$



Where U(LP) is up-shifting of potential barrier due to photovoltage.



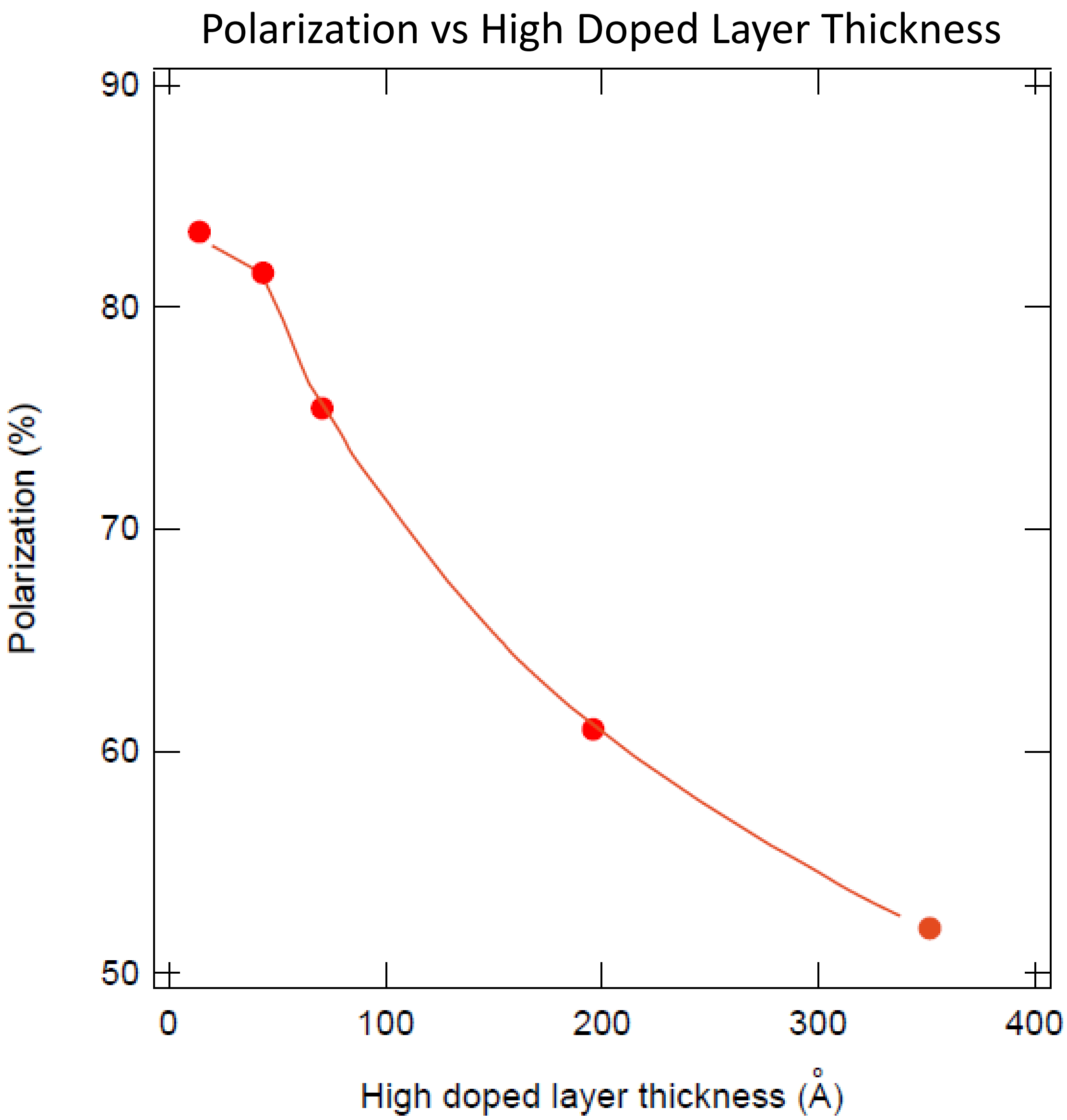
- For heavily Zn doped GaAs surface, $U(LP) \to 0$
- Higher Gun HV suppresses photovoltage



$$U(LP) \propto \sqrt{LP}$$

G. Mulhollan, et al., Physics Letters A 282 (2001) 309–318

Surface Charge Limit



- High doping depolarizes spin
- Possible to reach ~80 % polarization with 50 ~ 75 A of high surface doping

Slide info courtesy Takashi Maruyama, SLAC, e.g., his PESP2000 talk

Techniques to suppress surface charge limit

- Heavily doped surface layer
  - Can’t extend doping throughout, because this leads to lower polarization
    - ✓ Must lower heat cleaning temp
    - ✓ H cleaning helps reduce temps
    - ✓ As capping, avoid contamination of surface
    - ✓ Carbon doping? Less inclined to diffuse away?
- Add an electrostatic field to prevent electrons from accumulating at surface
  - Metallic grid was not very effective
  - Cathode biasing: gun R&D required
  - Superlattice structure with internal gradient
- Higher Gun HV
  - gun R&D required

Slide info courtesy Takashi Maruyama, SLAC, e.g., his PESP2000 talk

Surface Charge Limit

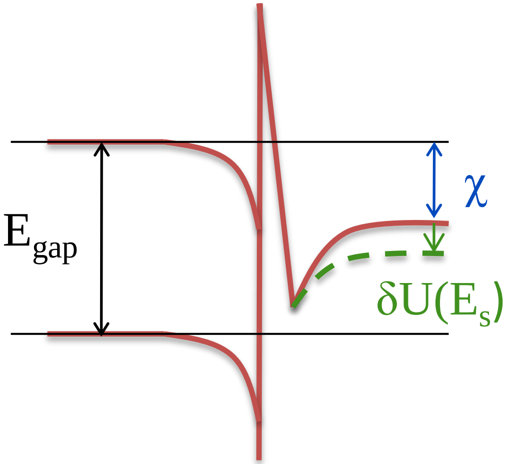
- NEA of GaAs depends on Gun HV. QE increases with external Electric Field at GaAs surface, E_s,

$$QE = QE_0 \left(1 + \frac{\delta U(E_s)}{\chi} \right)$$

Where χ (~200 meV) is the zero-field NEA value (G. Mulhollan, et al., Physics Letters A **282**, 309) and potential barrier lowering due to Electric Field is

$$\delta U(E_s) = \sqrt{\frac{e^3 E_s (\varepsilon_s - 1)}{4\pi\varepsilon_0 (\varepsilon_s + 1)}}$$

Where ε_s (= 13.1) is GaAs relative permittivity.



Gun HV (kV)	E_s (MV/m)	$\delta U(E_s)$ (meV)
100	2.0	50
140	2.8	59
200	4.0	70

Space Charge Limit at CEBAF

- Maximum current density that can be transported across cathode-anode gap is (for an infinite charge plane):

Child's Law (1D): $j_1 = \left(2.33\times 10^{-6}\right) V^{3/2} / d^2$ [A/cm²]

- For electron emission from a finite circular spot on the cathode:

Child's Law (2D) (PRL **87**, 278301) : $j_2 \geq j_1\left(1 + \frac{1}{4}\frac{d}{r}\right)$

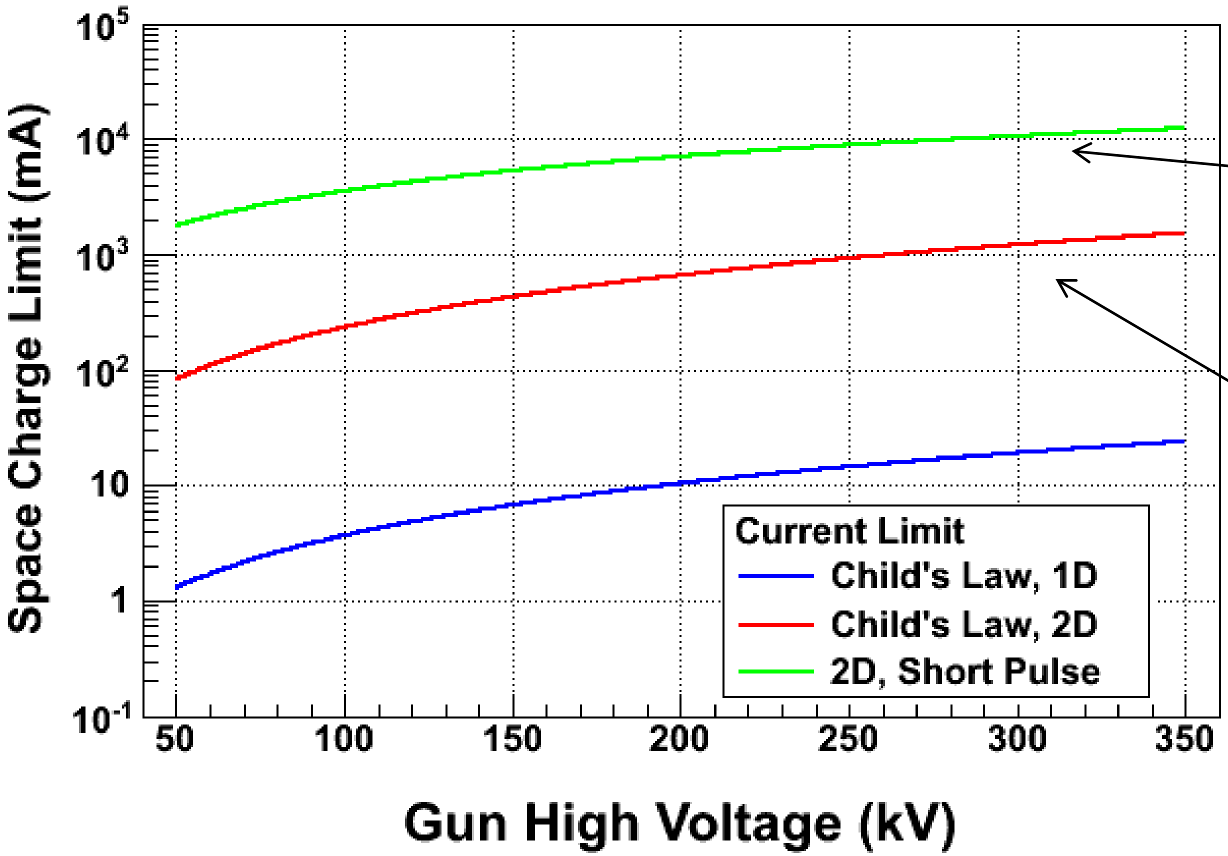
- For CEBAF electron beam (499 MHz):

Short Pulse (PRL **98**, 164802): $$j_{SCL} = j_2\left(2\frac{1-\sqrt{1-3X_{CL}^2/4}}{X_{CL}^3}\right),$$

$$X_{CL} = \frac{t_b}{\tau_{CL}}, \tau_{CL} = \frac{3}{2}\tau_{Single-electron}$$

V	Gun Voltage
d	Cathode-anode Gap (6.3 cm)
r	Laser Spot Size (0.5 mm = $2r$)
t_b	Micro-bunch length (50 ps)
τ	Gap Transit Time (0.96 ns at 100 kV)

CEBAF conditions permit extraction of very high peak current!!

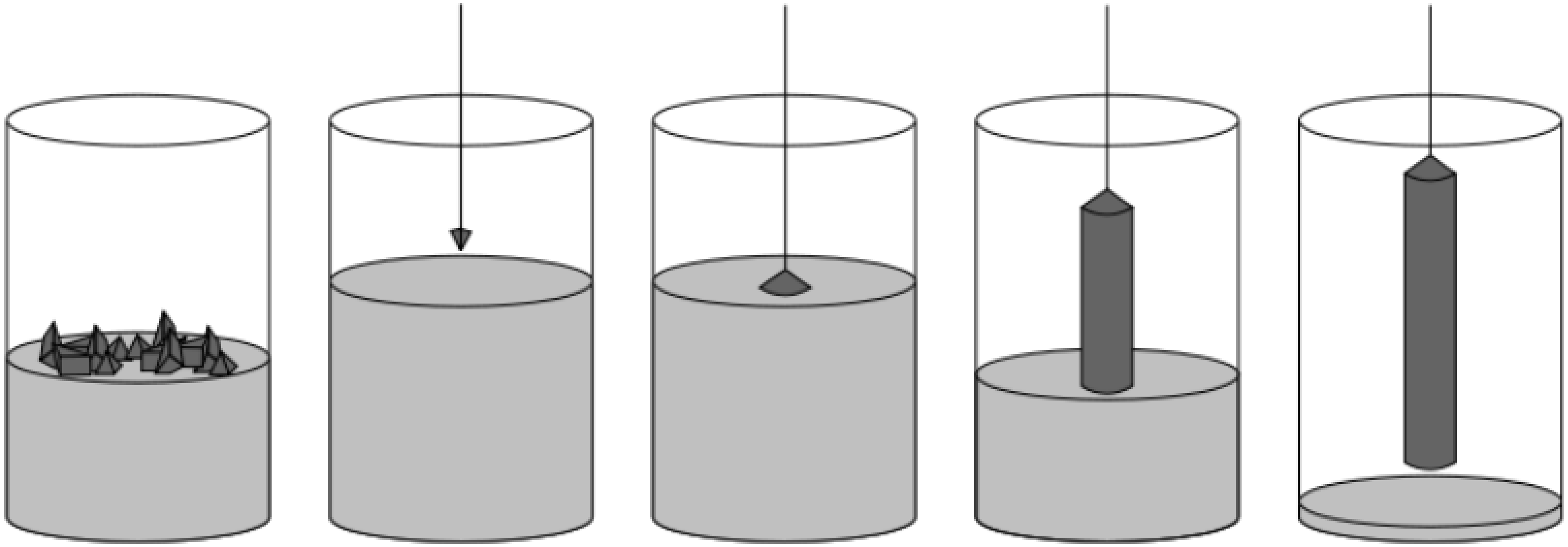


Not everyone gets this benefit

Everyone gets this benefit

Bulk GaAs

Czochralski method



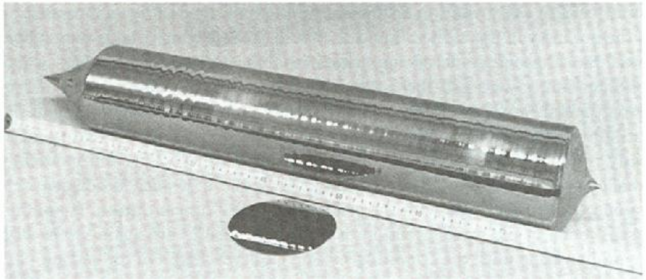
Melting of polysilicon, doping

Introduction of the seed crystal

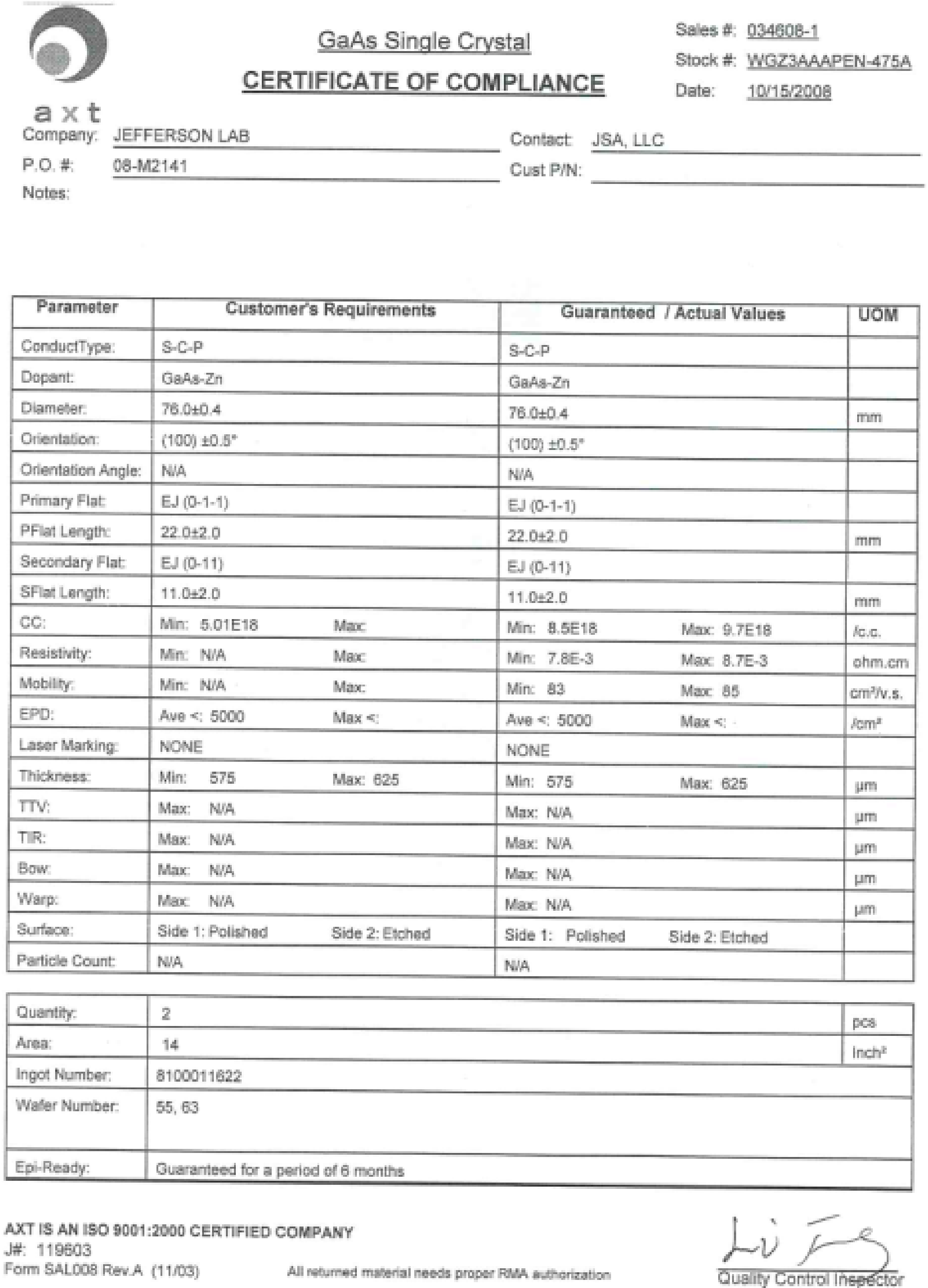
Beginning of the crystal growth

Crystal pulling

Formed crystal with a residue of melted silicon



Bulk GaAs



axt

GaAs Single Crystal

CERTIFICATE OF COMPLIANCE

Sales #: 034608-1
Stock #: WGZ3AAAPEN-475A
Date: 10/15/2008

Company: JEFFERSON LAB
Contact: JSA, LLC
P.O. #: 08-M2141
Cust P/N:
Notes:

Parameter	Customer's Requirements	Guaranteed / Actual Values	UOM
ConductType:	S-C-P	S-C-P	
Dopant:	GaAs-Zn	GaAs-Zn	
Diameter:	76.0±0.4	76.0±0.4	mm
Orientation:	(100) ±0.5°	(100) ±0.5°	
Orientation Angle:	N/A	N/A	
Primary Flat:	EJ (0-1-1)	EJ (0-1-1)	
PFlat Length:	22.0±2.0	22.0±2.0	mm
Secondary Flat:	EJ (0-11)	EJ (0-11)	
SFlat Length:	11.0±2.0	11.0±2.0	mm
CC:	Min: 5.01E18 Max:	Min: 8.5E18 Max: 9.7E18	/c.c.
Resistivity:	Min: N/A Max:	Min: 7.8E-3 Max: 8.7E-3	ohm.cm
Mobility:	Min: N/A Max:	Min: 83 Max: 85	cm²/v.s.
EPD:	Ave <: 5000 Max <:	Ave <: 5000 Max <:	/cm²
Laser Marking:	NONE	NONE	
Thickness:	Min: 575 Max: 625	Min: 575 Max: 625	µm
TTV:	Max: N/A	Max: N/A	µm
TIR:	Max: N/A	Max: N/A	µm
Bow:	Max: N/A	Max: N/A	µm
Warp:	Max: N/A	Max: N/A	µm
Surface:	Side 1: Polished Side 2: Etched	Side 1: Polished Side 2: Etched	
Particle Count:	N/A	N/A	

Quantity:	2	pcs
Area:	14	Inch²
Ingot Number:	8100011622	
Wafer Number:	55, 63	
Epi-Ready:	Guaranteed for a period of 6 months	

AXT IS AN ISO 9001:2000 CERTIFIED COMPANY
J#: 119603
Form SAL008 Rev.A (11/03)

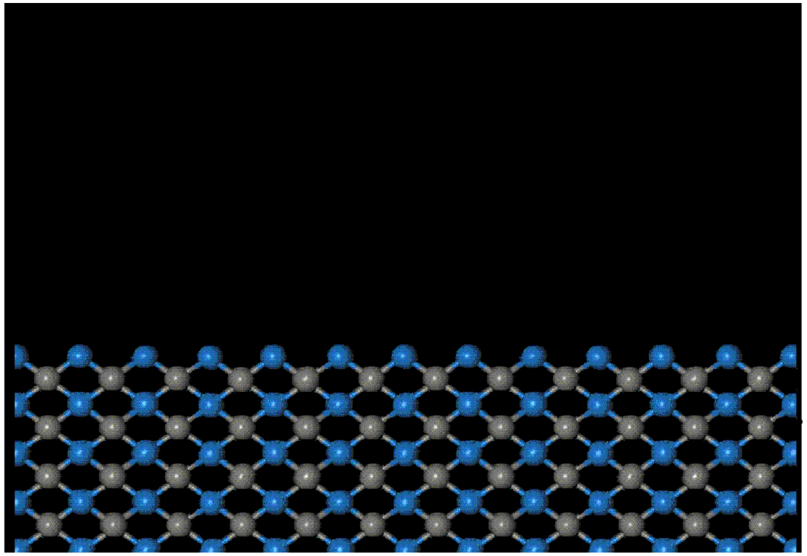
All returned material needs proper RMA authorization

Quality Control Inspector

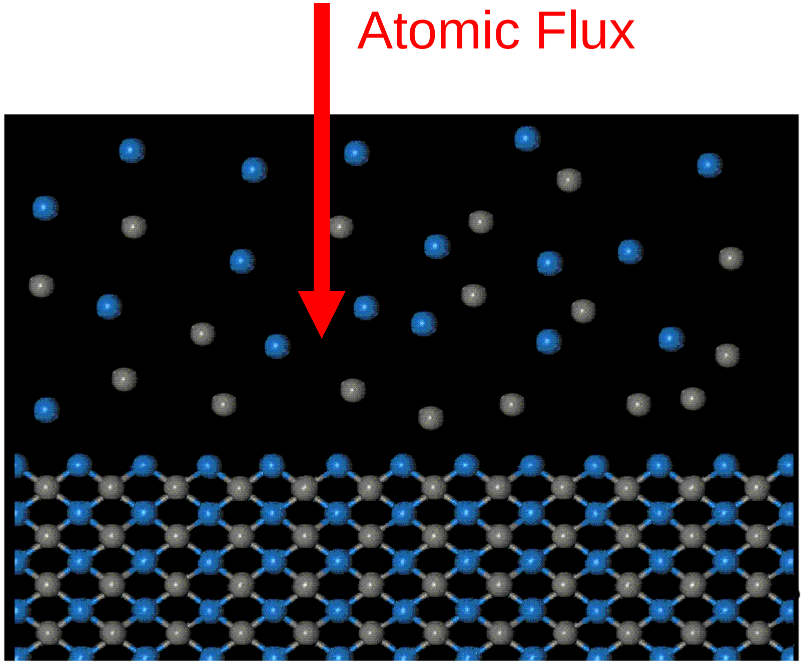
Things like cleave orientation, dopant, Etch Pit Density, mobility will affect QE and polarization

Epitaxy

Growth of thin film crystalline material where crystallinity is preserved, "single crystal"



Bare (100) III-V surface, such as GaAs

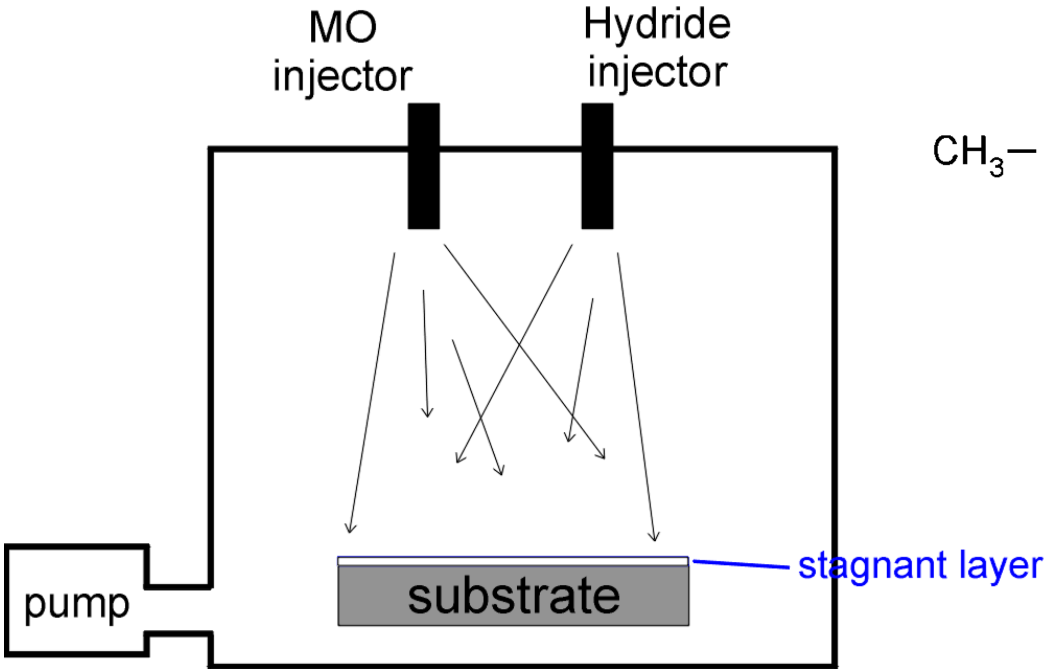


Deposition of crystal source material (e.g. Ga, As atoms)

Two kinds of Epitaxy to choose from: MOCVD and MBE

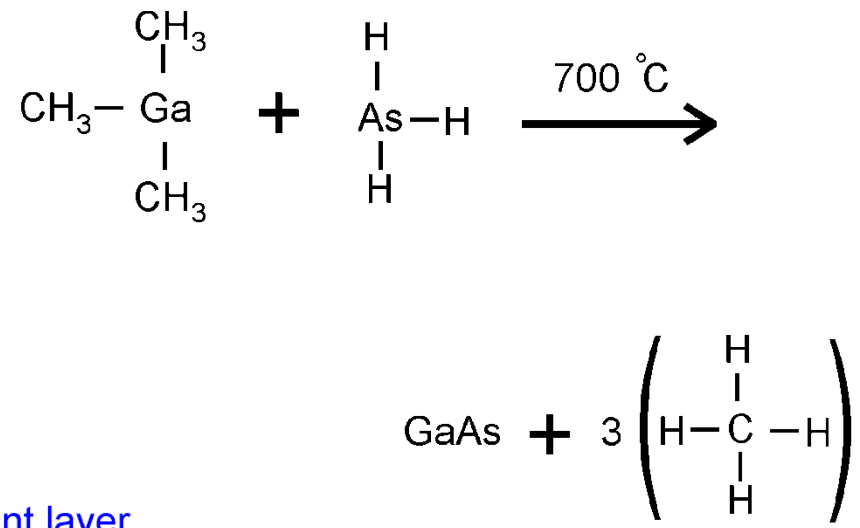
From Aaron Moy, PESP2002

MOCVD- Surface Chemistry



Basic layout of an MOCVD reactor

Surface chemistry-

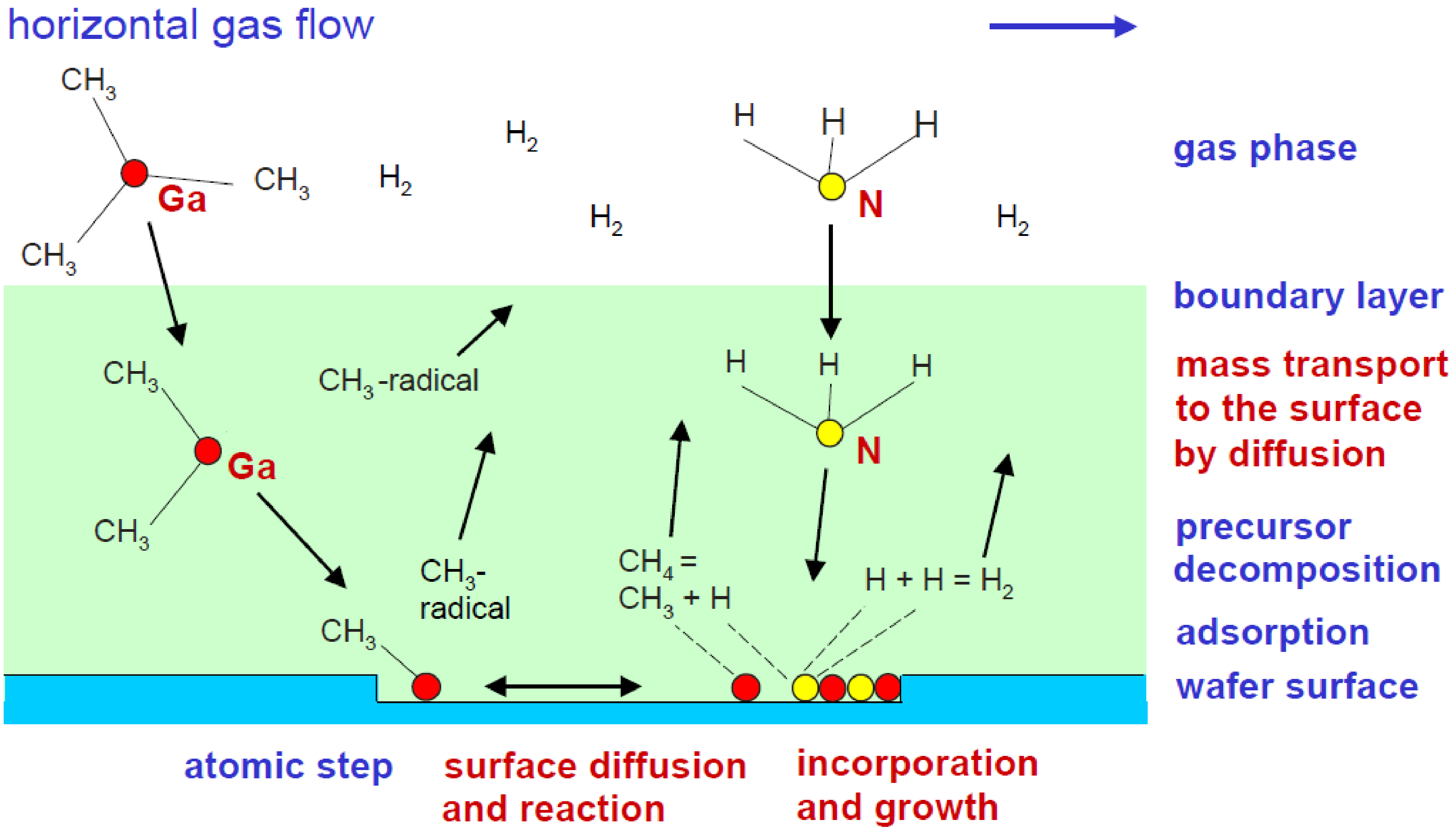


$$(CH_3)_3Ga + AsH_3 \xrightarrow{700\ ^{\circ}C} GaAs + 3\,CH_4$$

From Aaron Moy, PESP2002

MOCVD

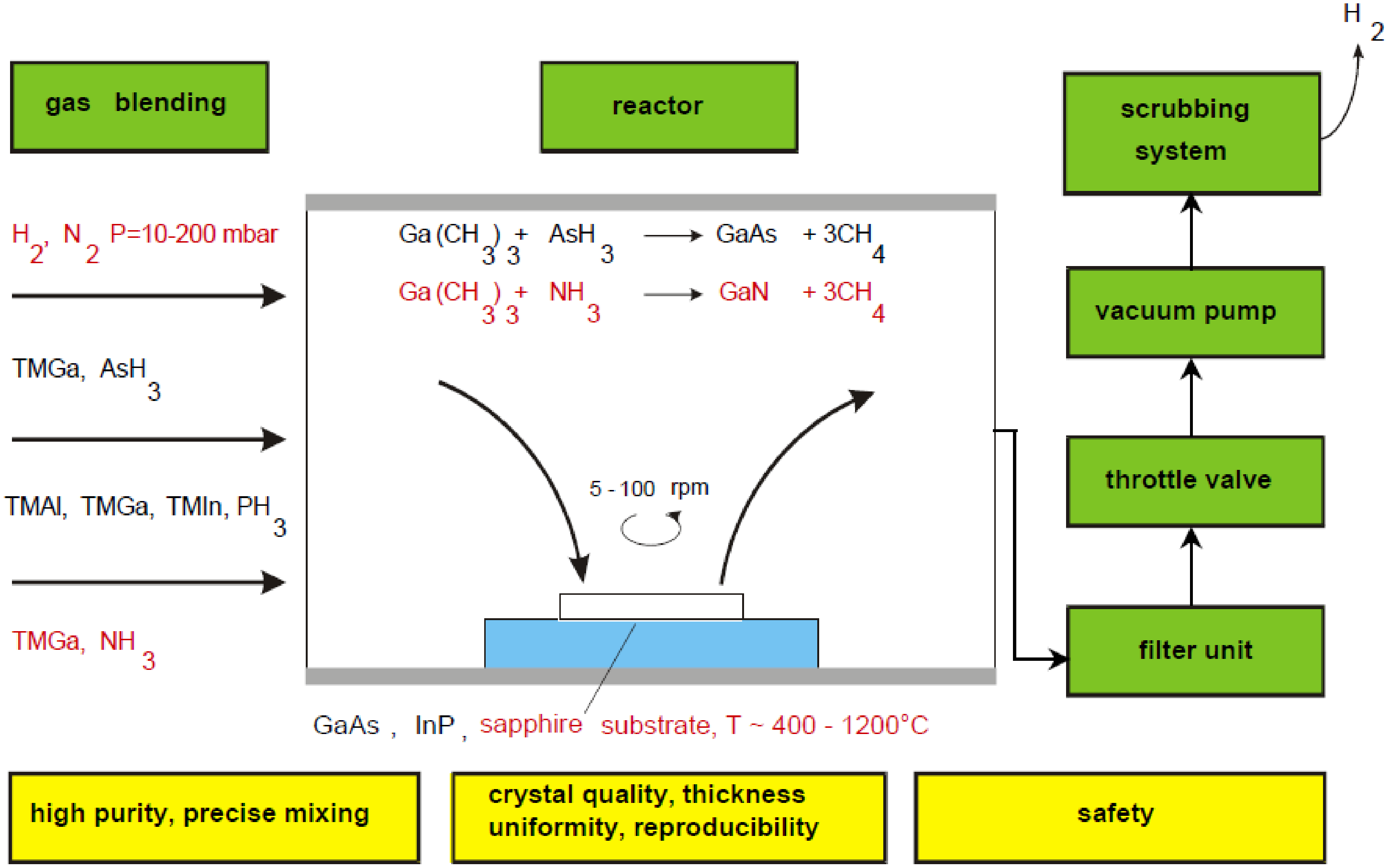
MOVPE Growth Mechanisms
(simplified)



From Samsung tutorial

MOCVD

Principle of LP-MOVPE



From Samsung tutorial

AIXTRON MOCVD System

transfer cabinet

wafer handler

vacuum pump
(inside)

reactor + heater

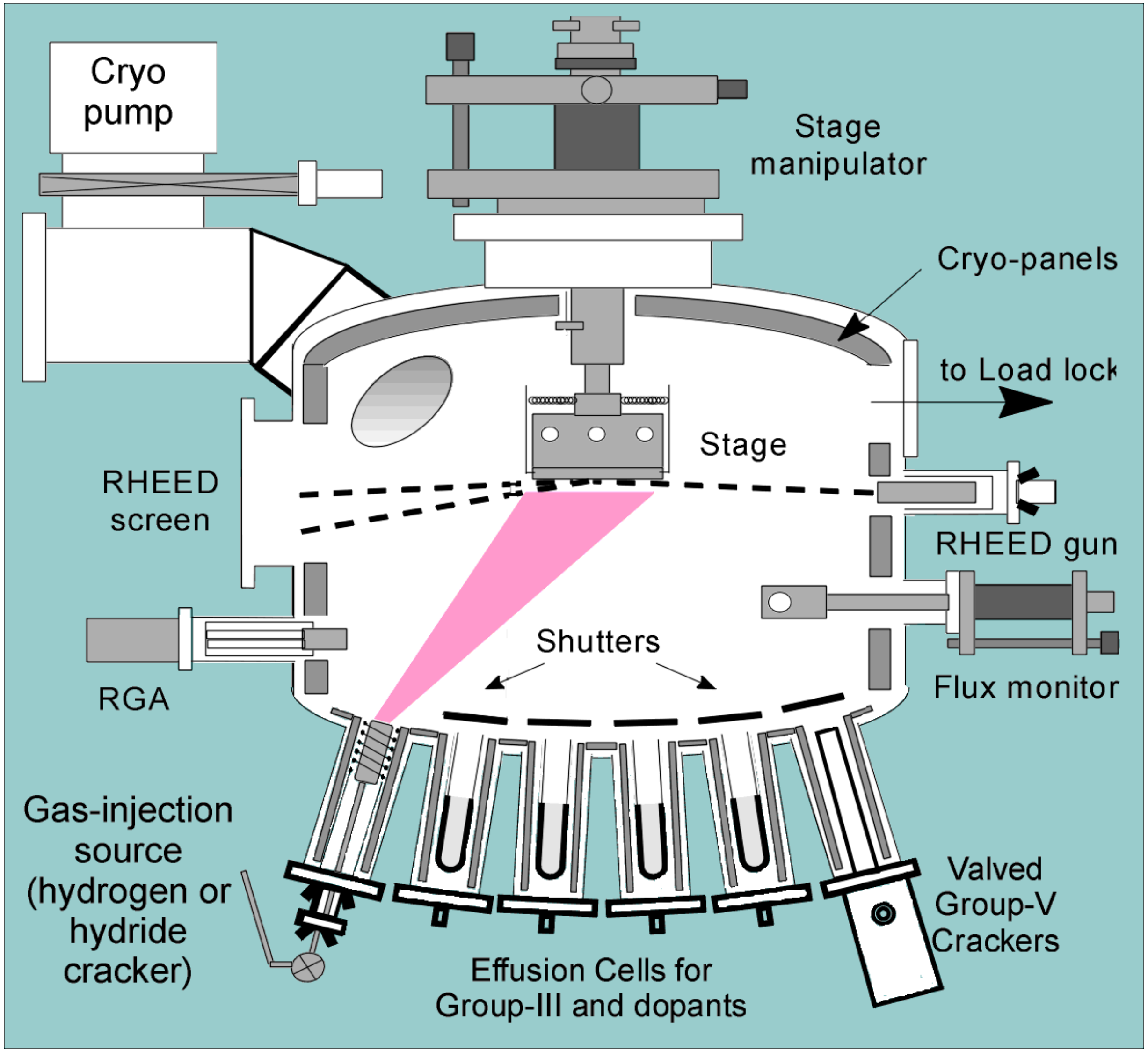
gas mixing system

computer

electronic control rack

From Samsung tutorial

Molecular Beam Epitaxy



Growth Apparatus

From Aaron Moy, PESP2002

MBE- System Photo

From Aaron Moy, PESP2002

MOCVD versus MBE

- Growth in chemical “reactor”
- Pressure 10s-100s of torr
- Metal organic group III source material
  - Trimethyl Gallium $Ga(CH_3)_3$
  - Trimethyl Indium $In(CH_3)_3$
  - MO vapor transported H_2 carrier gas
- Hydride group V source gas
  - Arsine AsH_3
  - Phosphine PH_3
- Thermal cracking at growth surface

- Growth in high vacuum chamber
  - Ultimate vacuum $< 10^{-10}$ torr
  - Pressure during growth $< 10^{-6}$ torr
- Elemental source material
  - High purity Ga, In, As (99.9999%)
  - Sources individually evaporated in high temperature cells
- In situ monitoring, calibration
  - Probing of surface structure during growth
  - Real time feedback of growth rate

From Aaron Moy, PESP2002

MOCVD versus MBE

- Growth rates 2-100 micron/hr
    - high throughput
- P-type doping
    - Zn (Diethyl Zinc), high diffusivity
    - C (CCl_4, CBr_4), amphoteric
- Complex growth kinetics
    - delicate interaction between injected gasses, temperatures
- High background pressure
    - Parasitic incorporation
    - Intermixing of atoms at interfaces

- Ultra high vacuum, high purity layers
- No chemical byproducts created at growth surface
- High uniformity (< 1% deviation)
- Growth rates 0.1-10 micron/hr
- More dopant options, Be
- Hydrogen cleaning
- Arsenic capping
- High control of composition
- In situ monitoring and feedback

From Aaron Moy, PESP2002

Photoemission: a three step process

old

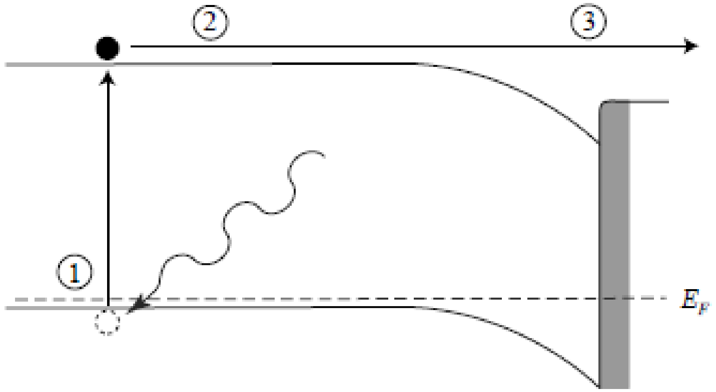
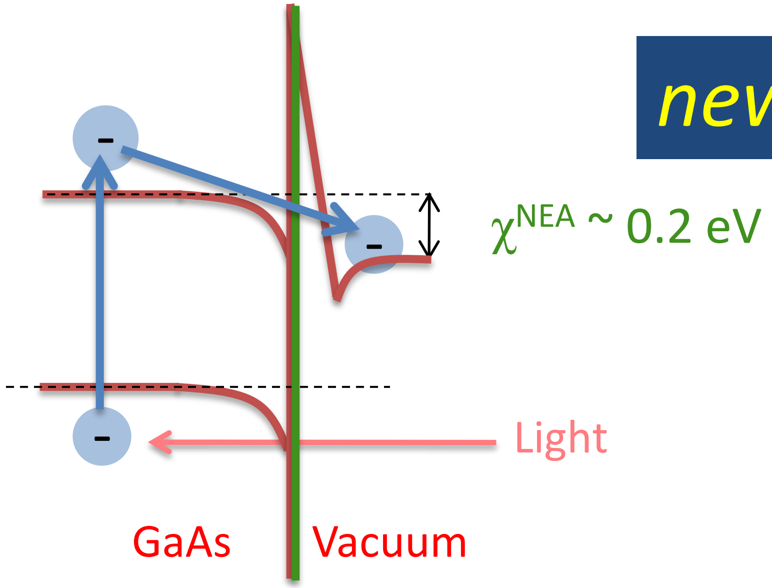


Figure 2.6: Spicer's Three–Step Photoemission Process: 1– photoexcitation of valence electrons into the conduction band (creation of electron–hole pair), 2– transport of electrons to the surface, 3– emission of electrons into the vacuum.

new

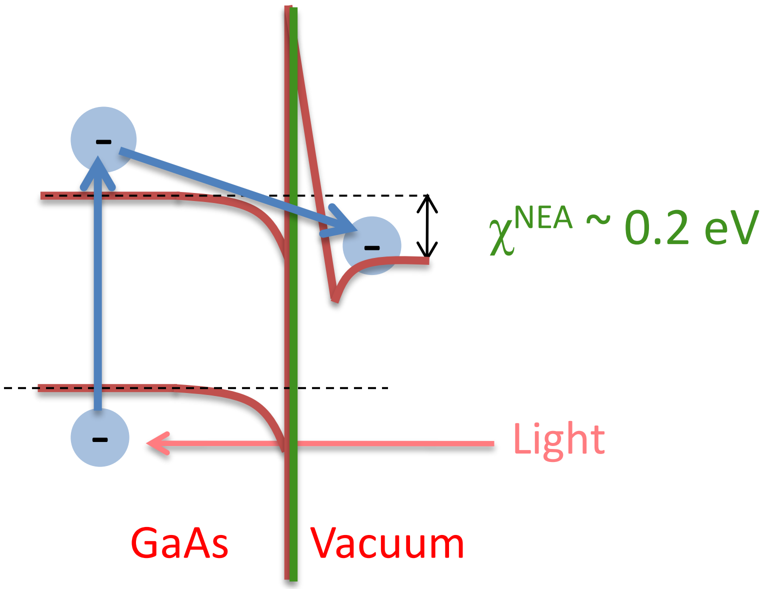


Step 1: Electrons are excited to conduction band by absorbing light

Step 2: (some) Electrons diffuse to the surface

Step 3: (some) Electrons leave material

Photoemission: a three step process



Everyone wants:
- High Polarization
- High QE
- No surface charge limit (i.e., same QE at low/high laser power)
- Fast response time, short pulses (no “tails”)
- Long operating lifetime

Fun Facts about GaAs:

Lifetime of electrons in conduction band: 200 to 300 psec

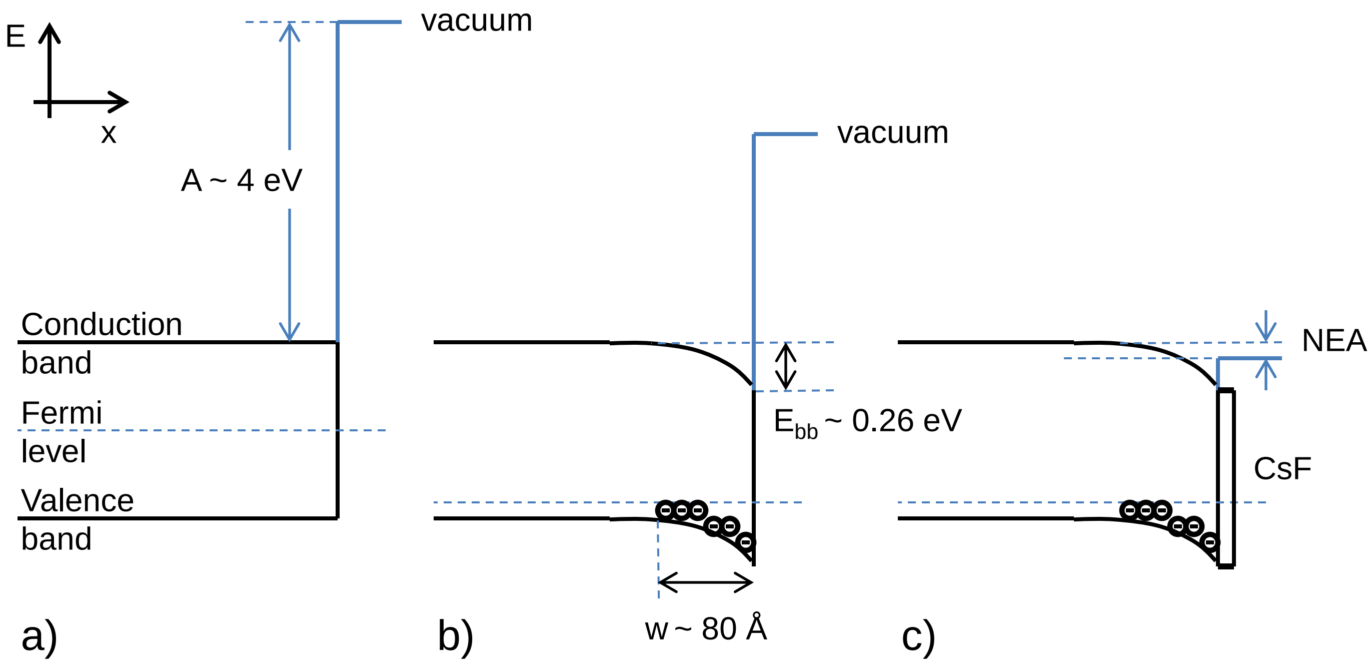
Diffusion length of electrons: ~ 10um

Width of the band bending (aka, depletion) region: ~ 100Å

Absorption depth of light: approx. = wavelength of light, λ

All of these things depend on dopant concentration, temperature, color of the light, etc. and can effect the bottom line

Reducing the Work Function



Intrinsic GaAs

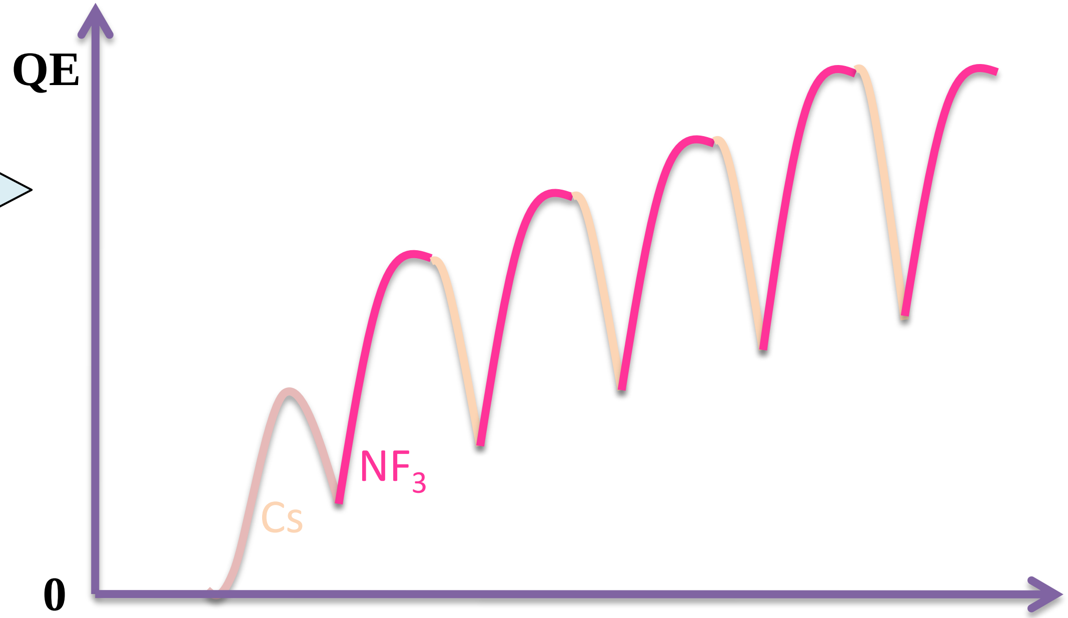
p-doped GaAs

CsF creates NEA

Fermi Level adjusts itself to keep the number of holes equal to the number of electrons plus ionized impurities, pulling E_c , E_v and vacuum level at surface with it…

NEA Activation of GaAs

“**Activate**” GaAs photocathode by applying about one mono-layer of Cesium and NF_3 to very clean surface



Different Activation Methods

- ➢ Yo-Yo: one chemical applied at a time, take photocurrent to ½ peak with each application of cesium, turn OFF oxidant at peak
- ➢ Nakanishi technique: same as yo-yo, but take photocurrent to Zero with each cesium application
- ➢ Constant Oxidant technique: leave valve to oxidant Open the entire time, apply cesium until photocurrent reaches maximum

Calculating QE

The ratio of the number of emitted electrons to number of incident photons

$$QE = \frac{N_e}{N_p} = \frac{124 \cdot I(uA)}{P(mW) \cdot \lambda(nm)}$$

$$\boxed{\sim 6uA \Big/ mW \big/ \%QE}$$

$$\boxed{\sim 6mA \Big/ W \big/ \%QE}$$

Homework: derive these equations….

Calculating QE

$$QE(h\nu) = \frac{i(h\nu)}{I_0(1-R)} = \frac{\frac{\alpha_{PE}}{\alpha} P_E}{1 + \frac{1}{\alpha L}}$$

W. E. Spicer, A. Herrera-Gomez,
SLAC-PUB-6306
SLAC/SSRL-0042, August 1993

$$QE(\hbar\omega) = (1-R)d\alpha(\hbar\omega)B(\chi)$$

R	GaAs Light Reflection Coefficient (= 0.3)
d	GaAs layer thickness (= 0.1 μm)
$\alpha(\hbar\omega)$	Photo-absorption Coefficient (= 5x10^{3} cm^{-1})
$B(\chi)$	Surface Tunneling Probability(= 0.2)

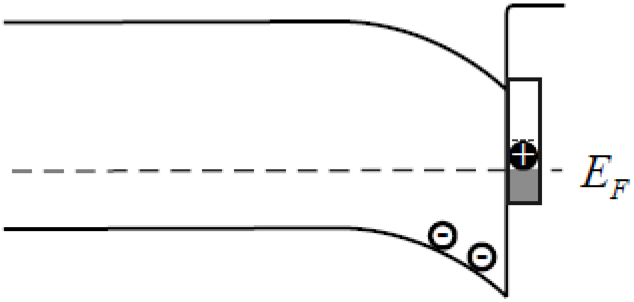
G. Mulhollan, et.al., Physics Letters A 282 (2001) 309–318

Homework: explain these equations and relate them to physical quantities, and previous Eqn.

Which Dopant?

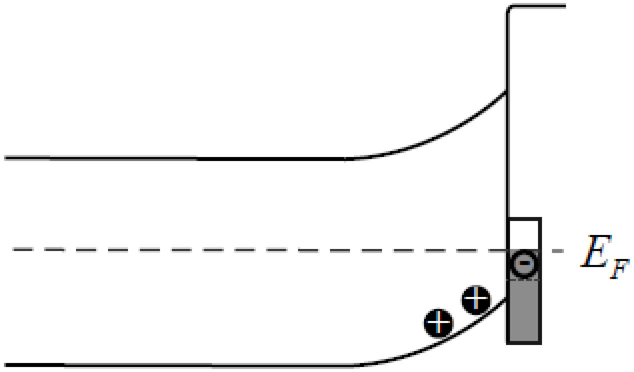
Intrinsic

(a)



p-doped

(b)



n-doped

(c)

Dopants are impurities added to the crystal lattice.

Dopants are described as *donors* or *acceptors*, related to their propensity to donate or accept electrons to/from the lattice

n-type, donates electrons

p-type, creates holes

Which Dopant? And How Much?

High dopant concentration leads to high QE (good)
However, high dopant concentration also leads to lower polarization (bad)

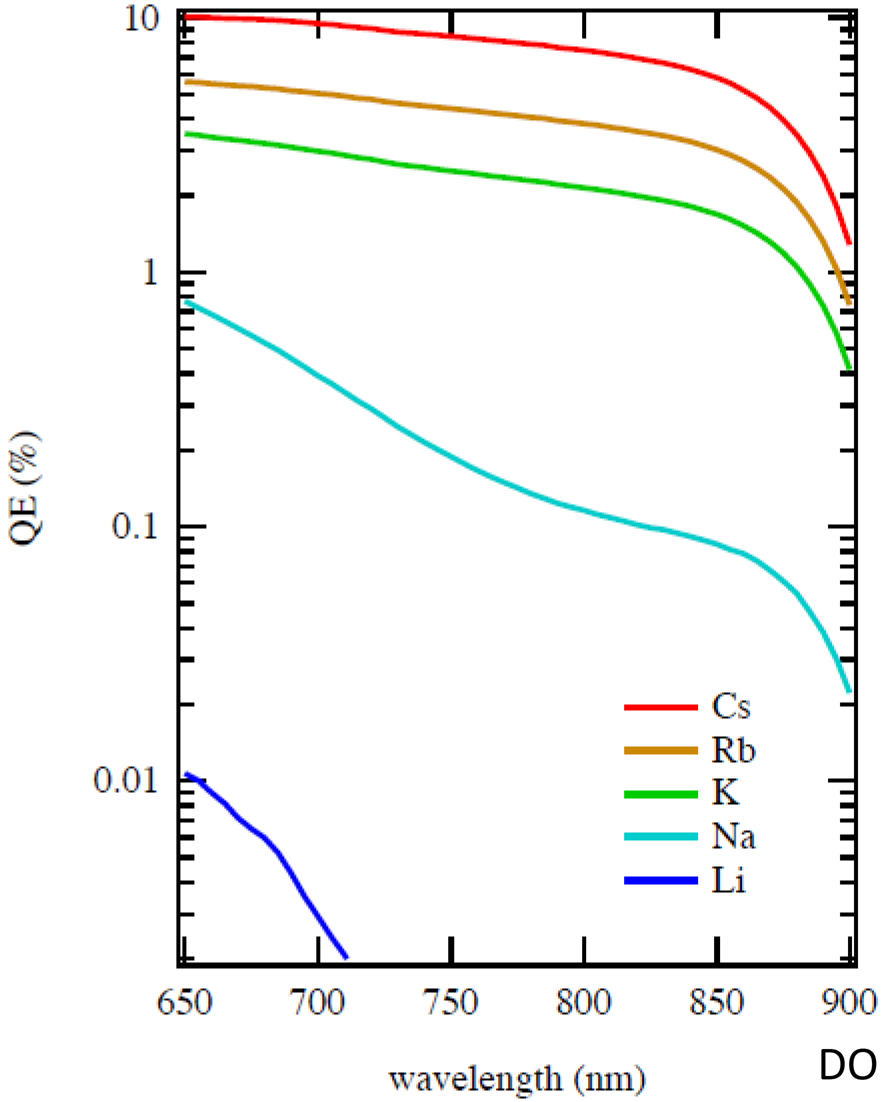
Doping reduces work function but causes spin relaxation

Polarization, generally most important concern

C, Be and Zn common acceptor dopant choices

- [Zn] at 5e18 cm^3, typical for bulk and strained layer GaAs
- [Be] at 5e17 cm^3 for strained superlattice but 5e19 cm^3 at surface
- [C] ?

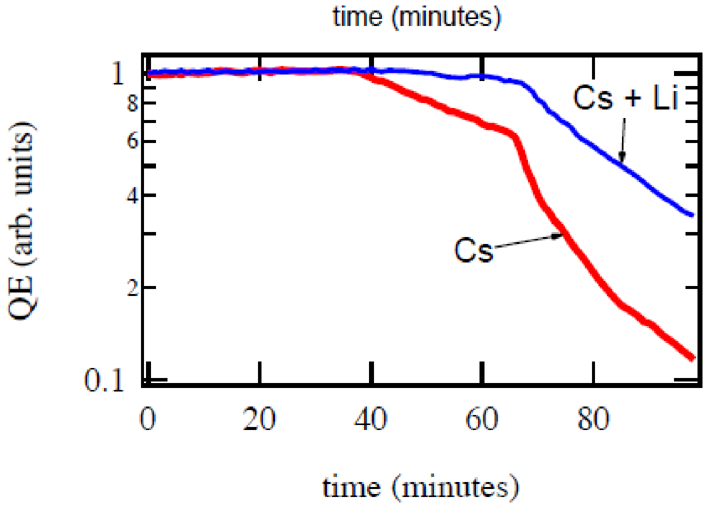
Which Alkali to Use?



Answer: Cesium

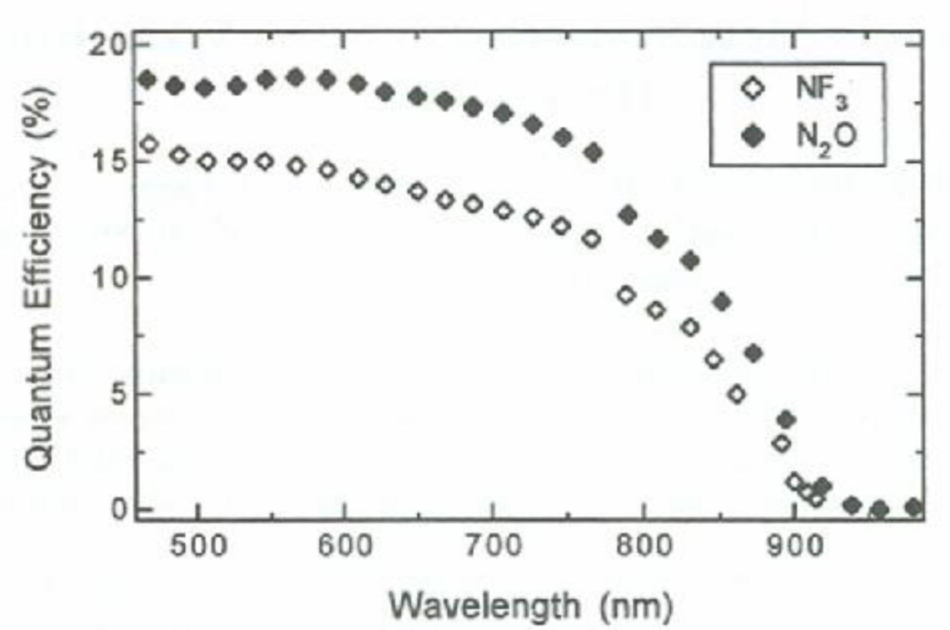
It provides the highest QE

Greg Mulhollan now researching multi-alkali activation to enhance photocathode lifetime



DOE-NP SBIR/STTR Exchange Meeting, Gaithersburg, MD, October 24-25, 2011 Gregory Mulhollan, Saxet Surface Science, Austin TX

Which Oxidant?

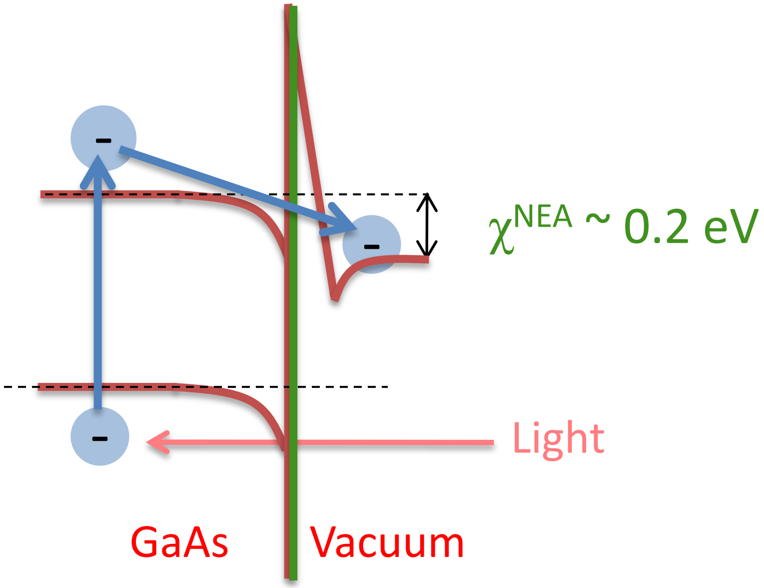


O_2, NF_3 and N_2O
Today's common oxidant choices

- There have been reports that one oxidant is better than another, including plot by Poelker and Sinclair (above) from PESP1996, but I think the consensus today…they all work well, providing pretty much the same result, i.e., QE
- There are environmental and health concerns related to NF3
- The "N" doesn't do any good, so why add it to your vacuum system?

What Does Cs/O2 layer do?

- It only takes ~ one monolayer of Cs and O to reduce work function
- Cs and O form a dipole at surface, with orientation that serves to reduce work function (the exact orientation still unclear)



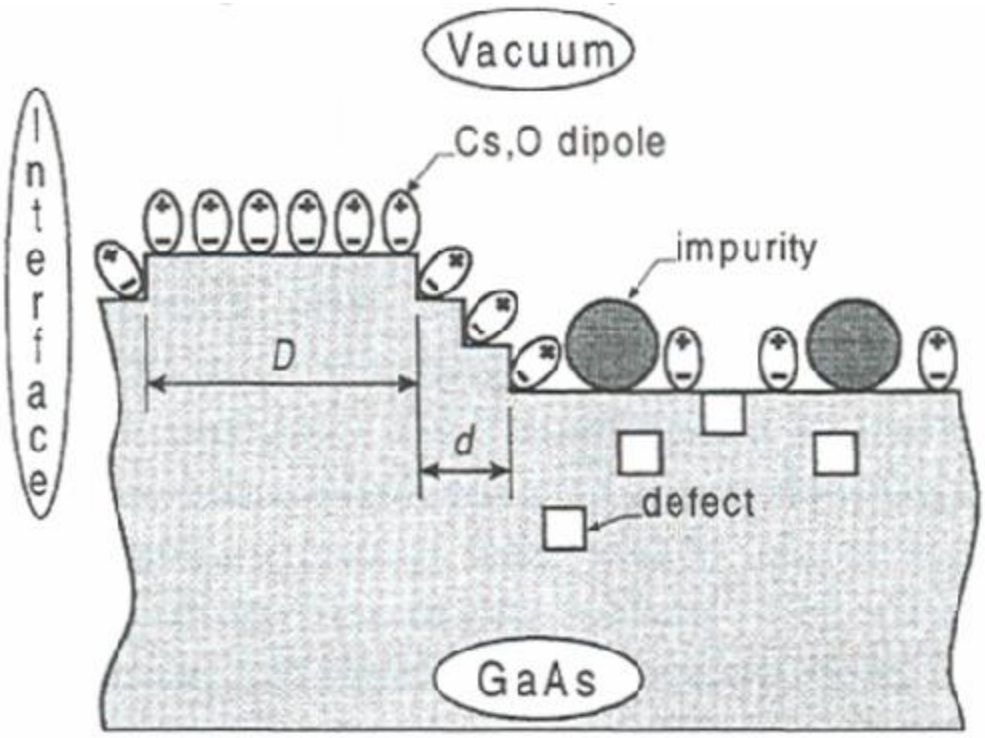


FIGURE 1. The model of (Cs,O)/GaAs interface.

Which Crystal Cleave Plane?

- The 100 and 110 surfaces have equal numbers of Ga and As atoms, produce similar band bending
- The 100 plane will reconstruct to 110 if heated too hot
- The 111A surface is comprised only of Ga atoms, has the largest valence band bending and the worst QE
- The 111B surface is comprised only of As atoms, has the smallest valence band bending and has the worst QE

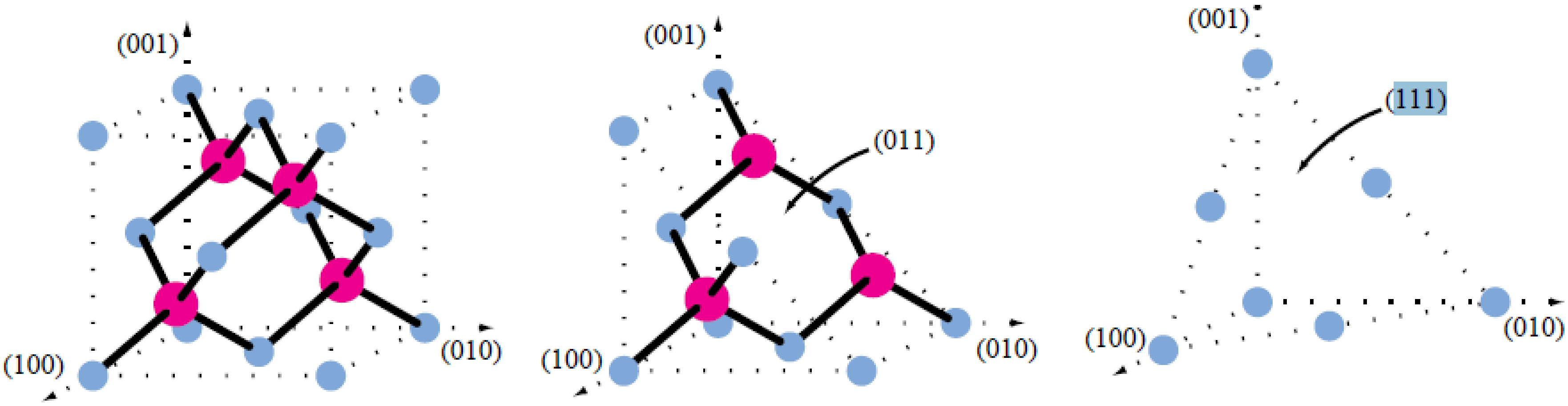


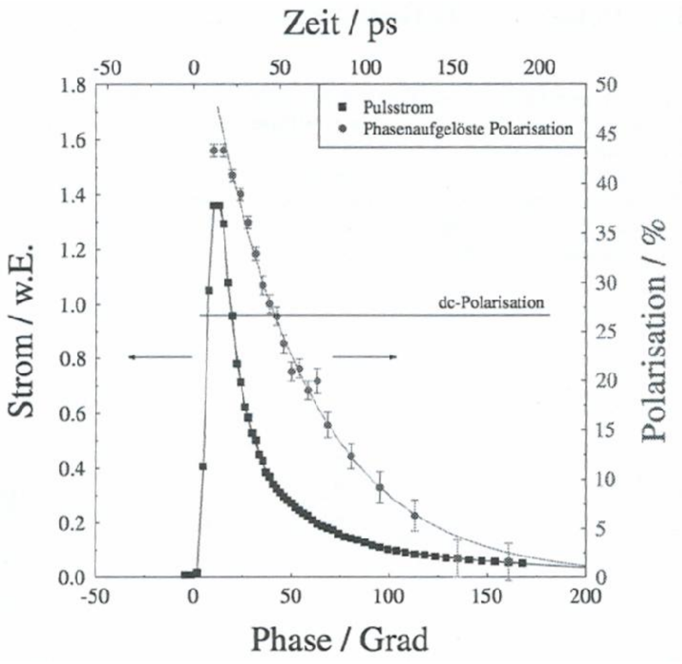
Figure 2.1: Symmetry planes of the GaAs crystal lattice.

From Pablo Saez PhD thesis, Stanford University, 1997

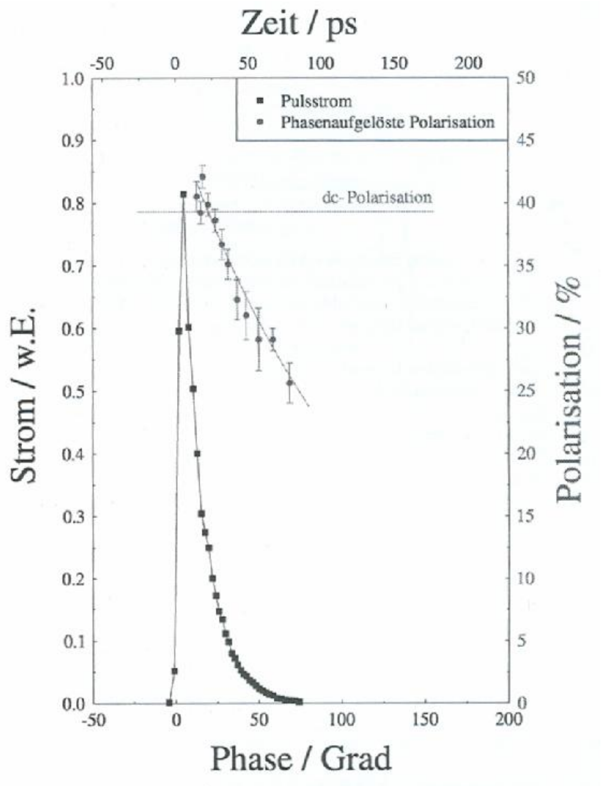
Channeling and H^+ Trapping

Temporal Response

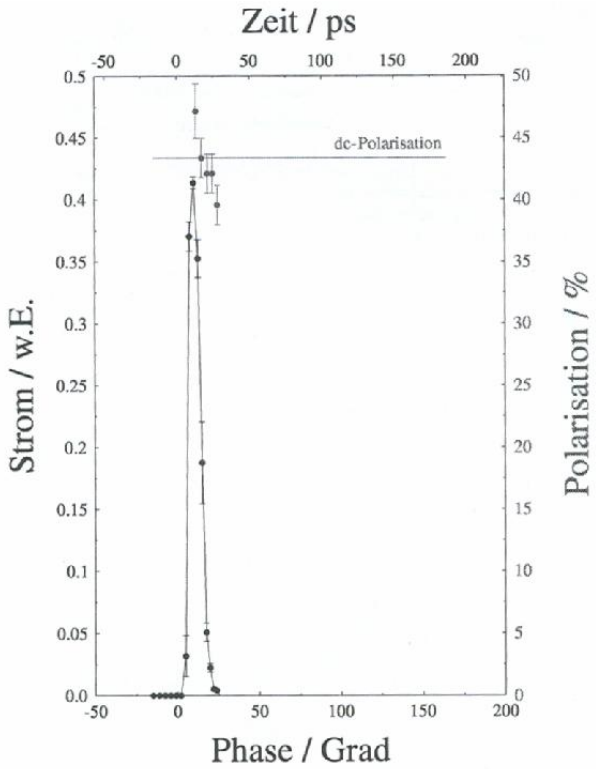
∞ Thick Bulk



0.4 um Bulk



0.2 um Bulk



Measurement of Electron Bunchlength and Polarization along length of bunch
For different photocathode thickness, Laser Pulse width always < 150 fs

Peter Hartmann PhD Thesis Mainz University, 1997

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