Special Topics Presentation on Electron Sources – Part 1

Joe Grames, Jefferson Lab

October 15, 2012

(with many thanks for slides borrowed from
Carlos-Hernandez Garcia, Matt Poelker, Dave Dowell)

Old Dominion University, Fall 2012

Electron emission in Nature

- Historically, electron emission musings go back to the Greek philosophers, who while rubbing pieces of amber (elektron in Greek) with fur noticed short flashes of light (sparks) jumping from the amber to the piece of silk.

- Effectively, a lighting strike is like a giant spark, generated when electrons ‘jump’ from the ground to the positively charged clouds.

Electron emission *with a Purpose*

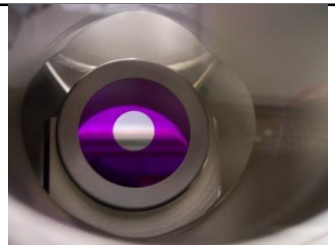
- Electron emission is the process in which electrons bound in a solid, are released and leave the surface of the solid.

- The process is statistical, as only those electrons with sufficient momentum component normal to the surface may overcome the surface barrier potential.

Why do accelerators need a particle source?

- Before being accelerated, the particles need to be generated first.
- Particles can be protons, ions, positrons, electrons, etcetera, depending on the specific accelerator application.
- The generation, or extraction mechanism, will depend on the desired type of particle and on the required beam characteristics.

Four essential ingredients are required to generate an electron beam

The cathode, a material from which the electrons are extracted.	 
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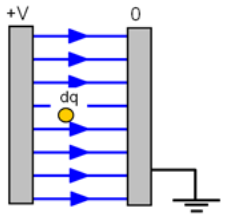
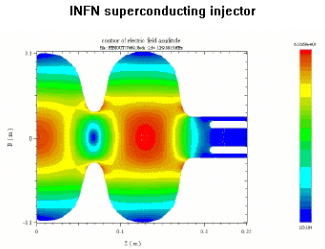
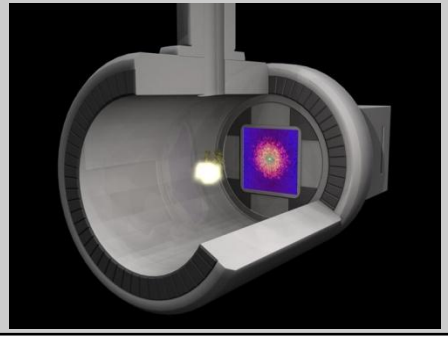
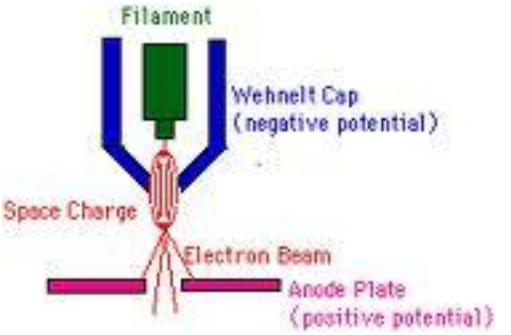
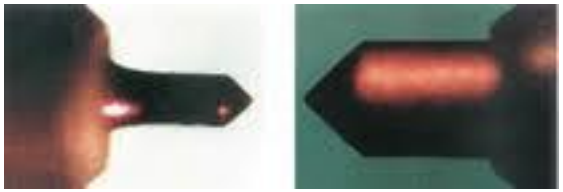
An accelerating electric field to form a collimated beam (DC or oscillating) and overcome mutual Coulomb repulsion.	 
A vacuum environment to prevent electron scattering by gas molecules and to preserve cathode chemistry	

Electron microscopes

- In devices such as electron microscopes the electron beam is only a few uA of direct current (DC), emitted with very little spread (emittance) at ~100 keV.
- Field emission from sharp (nm-size radius) metal needle cathodes is a typical choice, although many lower voltage devices (lower resolution) use thermionic cathodes.
- Required field at the tip for emission are in the order of Giga-Volts per meter.
- Tips are susceptible to contaminants (Carbon) and are easily damaged by over-current.



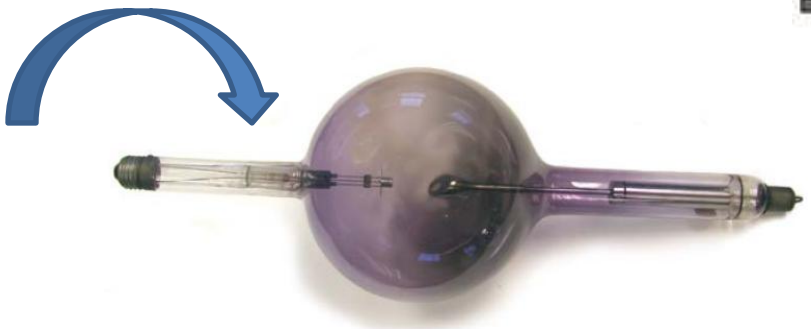


X-ray sources

Used to make x-ray light….

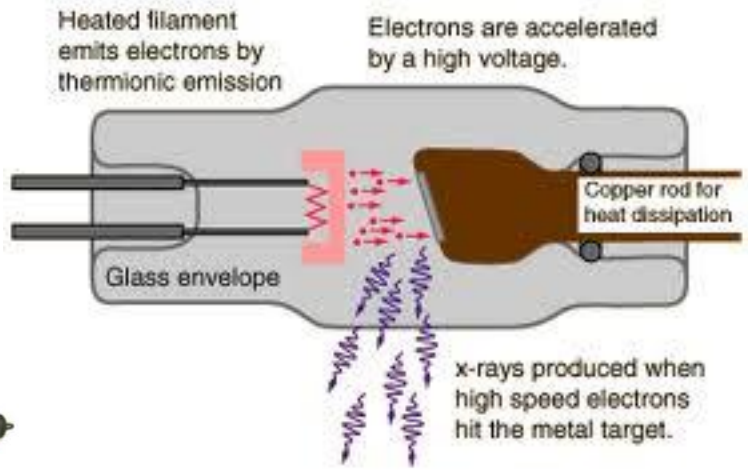
1880s

bias at high voltage

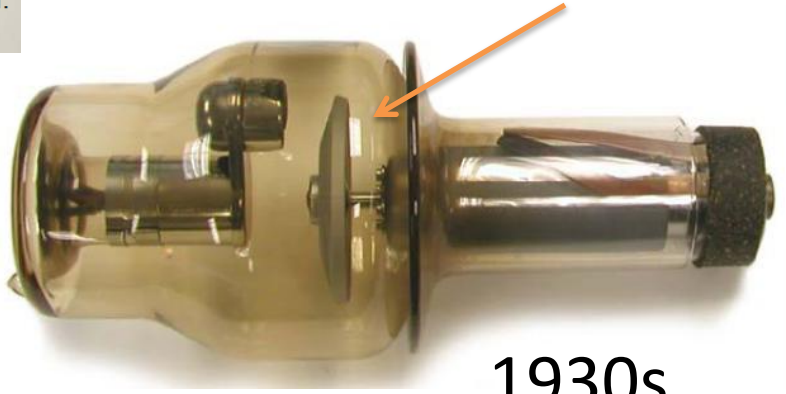


In 1913, William Coolidge invented an x-ray tube with high vacuum, a heated filament as electron source, and an x-ray producing anode. The tube, shown here, was produced in the 1920s by General Electric Corporation.

Photo: www.orau.org Oak Ridge Associated Universities



Rotating anode to distribute heat



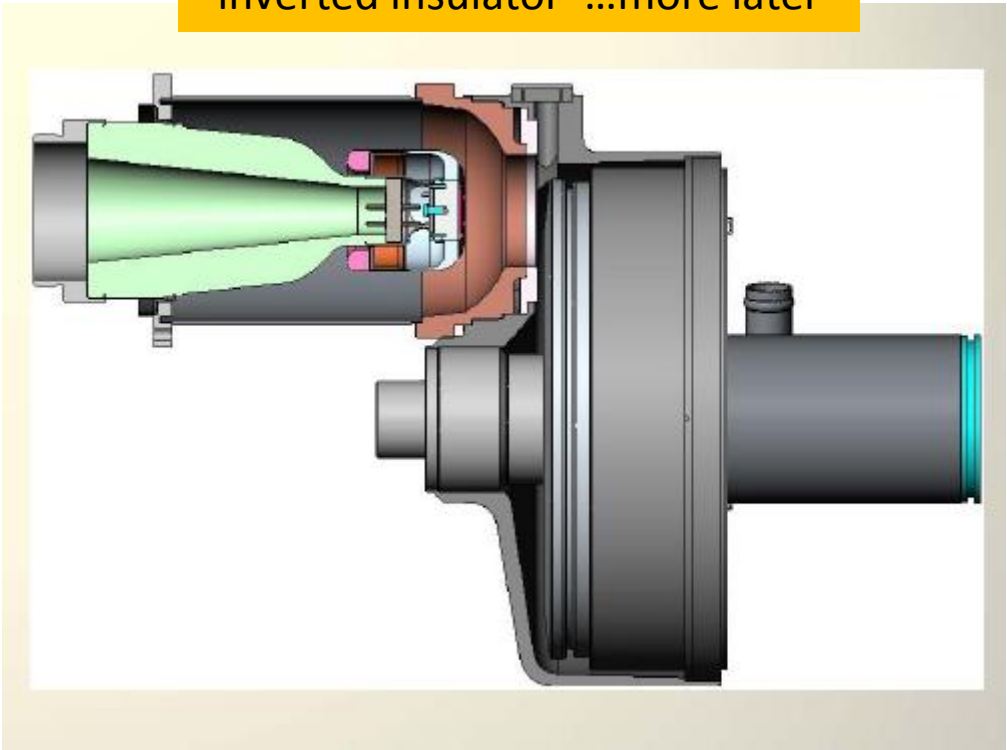
1930s

X-rays are generated when a DC electron beam, typically a few mA, strikes a tungsten target at 60-200 keV. e-Beam quality is not a big concern

Modern X-Ray Sources

Higher e-beam current…..
Higher x-ray flux

"inverted insulator"…more later

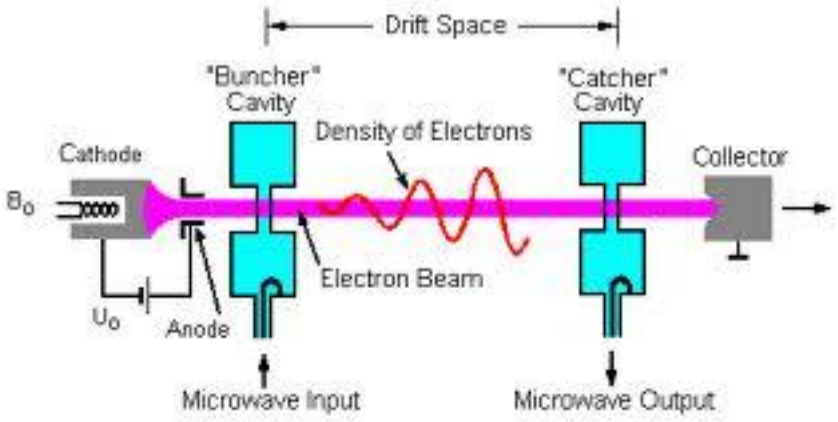


Higher Voltage….
More penetrating
x-ray beam

Courtesy Varian

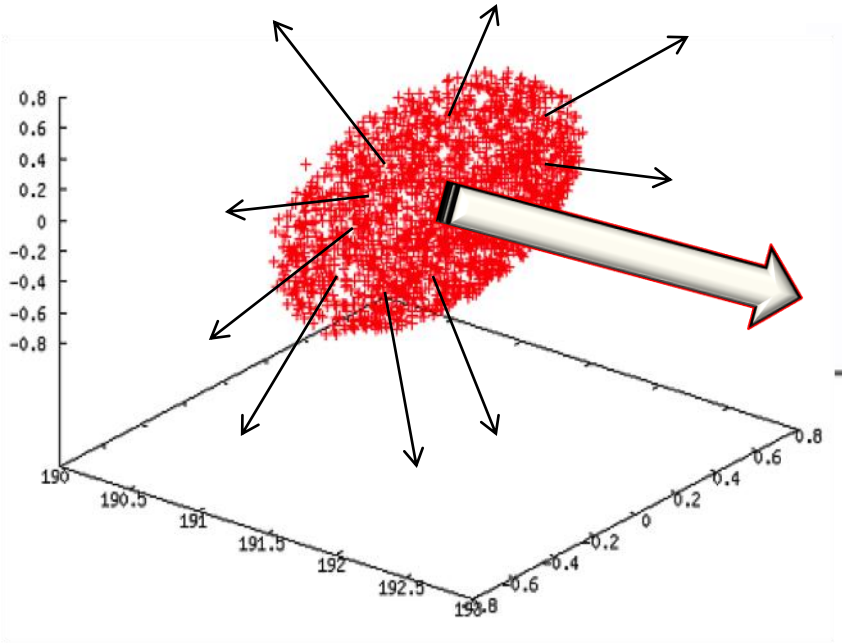
Klystrons—microwave generators

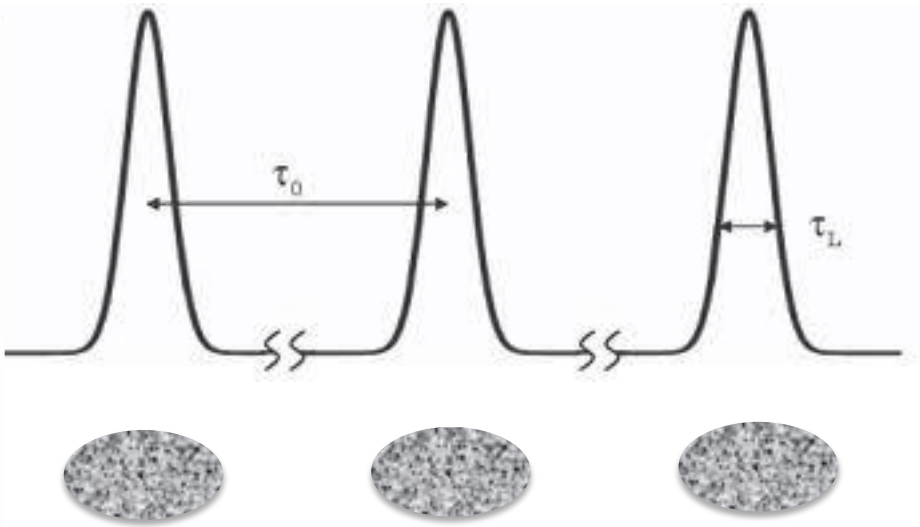
- Klystrons use a DC electron beam at a few mA to generate/amplify microwaves by velocity modulation.
- Klystrons use thermionic cathodes to generate the required electron beam.



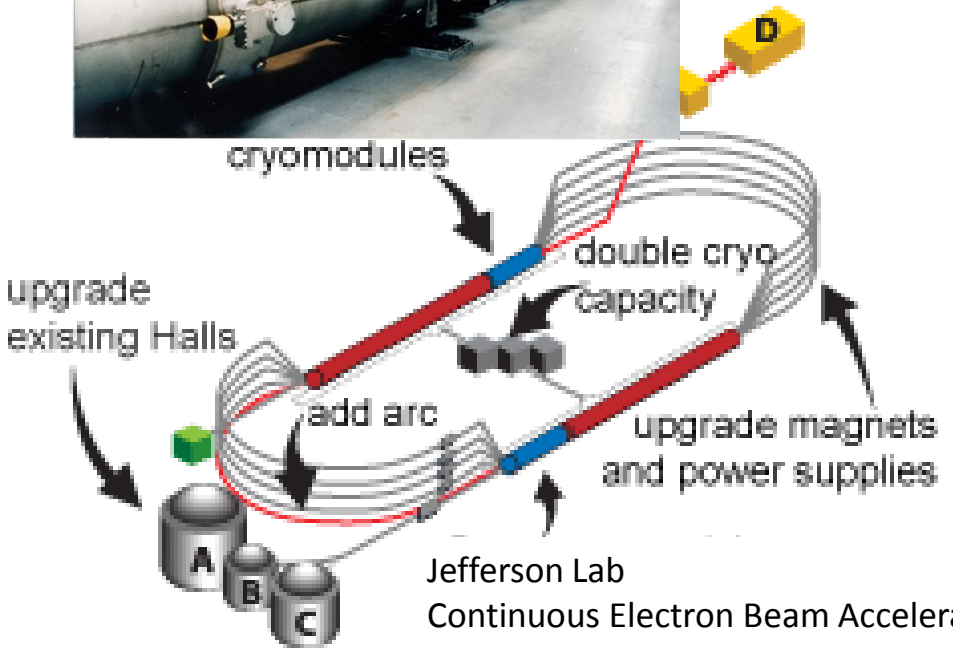
When electron beams need to be generated in pulses for accelerators

- The given examples so far use DC electron beams
- Most electron accelerators require the beam to be comprised of a train of electron pulses. In each pulse, there is a certain number of electrons with collective charge in the range of a few pC to a few nC. Each group of electrons is called an electron bunch.
- The rate at which the electron bunches are generated is called the pulse repetition rate.

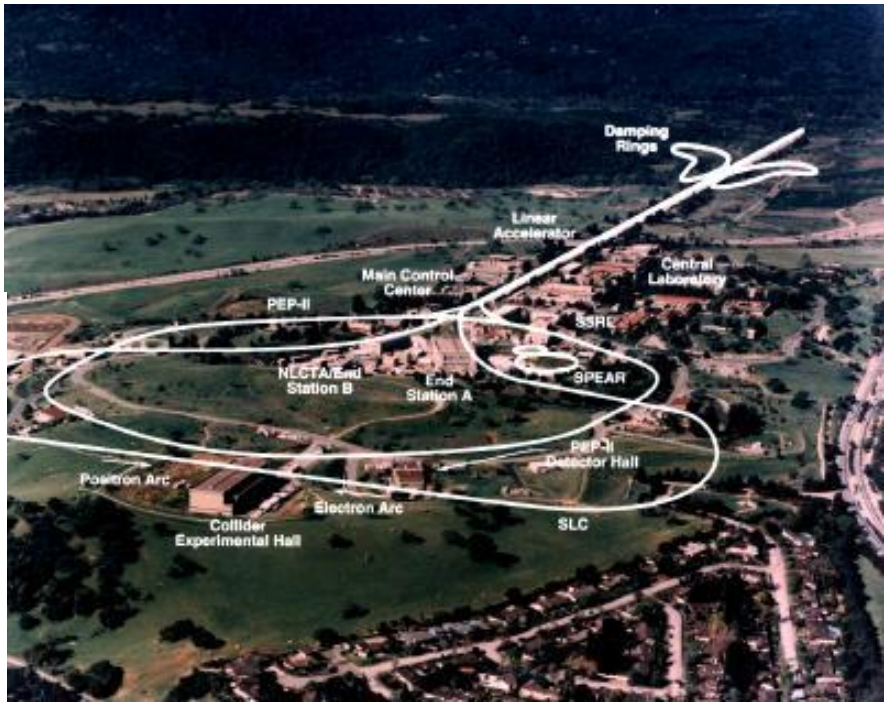




As a point-like probe in the form of *Polarized* electrons for High Energy and Nuclear Physics research



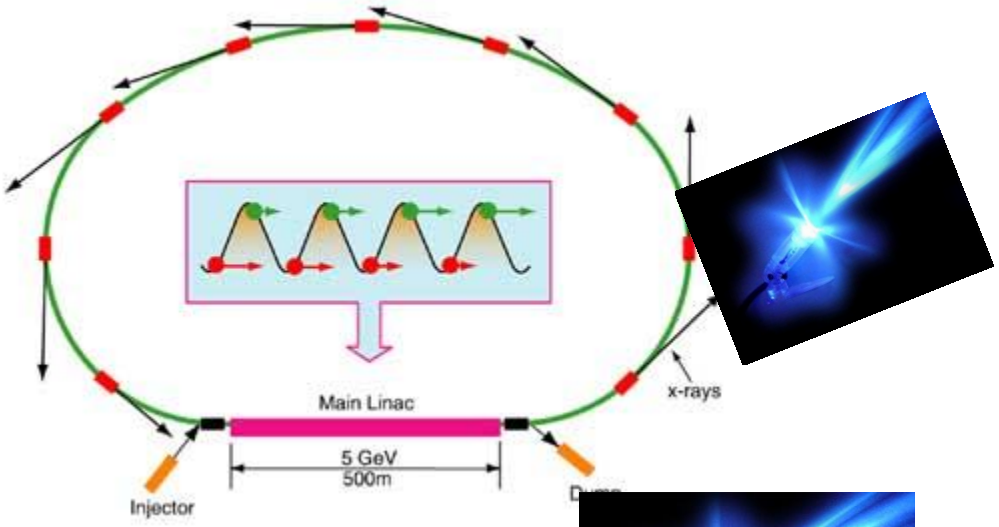
Jefferson Lab
Continuous Electron Beam Accelerator Facility

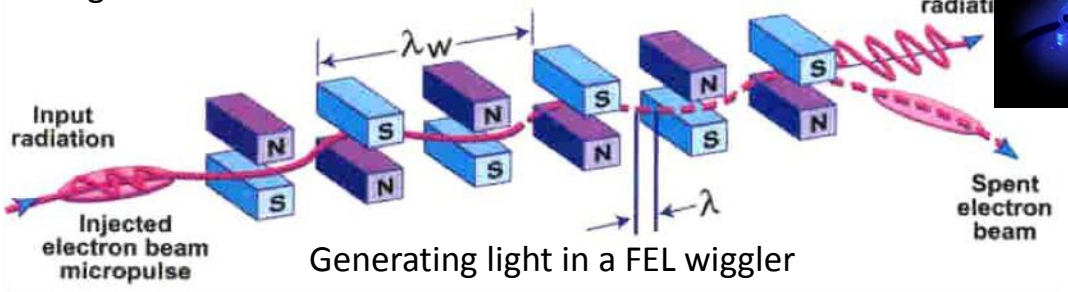


Stanford Linear Accelerator

As a source in the form of *Un-polarized* electrons for producing IR to X-ray photons in machines like Storage Rings, Synchrotrons and Free Electron Lasers

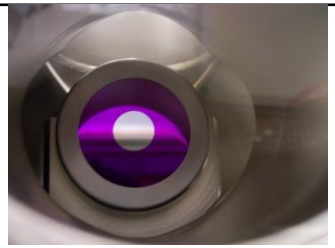
Argonne National Lab
Synchrotron light source





Generating light in a FEL wiggler

Four essential ingredients are required to generate an electron beam

The cathode, a material from which the electrons are extracted.	 
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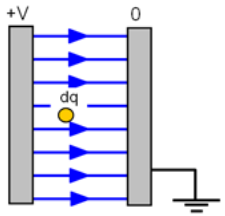
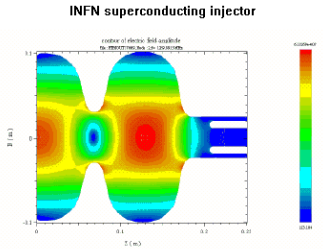
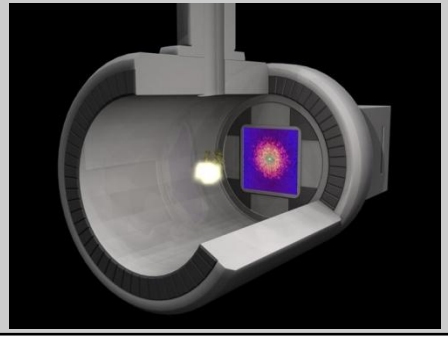
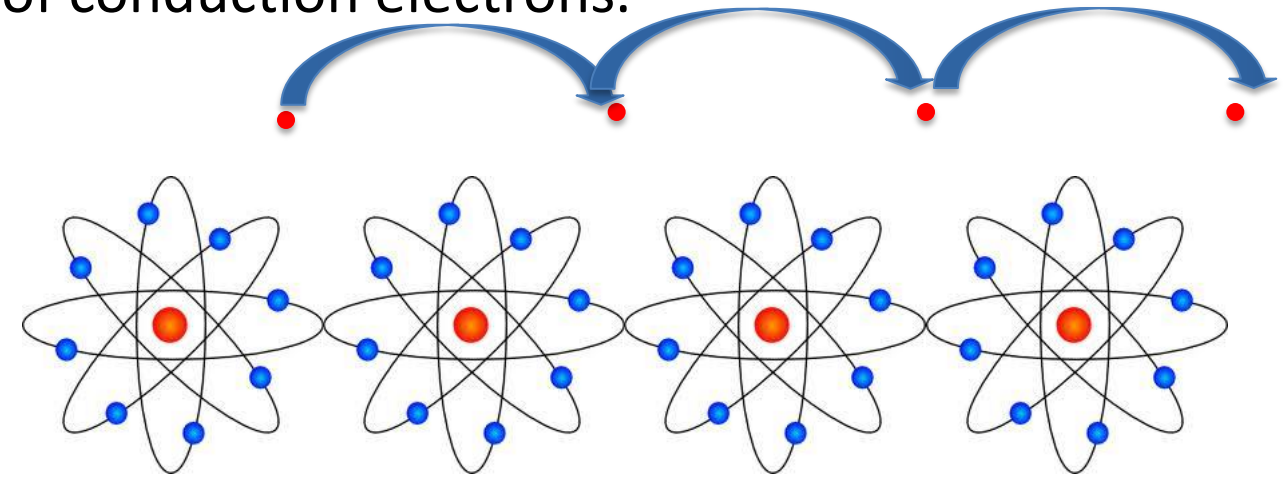
An accelerating electric field to form a collimated beam (DC or oscillating) and overcome mutual Coulomb repulsion.	 
A vacuum environment to prevent electron scattering by gas molecules and to preserve cathode chemistry	

Electron emission from metals

- In metals, electrons in the outer atom shells are not bound to a particular atom, rather they are in continuous motion "hopping" from atom to atom, but still bound to the metal surface.
- In some sense the electron can be considered as a "Free Electron Gas" in which the atomic cores are immersed in a sea of conduction electrons.



Why metals reflect light so well?

The free electron Fermi gas

- The Fermi energy is defined as the energy of the topmost filled level in the ground state of the N electron system, at absolute zero.

$$E_F = \frac{\mathrm{h}^2}{2m}\left(3\pi^2 N_e\right)^{2/3}$$

- What happens when the temperature is increased? The Fermi-Dirac distribution gives the probability that an electron state of energy E will be occupied at thermal equilibrium with temperature T.

$$f(E,T) = \frac{1}{1+\exp\left[\dfrac{(E-E_F)}{k_B T}\right]}$$

The free electron Fermi gas

- The density of states describes the distribution of possible states in the solid per unit volume:

$$\rho(E) = \frac{1}{2\pi^2}\left(\frac{2m}{\mathrm{h}^2}\right)^{3/2} E^{1/2}$$

- The number of electrons per unit volume, which is the baseline for calculating electron emission.

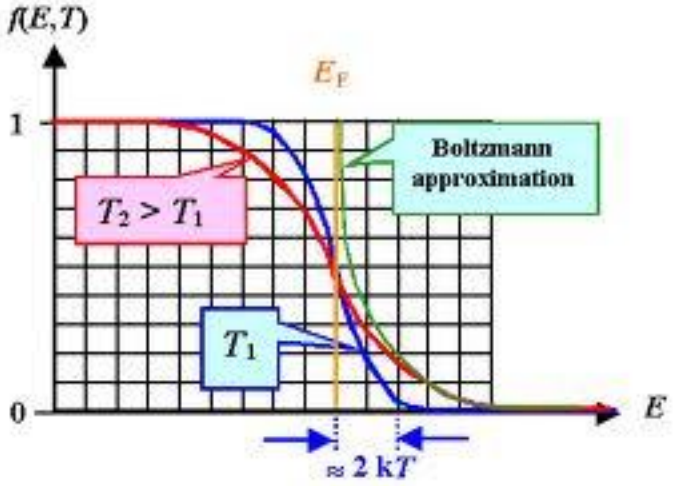
$$N_e = \int_0^\infty \rho(E) f(E,T) dE$$

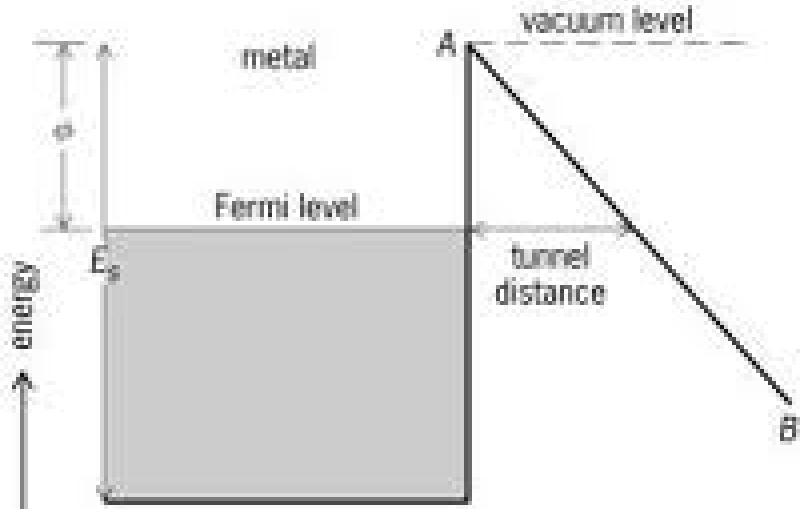
The free electron Fermi gas

As the temperature is increased, more and more electrons gain energies higher than the Fermi energy and higher probability to escape into the vacuum level.

The vacuum level is defined as the distance at which an electron is sufficiently far from the metal surface that its image charge is negligible (more than 100 Angstroms)

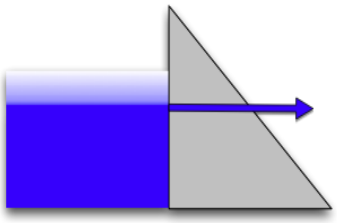
The work function Φ is defined as the difference in potential energy of an electron between the vacuum level and the Fermi level.





The canonical emission equations

(slide courtesy of Dr. K. Jensen, Naval Research Laboratory)

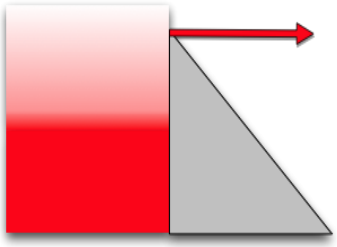


- **Field Emission**

  Fowler nordheim

  E.L. Murphy, and R.H. Good,
  Physical Review 102, 1464 (1956).

$$J_{FN}(F) = A_{FN} F^2 \exp\left(-\frac{B\Phi^{3/2}}{F}\right)$$

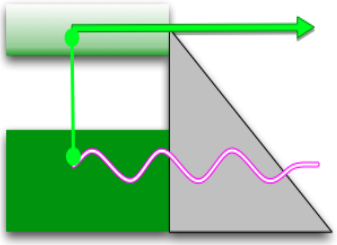


- **Thermal emission**

  Richardson-Laue-Dushman

  C. Herring, and M. Nichols,
  Reviews of Modern Physics 21, 185
  (1949).

$$J_{RLD}(T) = A_{RLD} T^2 \exp\left(-\frac{\Phi}{k_B T}\right)$$



- **Photoemission**

  Fowler-Dubridge

  L.A. DuBridge
  Physical Review 43, 0727 (1933).

$$J_{MFD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_\lambda(\omega)\{\hbar\omega - \Phi\}^2 I_\lambda$$

Listed chronologically

Field Emission

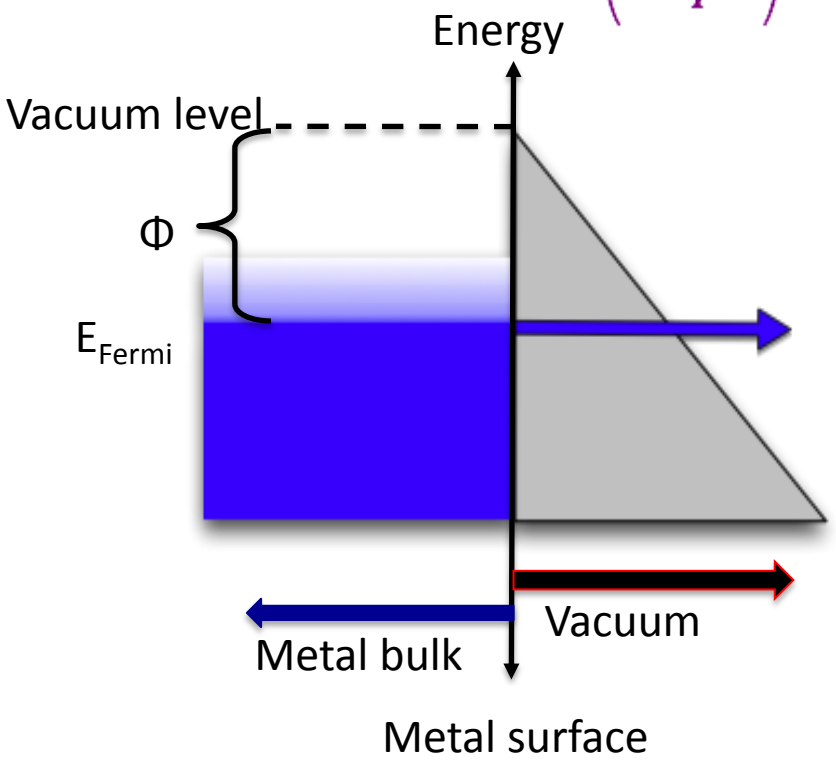
High field and low temperature

Fowler-Nordheim

E.L. Murphy, and R.H. Good, Physical Review 102, 1464 (1956).

- In Field Emission, the electrostatic field (F) at the metal surface is so high it thins the potential barrier.
- Electrons with energies below the Fermi level with momentum component perpendicular to the metal surface have then a finite probability to tunnel through the thinned potential barrier, with current density J(F).
- Field Emission occurs when the field is >1 GV/m, typically in sub-micron size metallic tips.

$$J_{FN}(F) = A_{FN} F^2 \exp\left(-\frac{B\Phi^{3/2}}{F}\right)$$



Φ = Work function, ~4-5 eV

Thermal Emission

High temperature and low field

Richardson-Laue-Dushman

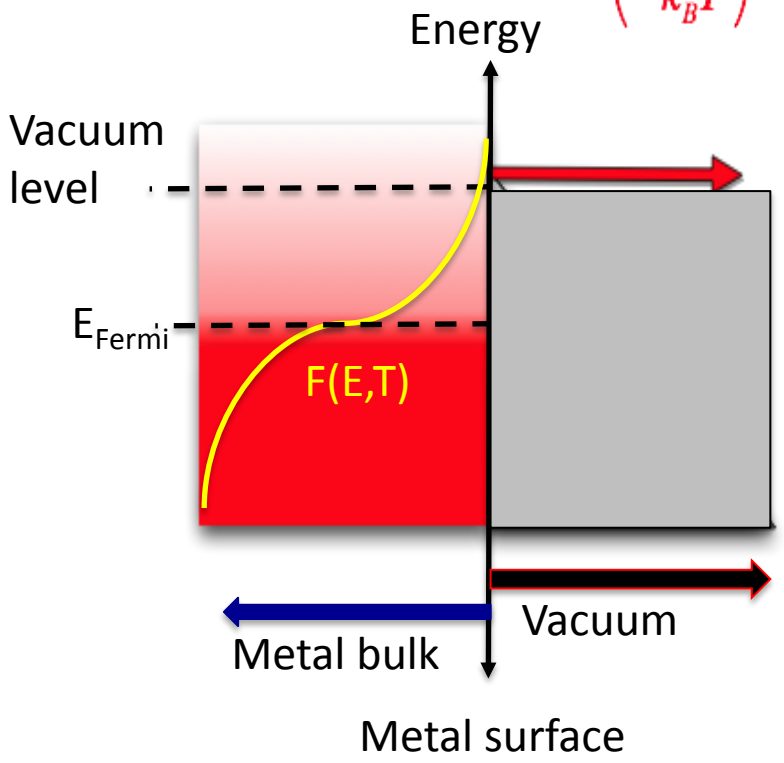
C. Herring, and M. Nichols, Reviews of Modern Physics 21, 185 (1949).

- In thermal emission, electrons gain sufficient thermal energy to overcome the vacuum level. Those electrons with momentum component perpendicular to the metal surface have a finite probability of being emitted with current density J(T).
- In thermionic emission, application of an external field lowers the metal work function. This is known as the Schottky enhancement factor.

$$\phi_{effective} = \phi_{metal} - \phi_{Schottky}$$

$$\phi_{Schottky} = e\sqrt{\frac{eE_{applied}}{4\pi\varepsilon_0}}$$

$$J_{RLD}(T) = A_{RLD}T^2 \exp\left(-\frac{\Phi}{k_B T}\right)$$



Φ = Work function, ~4-5 eV

Photoemission

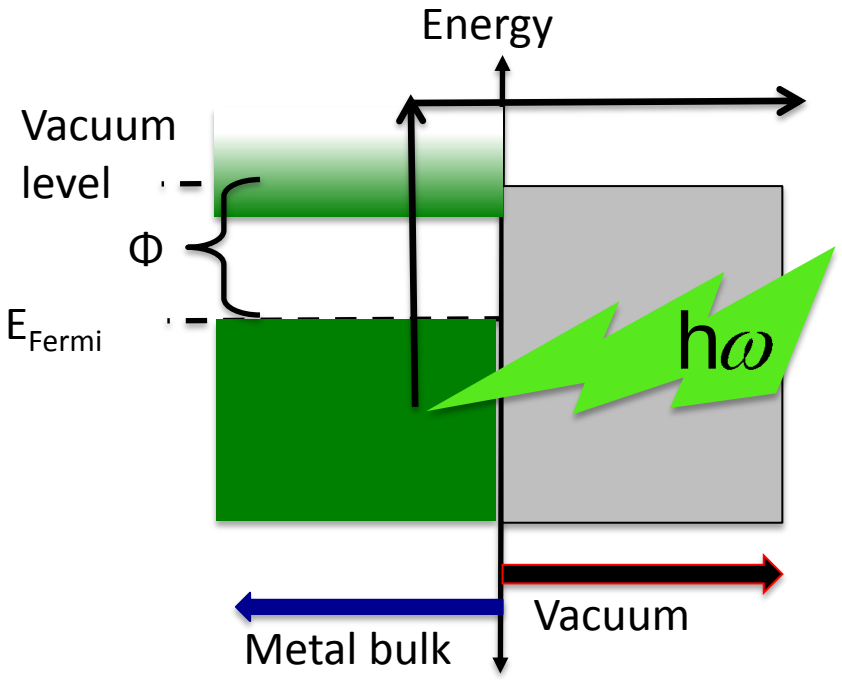
Low temperature and low field

Fowler-Dubridge

L.A. DuBridge, Physical Review 43, 0727 (1933).

- Photoemission occurs in metals when the incident photon energy exceeds the work function.
- The current density J depends on the photon flux, absorption and wavelength, as well as scattering and emission probability mechanisms.
- Photoemission is a three step process

$$J_{MFD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_{\lambda}(\omega)\{\hbar\omega - \Phi\}^2 I_{\lambda}$$



Metal surface

Φ = Work function, ~4-5 eV

hω Photon energy in eV

Photoemission from intrinsic semiconductors

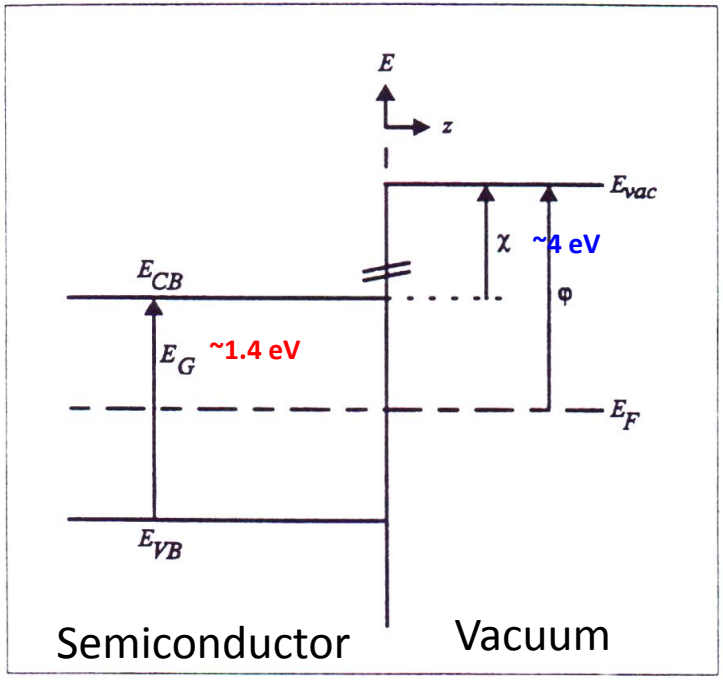
E_{VB} = Valence band

E_{CB} = Conduction band

E_{vac} = Vacuum level

E_F = Fermi level

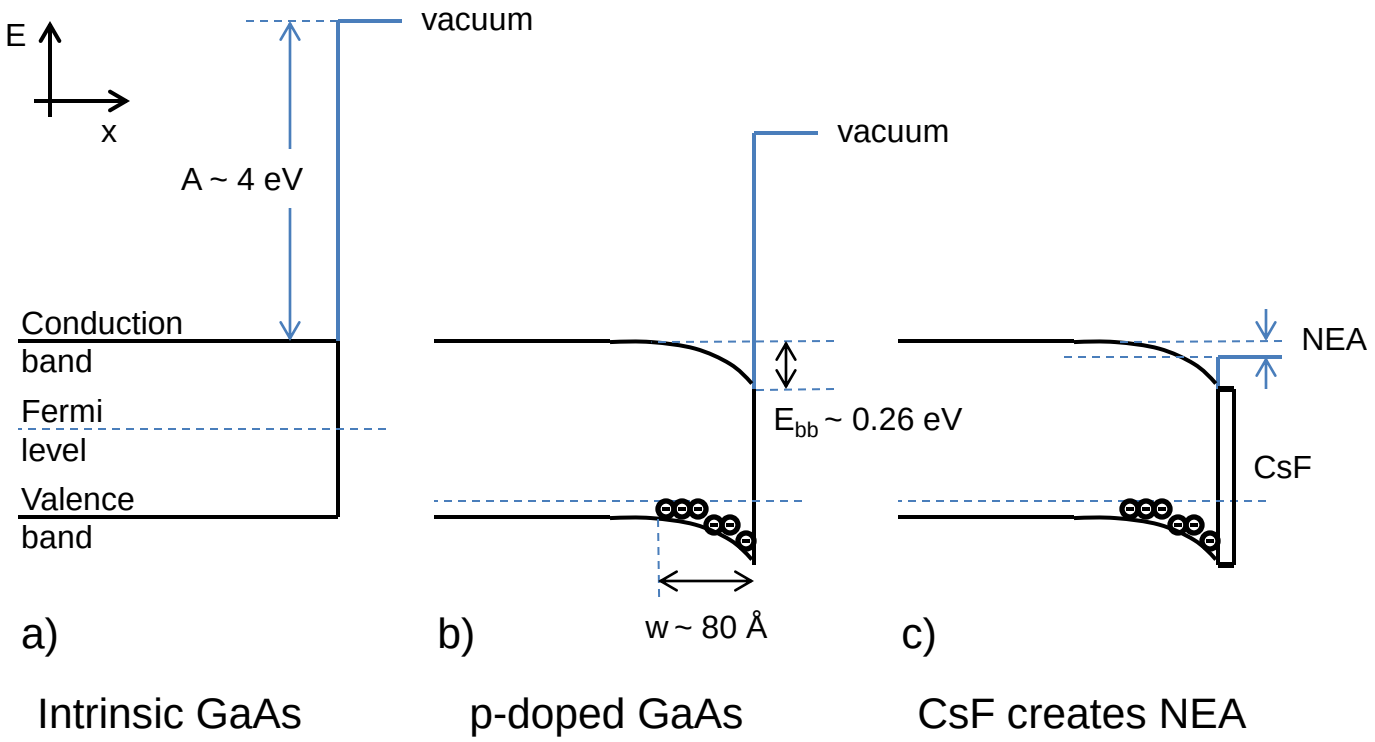
χ = Electron affinity, typically around 4 eV



$\chi = E_{Vac} - E_{CB}$ Electron affinity ~ 4 eV for GaAs

$\phi = E_{Vac} - E_F$ *Work function*

Reducing the Work Function



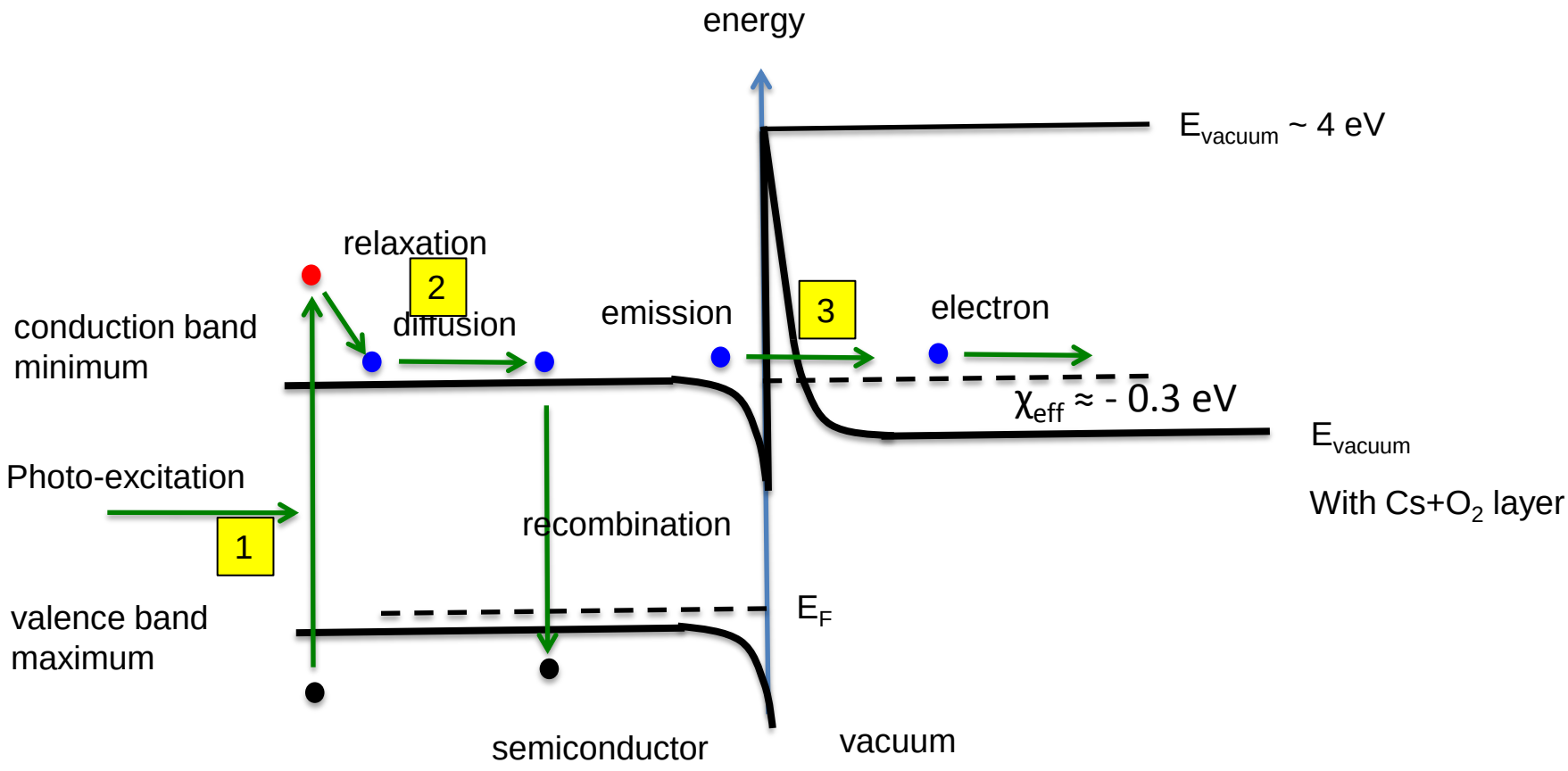
Doping adds additional energy states in the gap, adjusting the Fermi level in the bulk, pulling E_c , E_v and vacuum level at surface (forming so-called band bending region)…

The three components of Photoemission process (Spicer model, 1958)

(slide courtesy of Dr. K. Jensen, Naval Research Laboratory)

1. **Absorption** of light in bulk material and photo-excitation of electrons.
   - Light intensity and wavelength (photon energy)
   - Material reflectivity
   - Light penetration depth
2. **Transport** of photo-excited electrons to the surface
   - Electron energy
   - Scattering rates (relaxation times)
3. **Emission** probability
   - For metals: Chemical potential and work function
   - For semiconductors: barrier height and band gap
     - Electron affinity measured from the conduction band minimum

Three step photoemission in NEA-GaAs (Spicer model, 1958)*

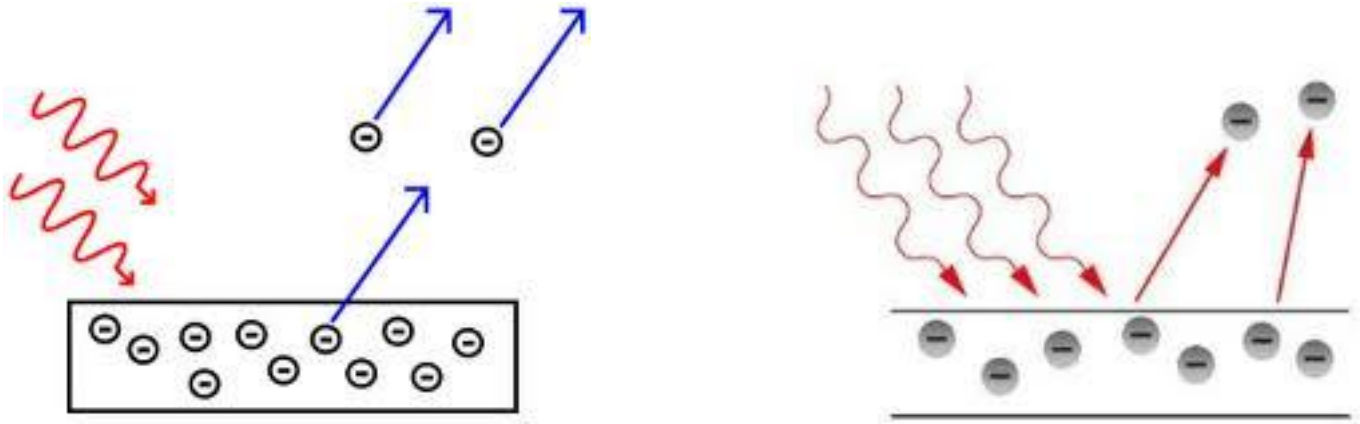


* Still not fully understood

Quantum Efficiency

- Generically the quantum efficiency is defined as the ratio of emitted electrons to incident photons.

$$QE = \frac{N_{electrons}}{N_{photons}}$$



Quantum Efficiency

(slide courtesy of Dr. K. Jensen, Naval Research Laboratory)

- In Metals, QE is dominated by the energy difference between the incident photon and the work function.

$$QE = (1 - R(\omega))F_{\omega}(\delta, \tau)\left[P(\mathrm{h}\omega) \propto (\mathrm{h}\omega - \phi)^2\right]$$

Modified Fowler-Dubridge Model for Metals

- In Semiconductors, QE is dominated by the energy difference between the incident photon and the band gap.

$$QE \approx \frac{B}{1 + g\left[\mathrm{h}\omega - (E_g + E_a)\right]^s}$$

Spicer's three Step Model for semiconductors

Eg = Energy gap between bottom of conduction band and top of valence band

Ea = Energy gap between bottom of conduction band and vacuum level. *This is the effective electron affinity*

B = escape X transport term

g = abosrption factor

s = semi-empirical, argued 3/2.

In practical terms, this is the QE equation

$$QE(\%) = \frac{124}{\lambda_{laser}} \cdot \frac{I}{P_{laser}}$$

λ = laser wavelength (nm)
P = (mW)
I = Photo-current (μA)
124 = Constant. Hint! Derive this constant.

QE is low in metals (<0.003%) because of electron-electron scattering in the conduction band

QE in semiconductors is typically 1-10% because scattering is between electrons and phonons, i.e. electrons thermalize with the lattice

Practicalities

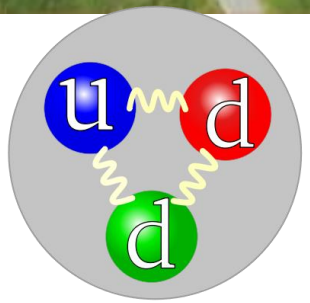
- The choice of a particular emission mechanism and associated cathode is mainly driven by the electron beam requirements, specified by the device/accelerator, and by the technical constraints of the electron source as a whole system.
- There is no single source that can meet the requirements for all applications.
- Let’s explore an electron source of a particle accelerator.

Jefferson Lab

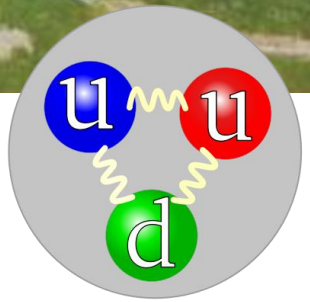
Thomas Jefferson National Accelerator Facility

Exploring the Nature of Matter

Electron



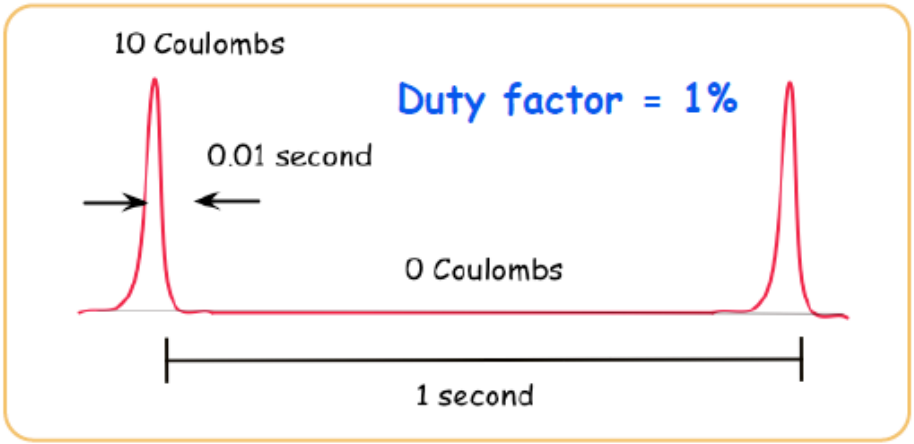
Neutron



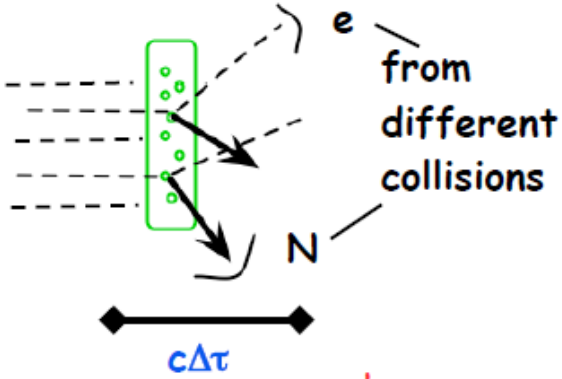
Proton

The “C” in CEBAF

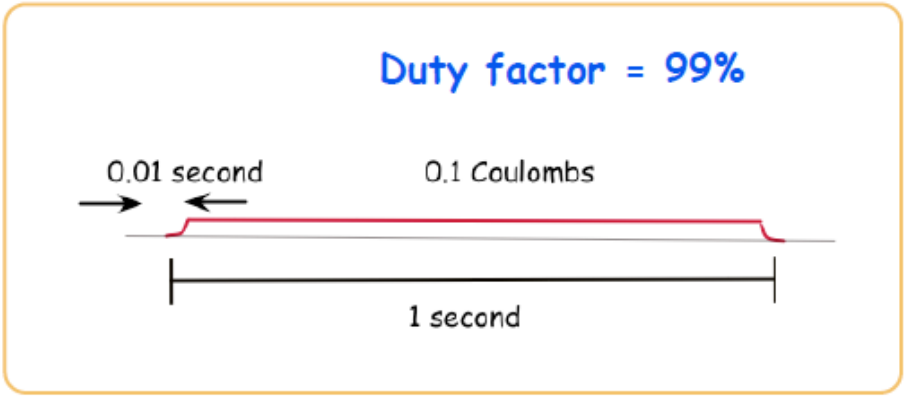
★ Pulsed beams used prior to 1980 (100 mA)



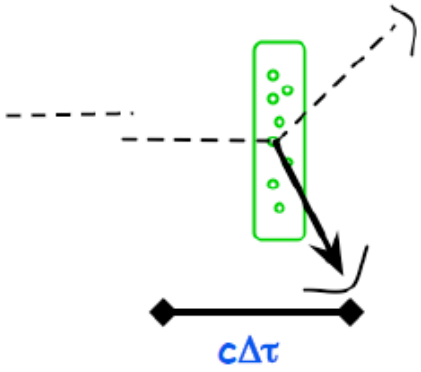
too many electrons in the target over the time interval $\Delta\tau$
lots of random coincidences



★ Advantages of a continuous beam with the same average current

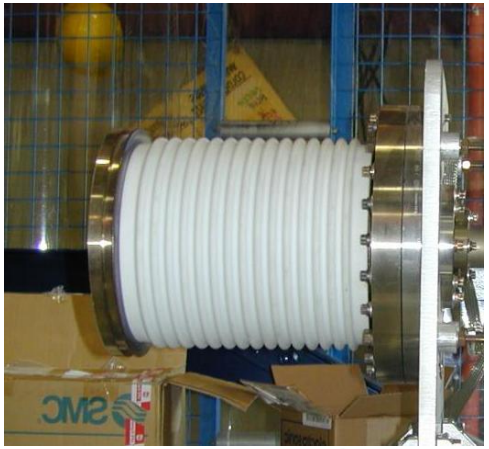


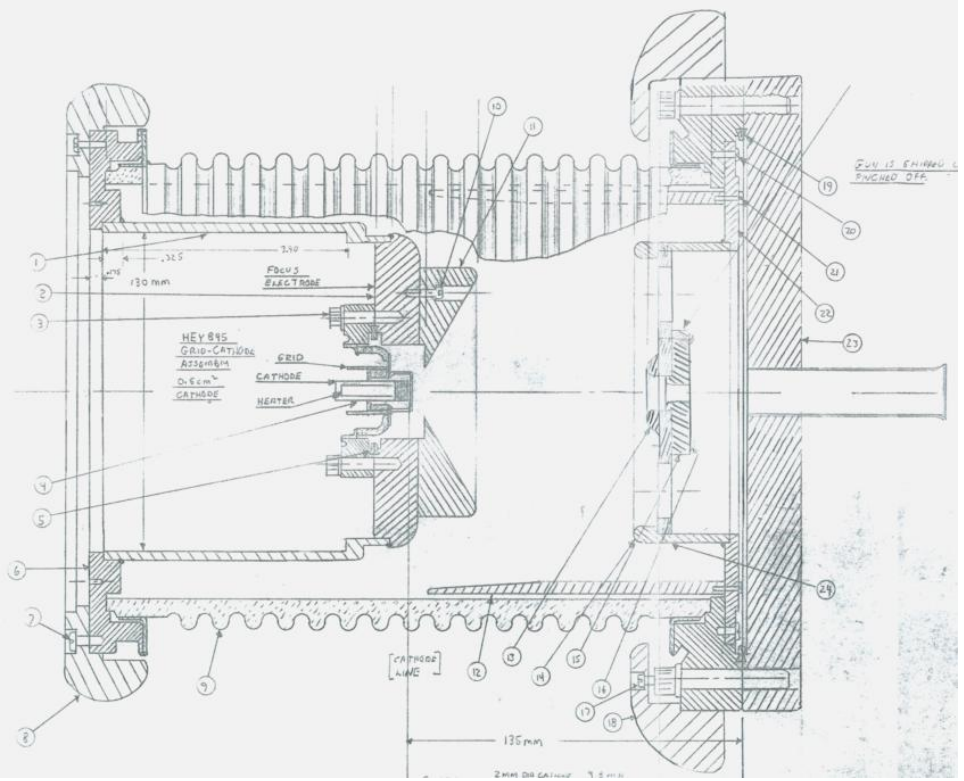
few electrons in the target -- few random coincidences



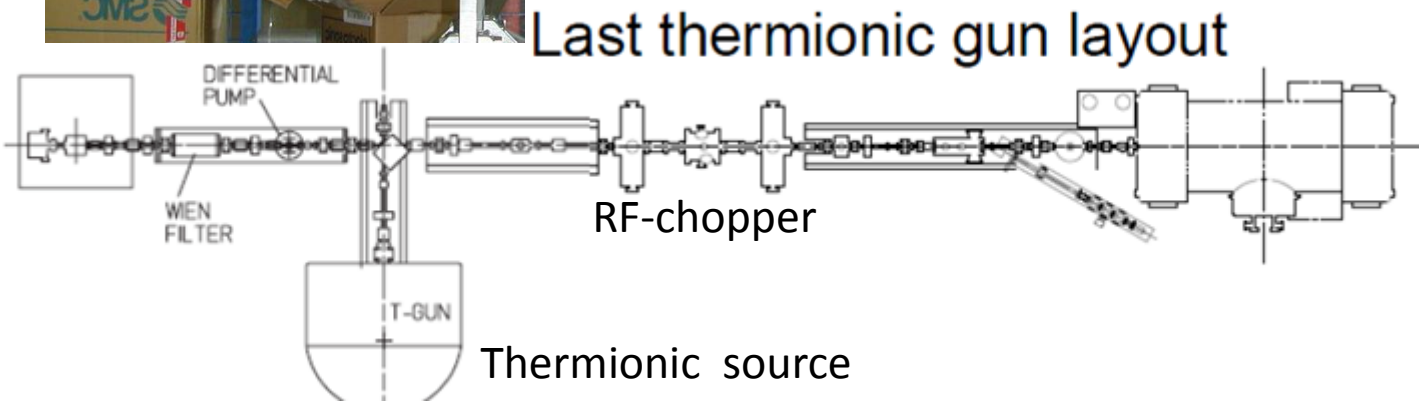
CEBAF's First Electron Source

- Make beam by running current through the filament biased at 100kV
- Use "grid" to turn beam ON/OFF, i.e., create machine-safe macropulses
- Apertures to improve emittance
- Use RF "chopper" to create RF structure





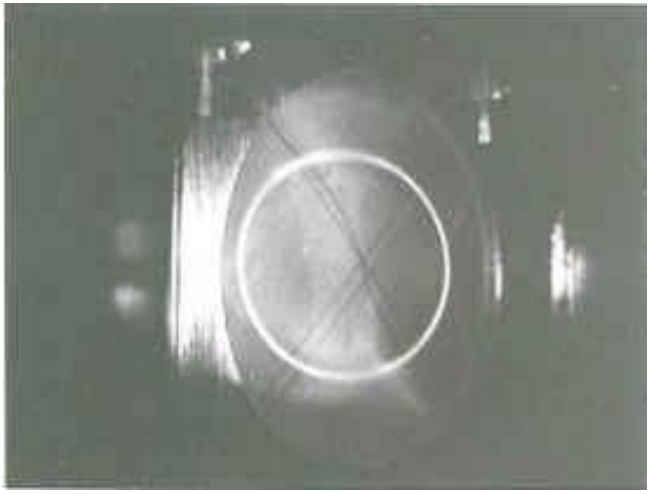
Polarized GaAs photosource



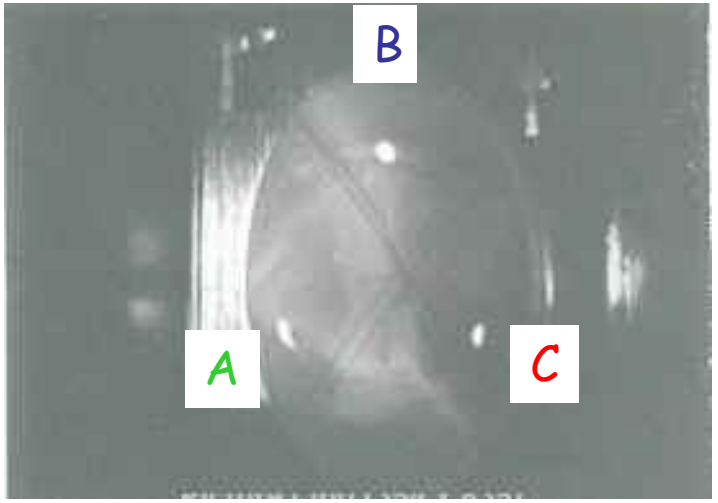
Thermionic source

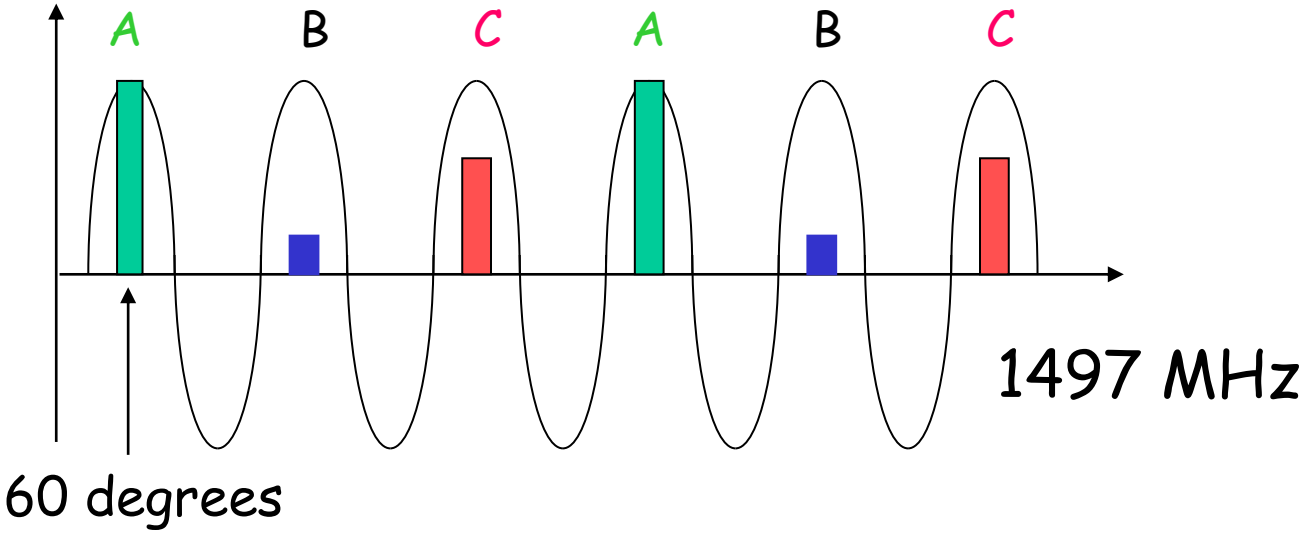
Photo Finish, but at 2 billionths of a second !!!

DC beam, not so useful for RF acceleration

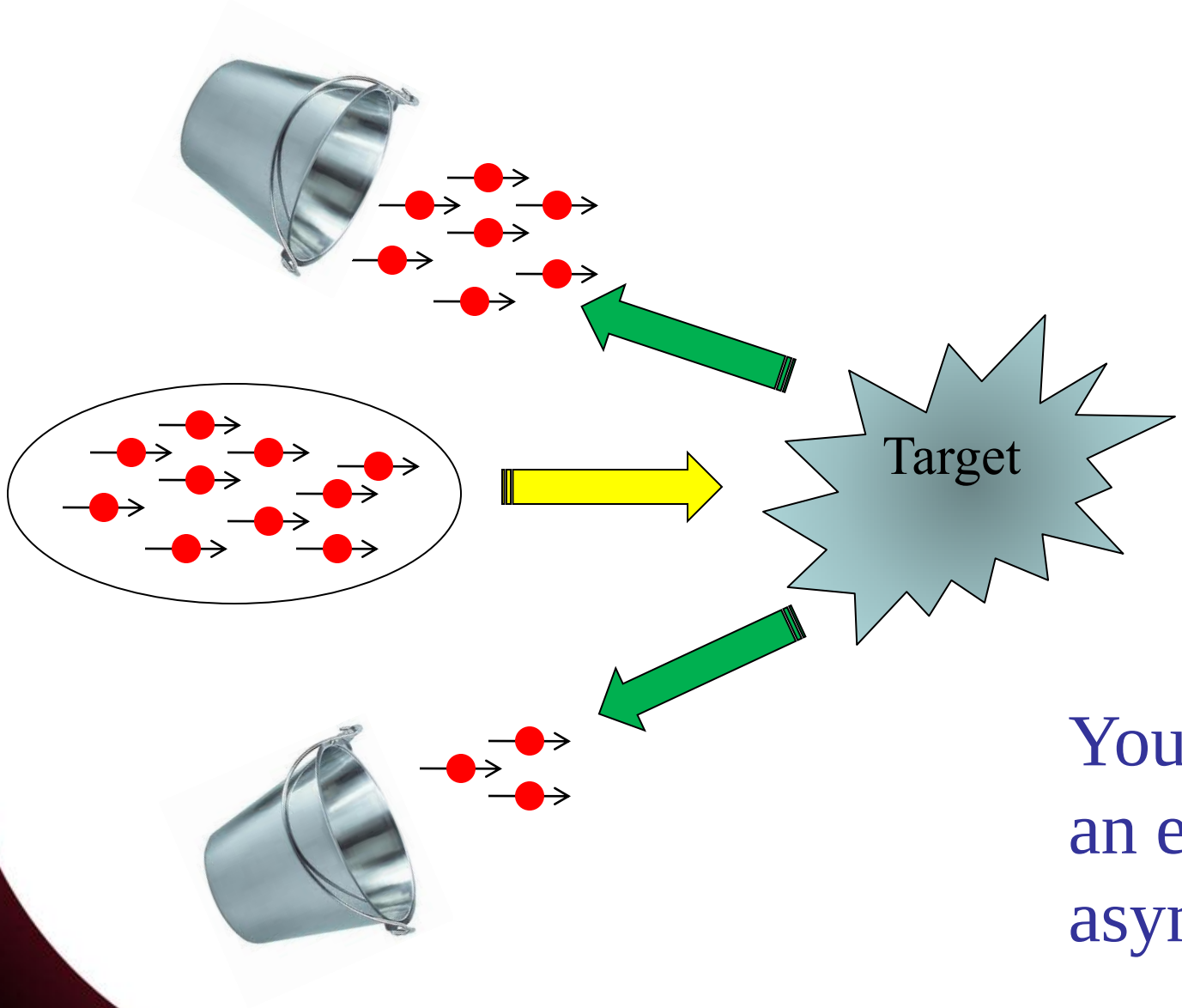


Beam of Bunches!





What about the probing with spin ?



You measure an experimental asymmetry

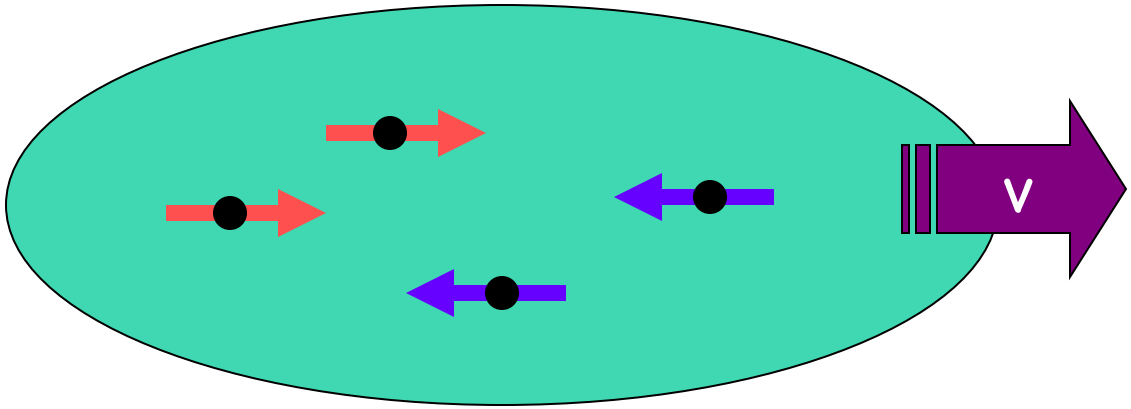
Electron Bunch Spin & Polarization

People with very different opinions

Light: a preference for the electric field vector to be oriented a certain way

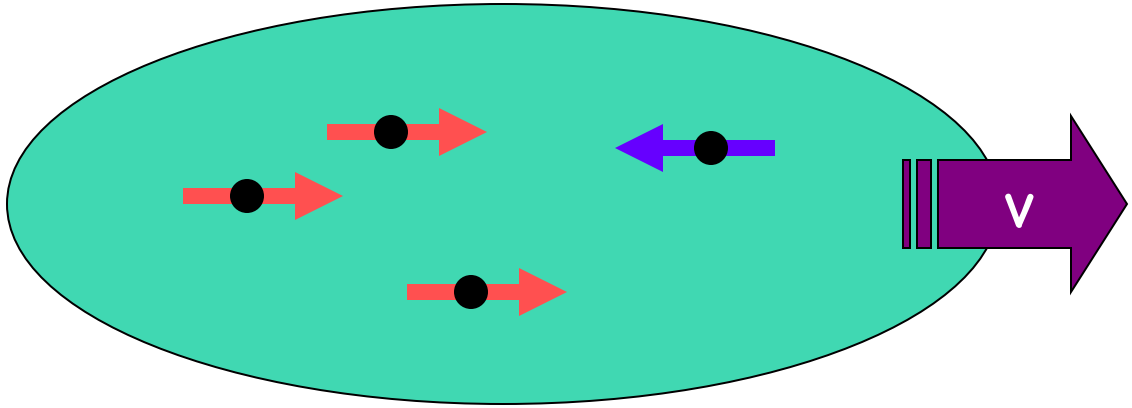
Electrons: a preference for electrons to spin in one direction

$$P_e = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



0% Polarization

☹



50% Polarization

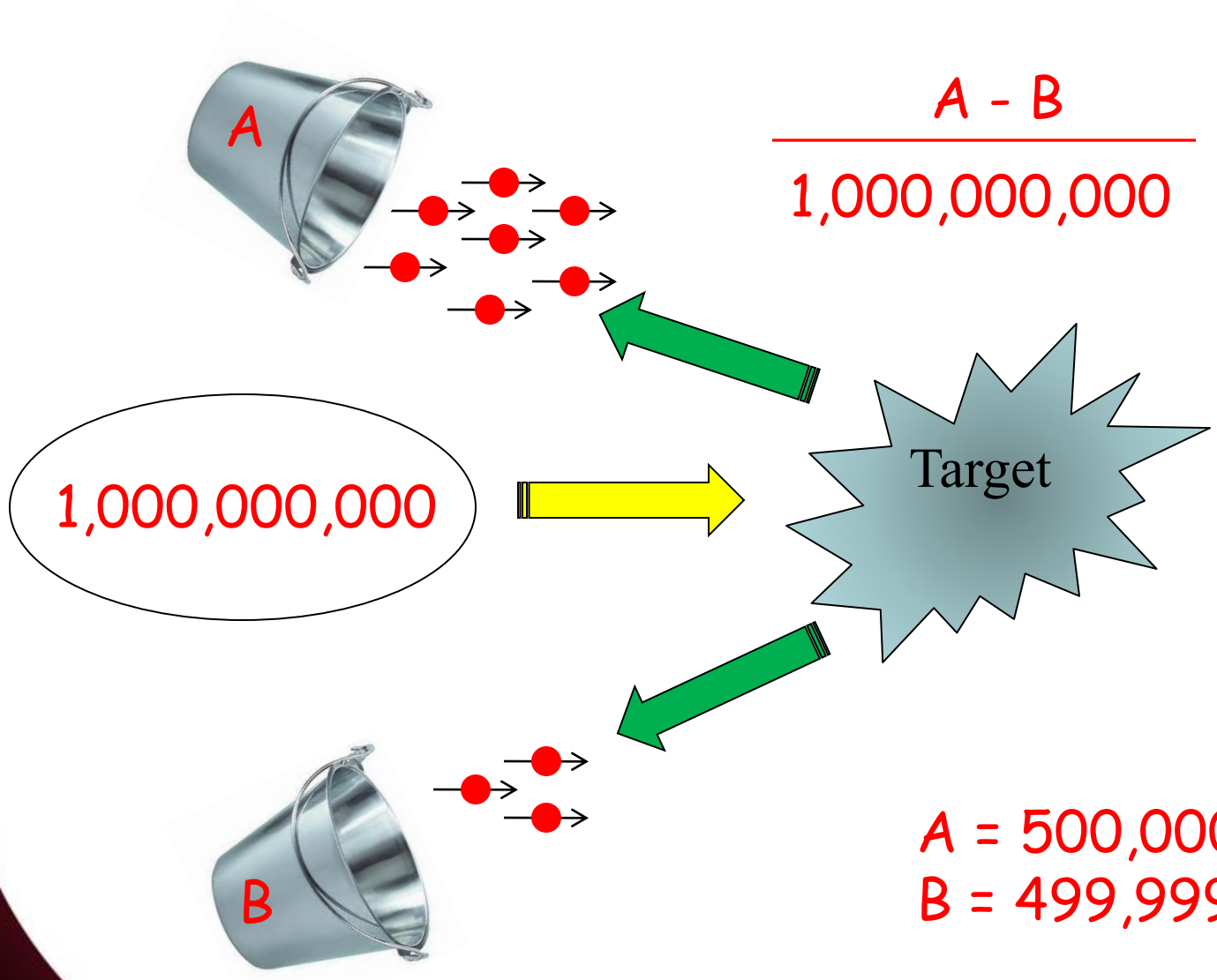
☺

Parity Violation Experiments at CEBAF

Experiment	Energy (GeV)	I (μA)	Target	A_{pv} (ppb)	Maximum Charge Asym (ppb)	Maximum Position Diff (nm)	Maximum Angle Diff (nrad)	Maximum Size Diff (δσ/σ)
HAPPEx-II (Achieved)	3.0	55	^{1}H (20 cm)	1400	400	1	0.2	Was not specified
HAPPEx-III (Achieved)	3.484	100	^{1}H (25 cm)	16900	200±100	3±3	0.5±0.1	10^{-3}
PREx	1.063	70	^{208}Pb (0.5 mm)	500	100±10	2±1	0.3±0.1	10^{-4}
QWeak	1.162	180	^{1}H (35 cm)	234	100±10	2±1	30±3	10^{-4}
Møller	11.0	75	^{1}H (150 cm)	35.6	10±10	0.5±0.5	0.05±0.05	10^{-4}

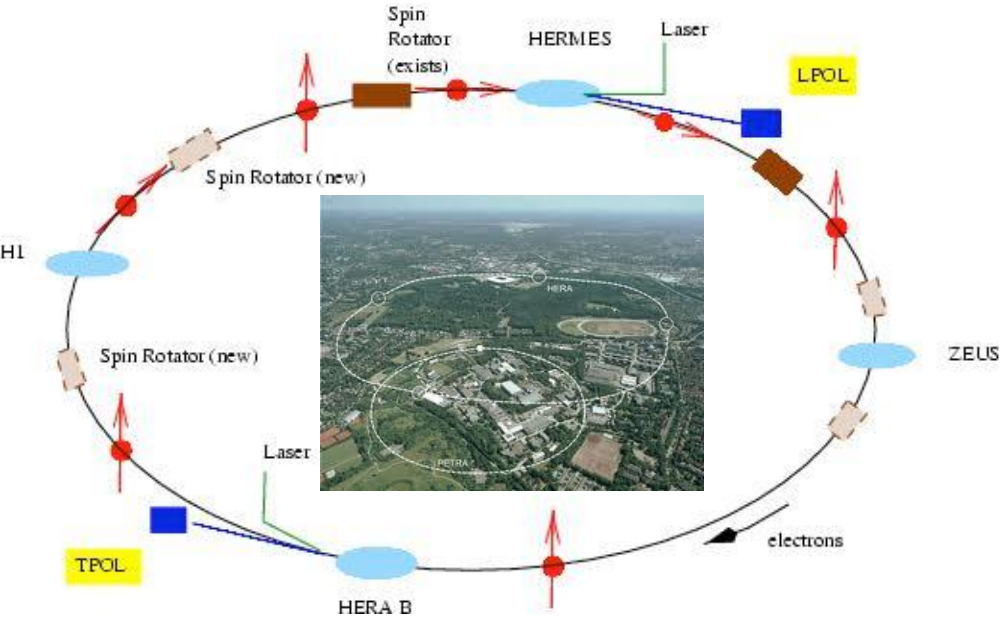
PV experiments motivate polarized e-source R&D

What does “234 ppb” even mean?



Self-Polarization: Sokolov-Ternov Effect

- Electrons (positrons) self-polarize in storage rings due to spin-flip synchrotron radiation: one spin state dominates the other
- First observed @ VEPP-2 Ring at Budker Institute, Novosibirsk, 1971
- Requires spin rotation (Siberian Snake) to create longitudinal polarization at target & depolarizing resonances must be avoided
- Process is slow, need storage lifetime to be longer than self-polarization time & happy to end up with ~70% polarization



$$P_{ST} = \frac{\omega_{\uparrow\downarrow} - \omega_{\downarrow\uparrow}}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} = \frac{8}{5\sqrt{3}} \approx 92.4\%$$

$$P_Y(t) = -P_{ST}\left(1 - e^{-t/\tau_{ST}}\right)$$

$$\tau_{ST} = \frac{1}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} = \frac{8\rho^3}{5\sqrt{3}c\lambda_c r_0 \gamma^5}$$

~ 1 hour at HERA

What if you need a Direct Source of Polarized Electrons?

TABLE III. Comparison of some sources of spin-polarized electrons.

Method	Ref.	$\|P\|$	Reversal of $\vec{P}$	I_{dc} (A)	I_{pulse}	E (eV)	ΔE (eV)	H (kOe)	Emittance	Brightness
1. Photoemission from NEA GaAs	3	0.40	$\Delta\vec{L}$	10^{-6} [10^{-3}]	[10^{12} electrons/ 1.5 μsec]	0.2	0.2	0	2 mrad-cm at 1 eV	very high
2. Photoemission from EuO	27	0.61 [0.80]	$\Delta\vec{H}$	10^{-6}	3×10^{9} electrons/ 1.5 μsec	2	2	21 [30]		medium
3. Photoionization of polarized Li atomic beam	53	0.76	$\Delta\vec{H}$		3×10^{9} electrons/ 1.5 μsec		1500	0.2	7 mrad-cm at 70 keV	medium
4. Fano effect, photoionization of Cs atoms	55	0.90	$\Delta\vec{L}$		3×10^{9} electrons/ 0.5 μsec		500	0	0.6 mrad-cm at 115 keV	high
5. Optically pumped He discharge	56	0.30	$\Delta\vec{L}$	10^{-6}		500 [30]	0.5	0	10 mrad-cm at 500 eV	high
6. Field emission (EuS)	57	0.89	$\Delta\vec{H}$	[10^{-6}]			0.1	2–20		very high
7. Electron scattering from Hg atomic beam	58	0.27	$\Delta\theta$	2×10^{-8}		7	0.2	0		medium
8. Electron scattering from W	62	0.40	$\Delta\theta,\Delta E$	5×10^{-8} [10^{-4}]		80	0.2	0		high

GaAs….the method that caught on

PHYSICAL REVIEW B VOLUME 13, NUMBER 12 15 JUNE 1976

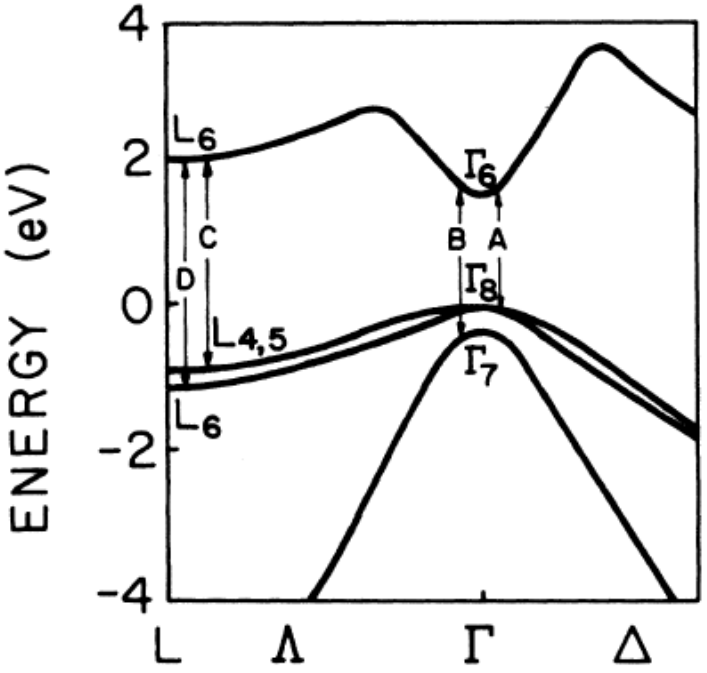
Photoemission of spin-polarized electrons from GaAs

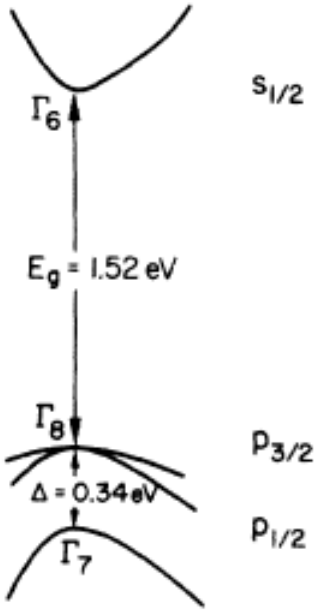
Daniel T. Pierce* and Felix Meier
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, CH 8049, Zürich, Switzerland
(Received 10 February 1976)

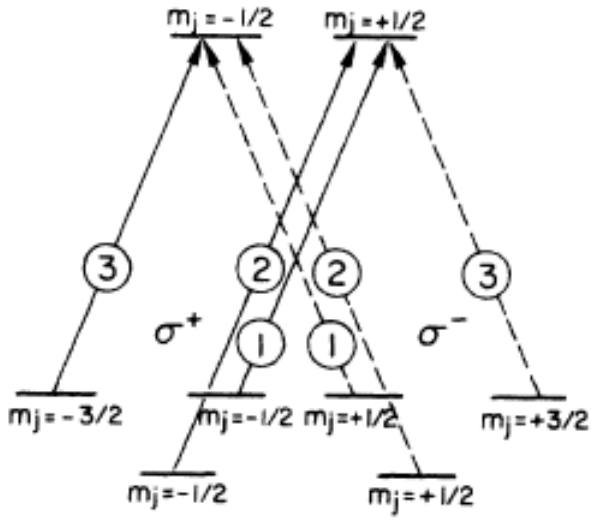
The spin polarization of electrons photoemitted from (110) GaAs by irradiating with circularly polarized light of energy $1.5 < \hbar\omega < 3.6$ eV was measured by Mott scattering. The GaAs surface was treated with cesium and oxygen to obtain a negative electron affinity (NEA). The spectrum of spin polarization $P(\hbar\omega)$ exhibits a peak ($P = 40\%$) at threshold arising from transitions at Γ, and positive ($P = 8\%$) and negative ($P = -8\%$) peaks at 3.0 and 3.2 eV, respectively, arising from transitions at L (Λ). Anomalous behavior, consisting of a depolarization at threshold and an increase and shift in the peak polarization to 54% at 1.7 eV, is attributed to a small positive electron affinity (PEA) characteristic of some samples. Restriction of the photoelectron emission angle by the PEA leads directly to the anomalously high P. Results of calculations show that P cannot be increased above 50% for emission arising from transitions at Γ in NEA GaAs. Our detailed interpretation of the spectra indicates how spin-polarized photoemission can be used to study the spin-dependent aspects of electronic structure. The outstanding qualities of NEA GaAs as a source of spin-polarized electrons are discussed and compared with other sources.

GaAs Energy Levels

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



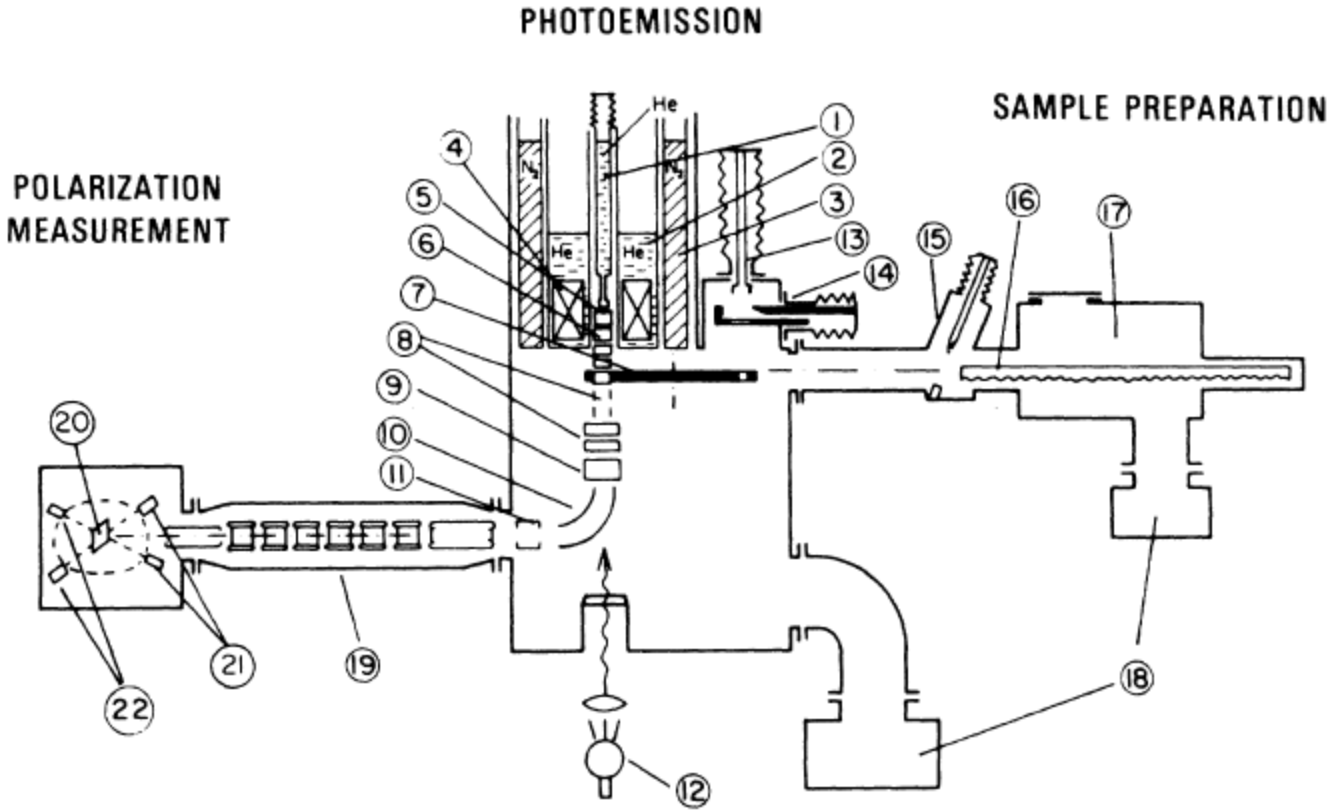




$$P_e = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{3-1}{3+1} = 50\%$$

- 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

Pierce-Meier Apparatus



First Observation of Polarization

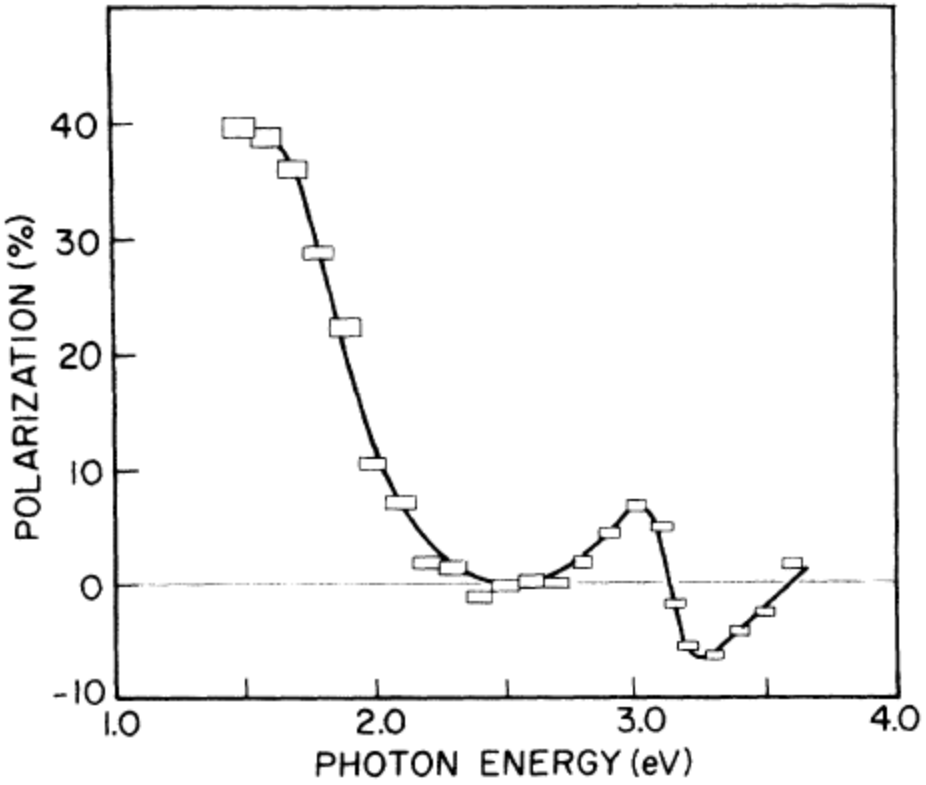
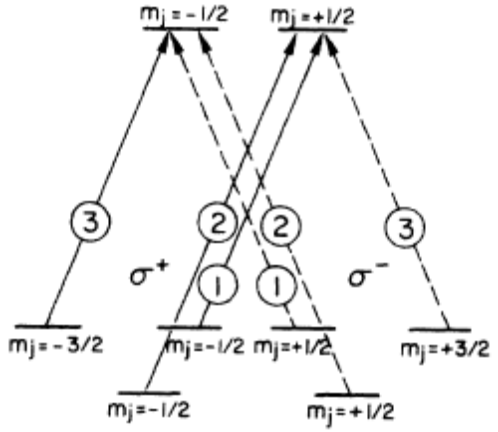


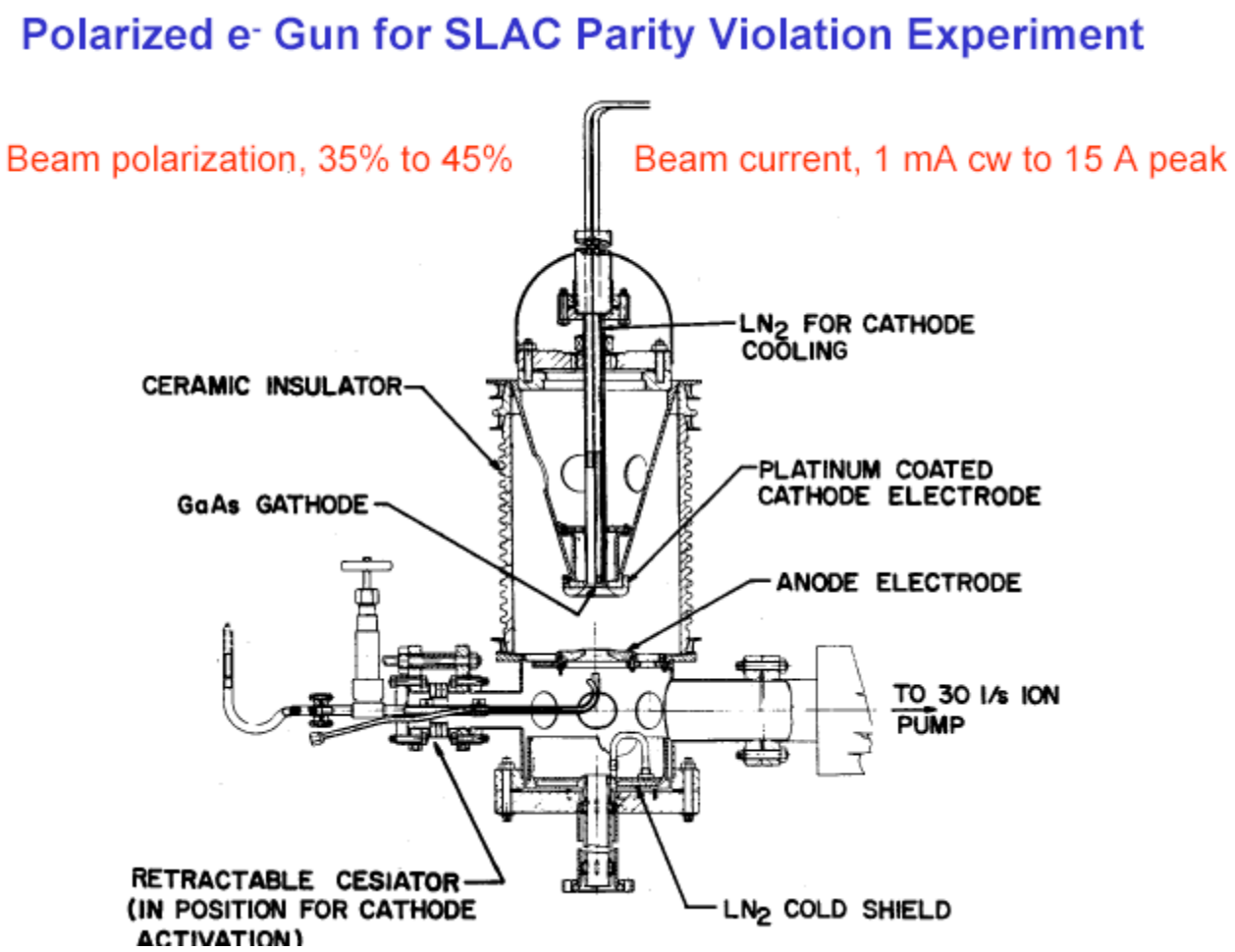
FIG. 6. Spectrum of spin polarization from GaAs + CsOCs at $T \leq 10$ K [the same sample and conditions as curve (a) of Fig. 5] . Note the high value of $P = 40\%$ at threshold ($\hbar\omega \sim 1.5$ eV) and positive and negative peaks at $\hbar\omega = 3.0$ and 3.2 eV.

- 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



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

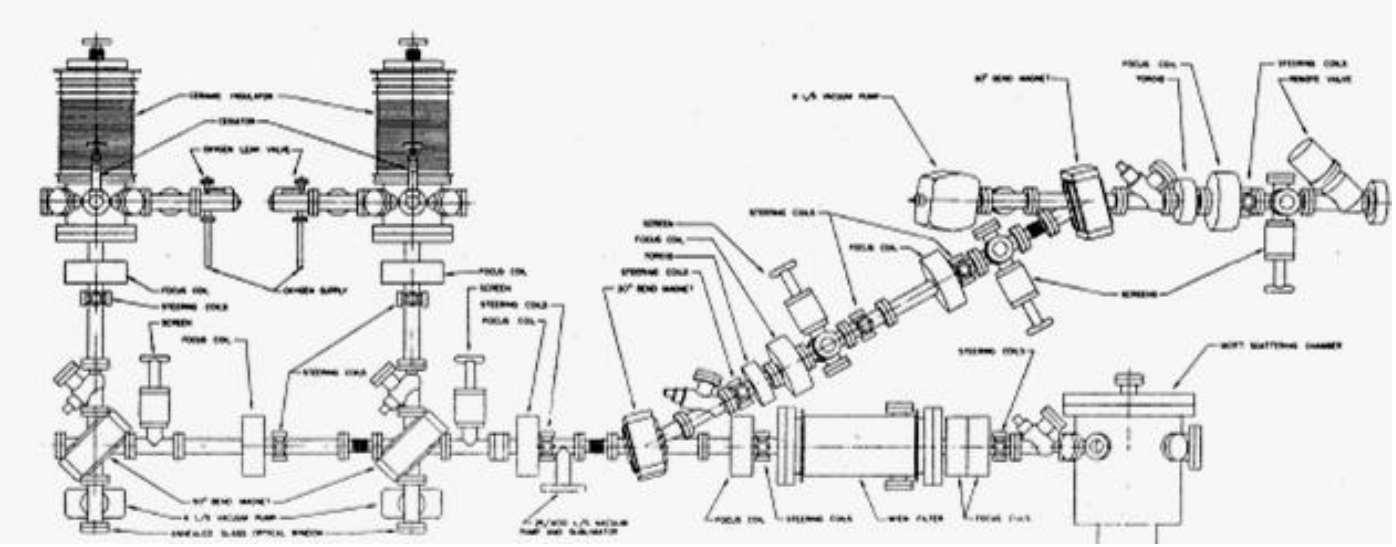
First High Voltage GaAs Photogun

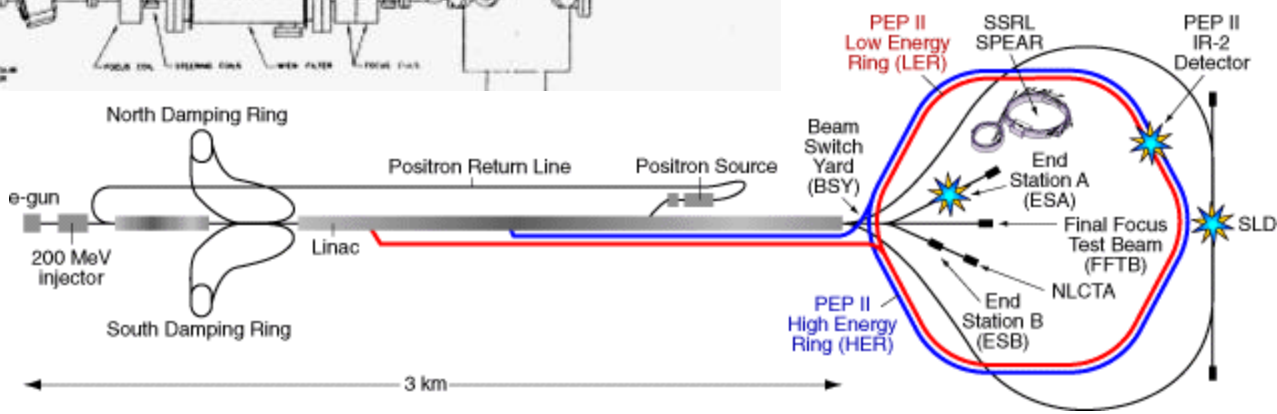


Started with a thermionic gun housing?

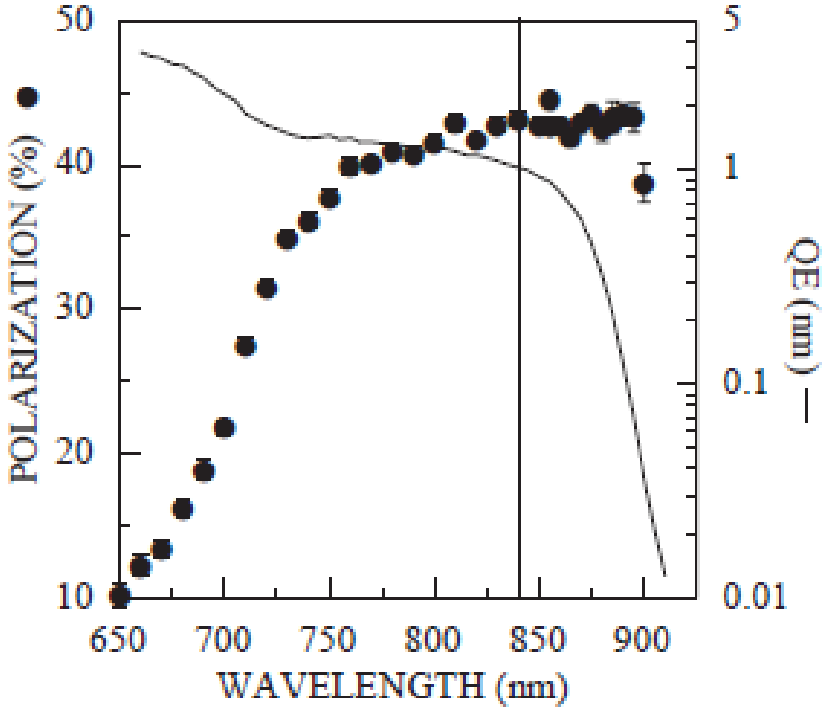
First GaAs Photoinjector

- Built for SLAC parity-violation experiment E122
- Polarized electrons accelerated December, 1977
- E122 announces parity violation June, 1978 - an important verification of the Standard Model





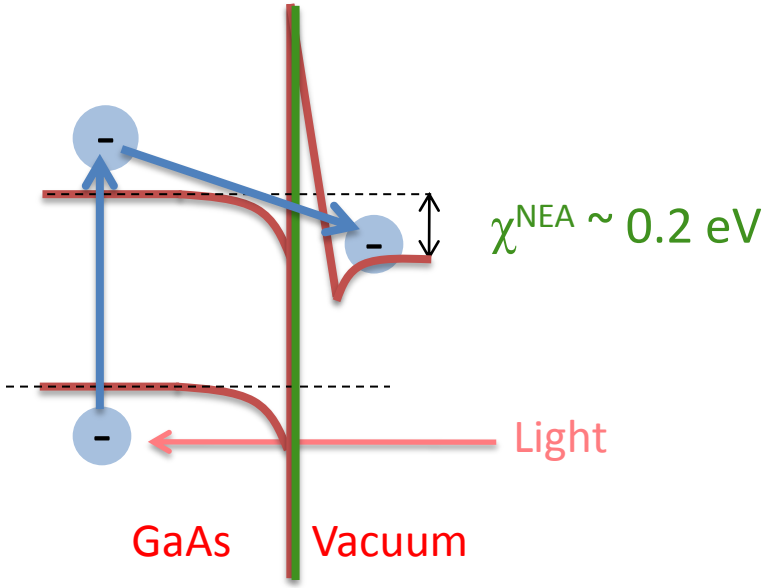
Typical bulk GaAs Result



- QE at bandgap (i.e., where you get highest polarization) can be 10% or more

Pablo Saez, PhD Thesis, SLAC Report 501, 1997

Depolarization Mechanisms



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)

What limits polarization?

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

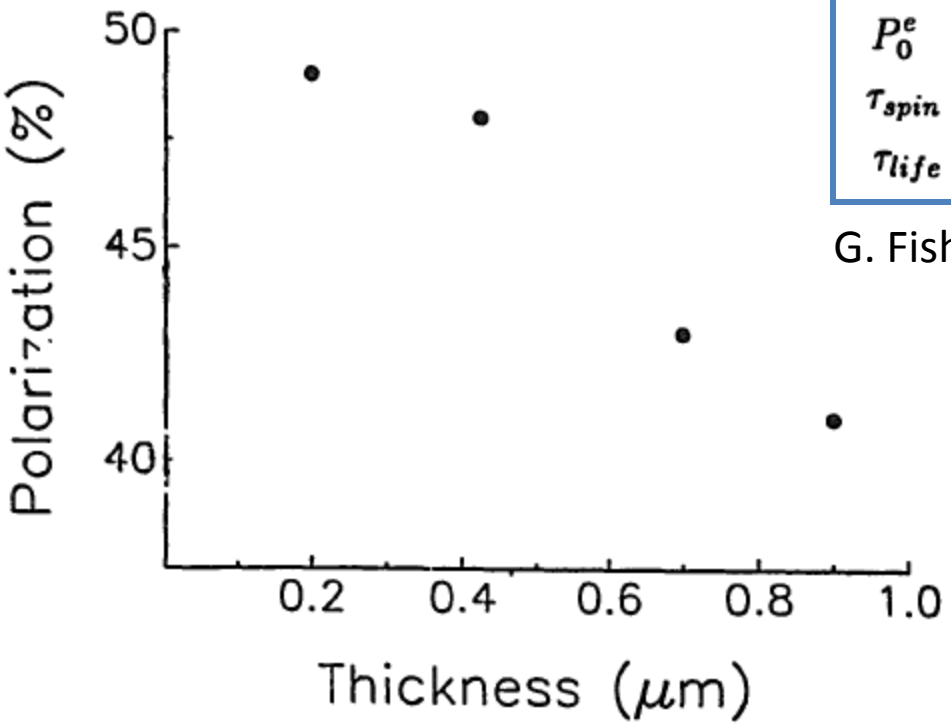
P^e_{obs} = the observed spin polarization;

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)



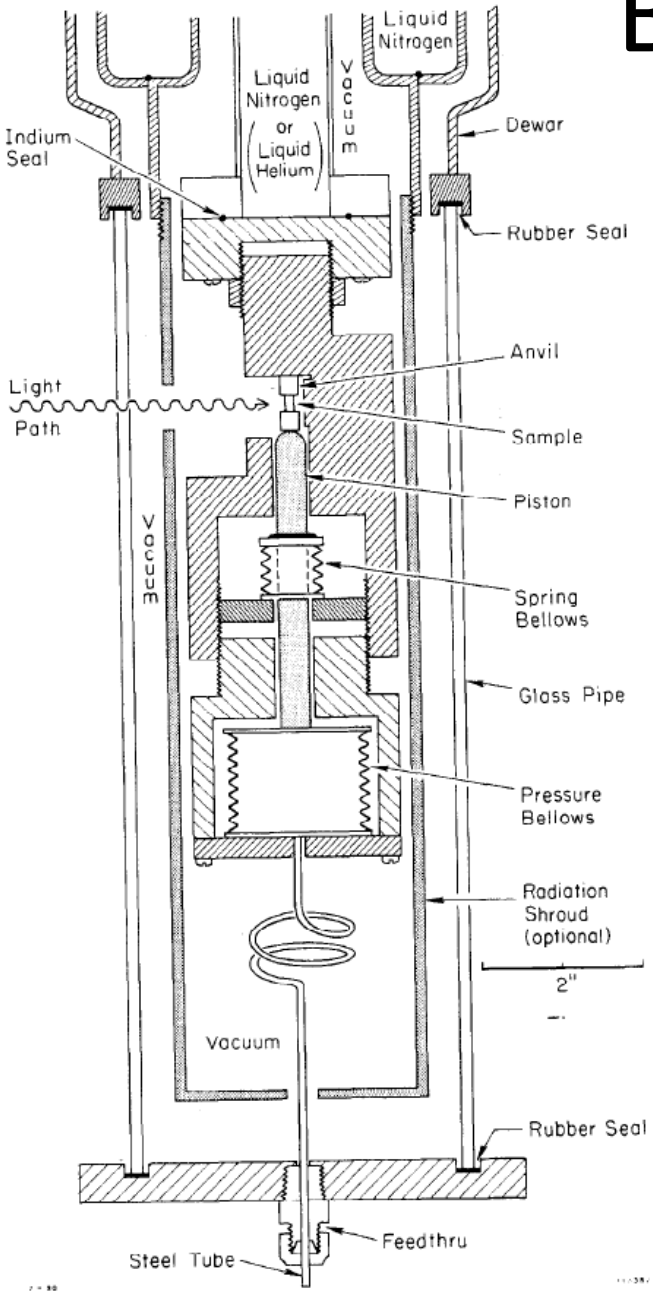
Maruyama et al., Appl. Phys. Lett., 55, 1686 (1989)

Absorption depth ~ 1um in GaAs

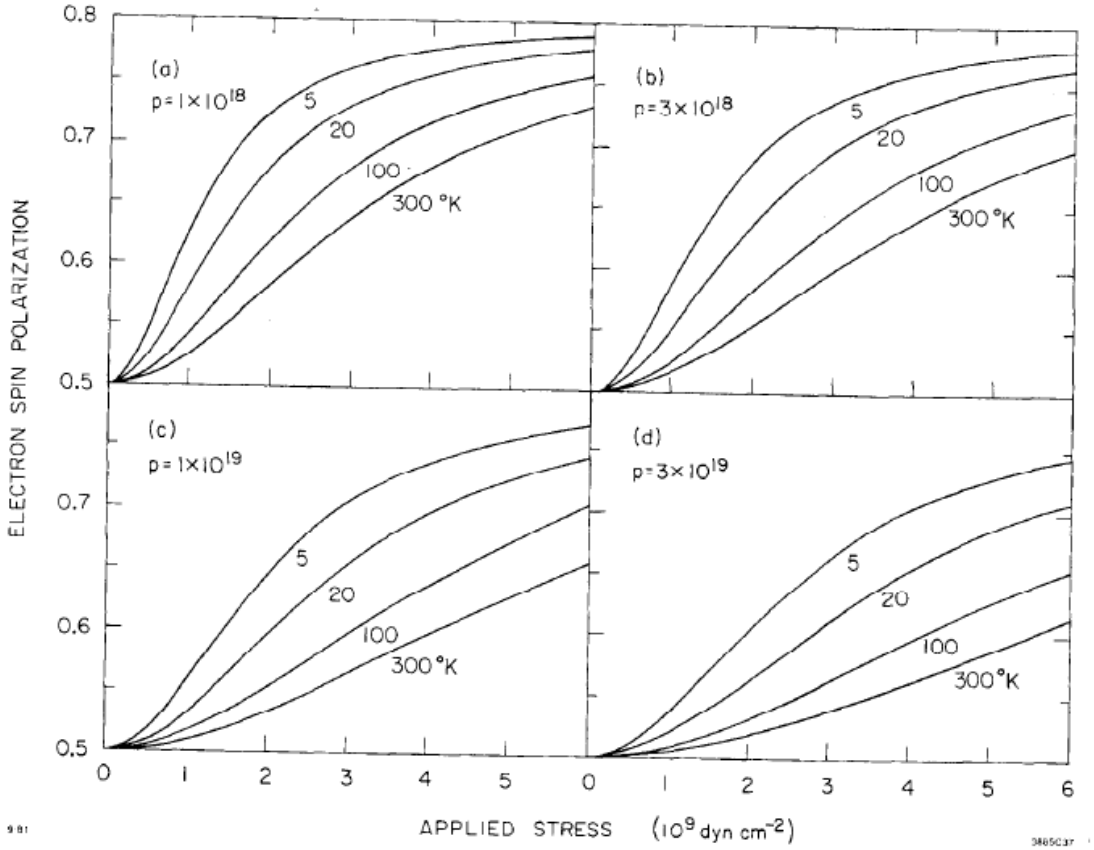
Polarization lost as electrons diffuse to the surface: thin samples provide higher polarization, at expense of QE

Breaking the 50% barrier

PhD thesis, Paul Zorabedian, SLAC Report 248, 1982



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"

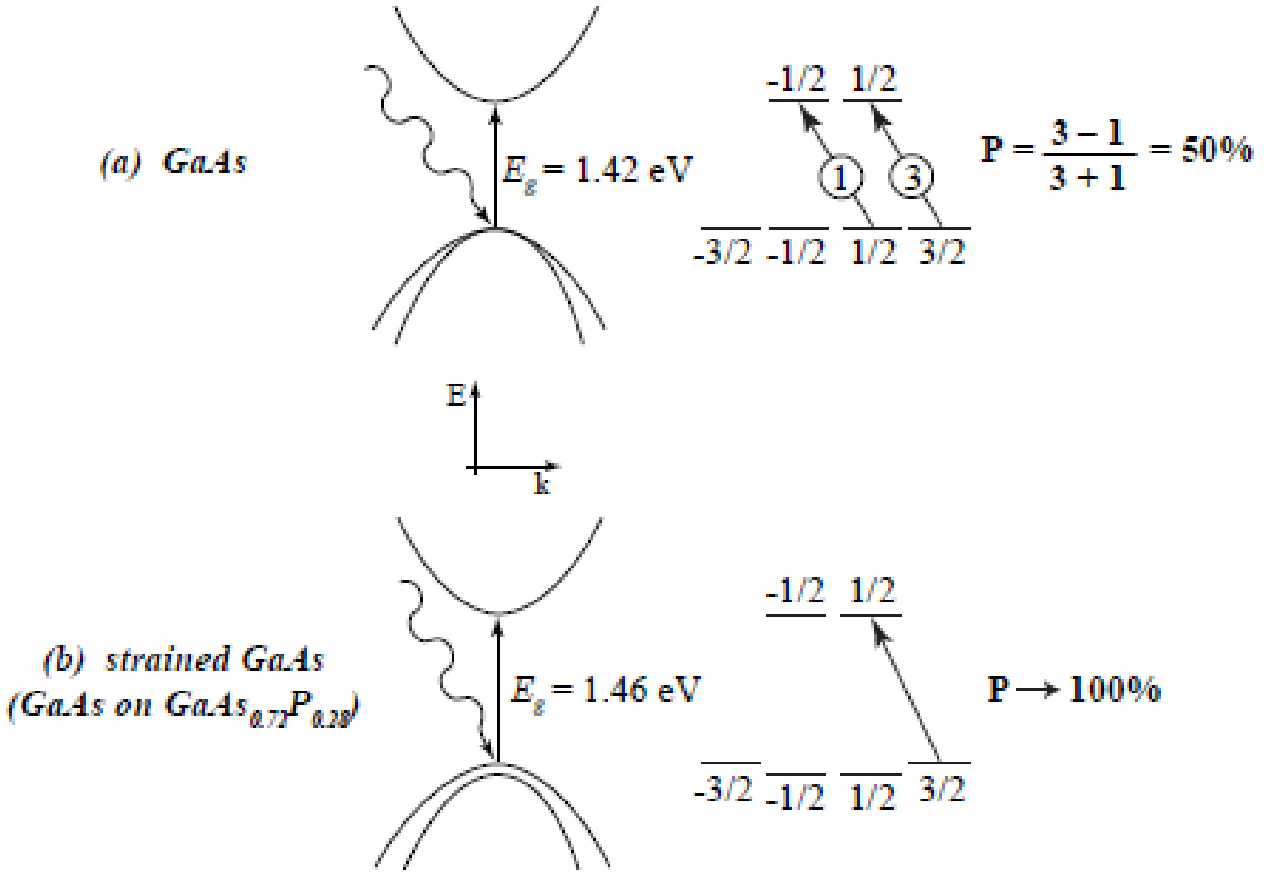
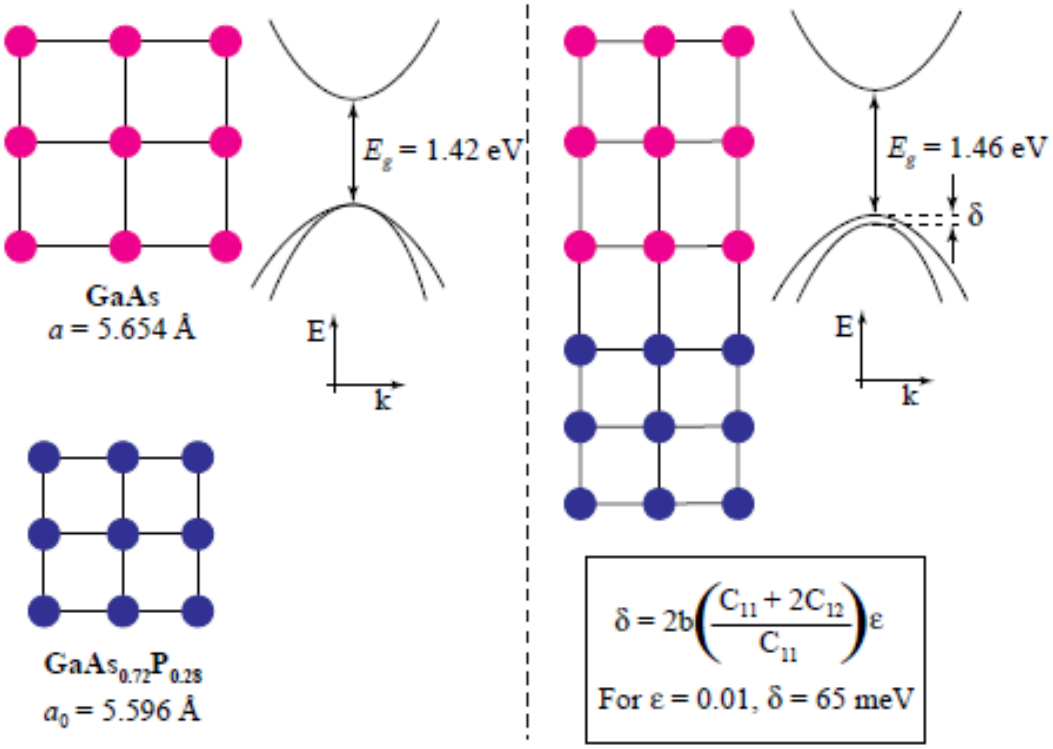


Image from Pablo Saez, PhD Thesis, Stanford University, SLAC Report 501, 1997

Lattice mismatch provides stress



- 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

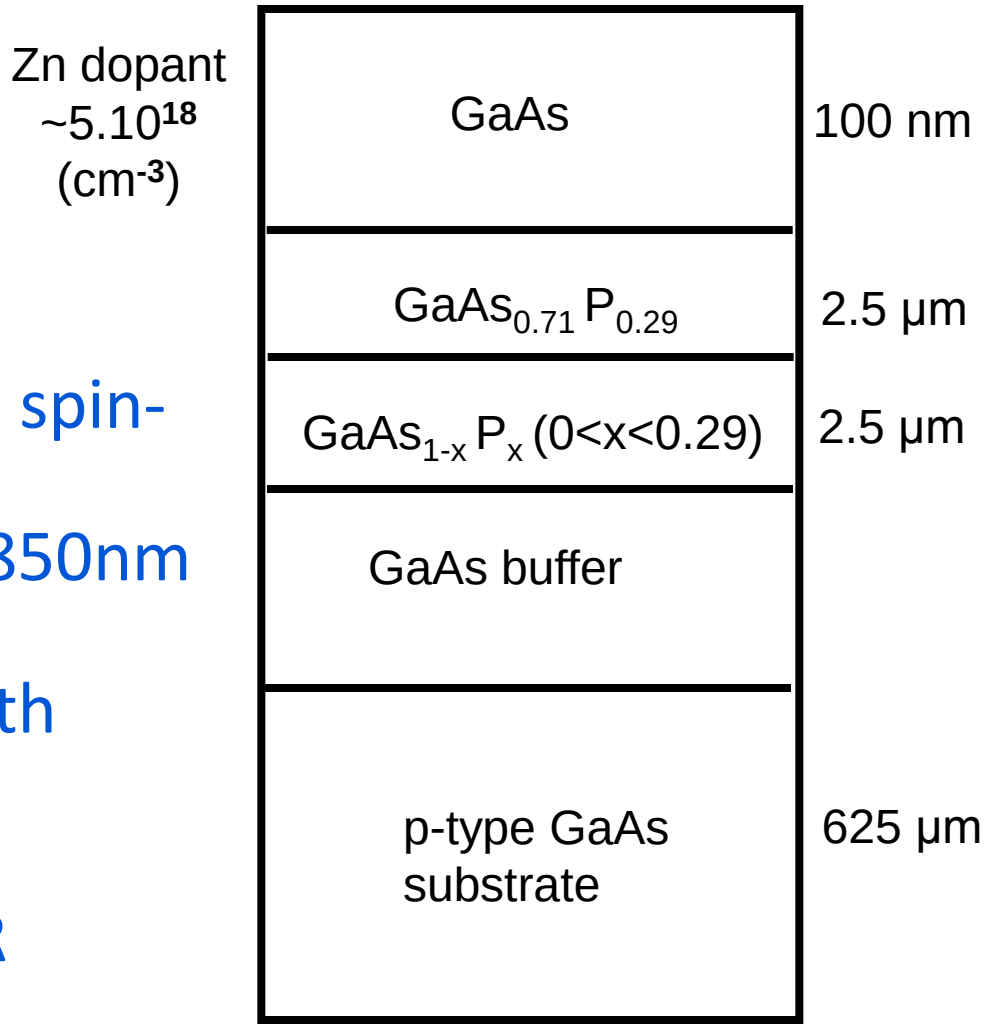
Pablo Saez, PhD Thesis, SLAC Report 501, 1997

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

1% lattice mismatch provides equivalent force as hydraulic press!

Strained-layer GaAs

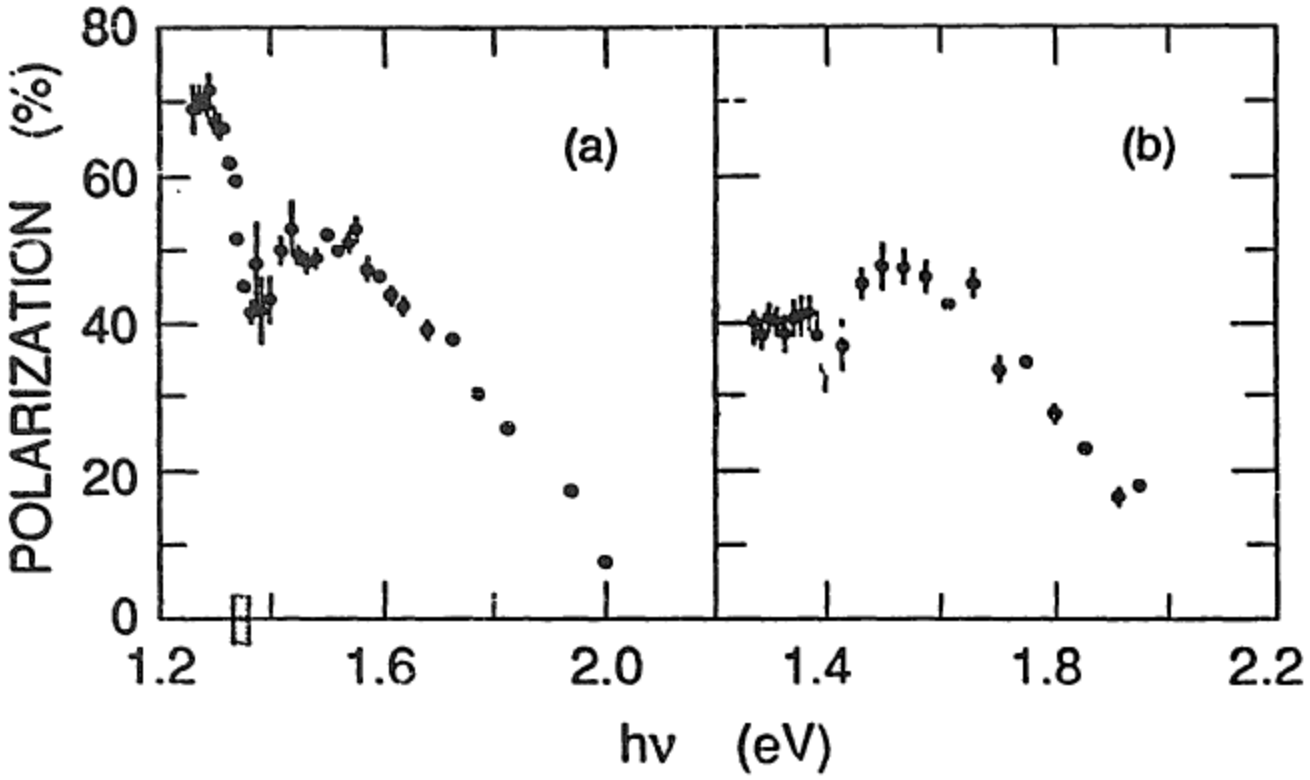
- MOCVD-grown epitaxial spin-polarizer wafer
- Polarization ~ 75% at ~ 850nm
- QE ~ 0.1%
- Available from Bandwidth Semiconductor
- 3” dia. wafer ~ 10k$
- Developed via DOE-SBIR program

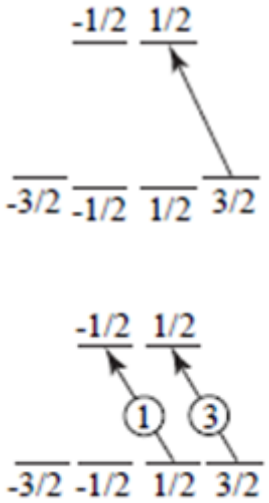


Manufactured by Bandwidth Semiconductor

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)

Period	Group II	Group III	Group IV	Group V	Group 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

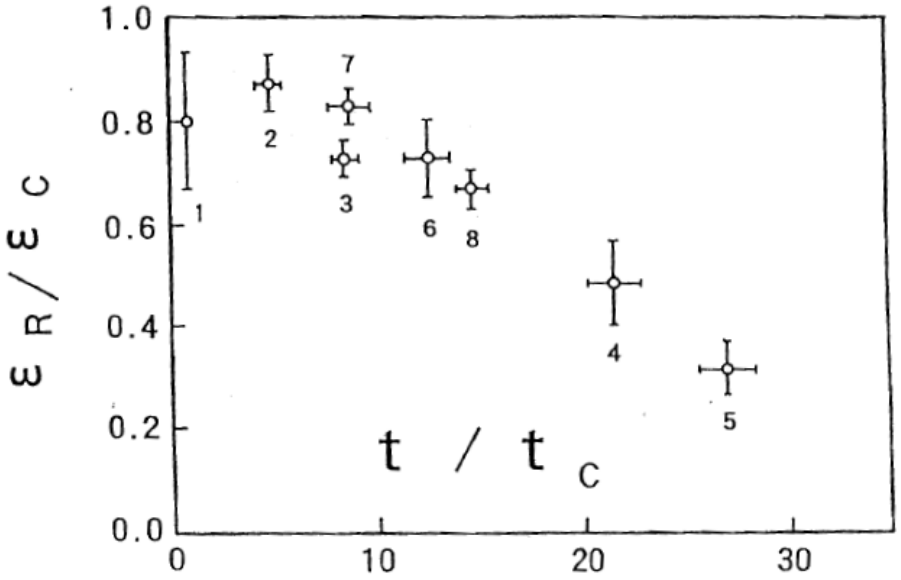
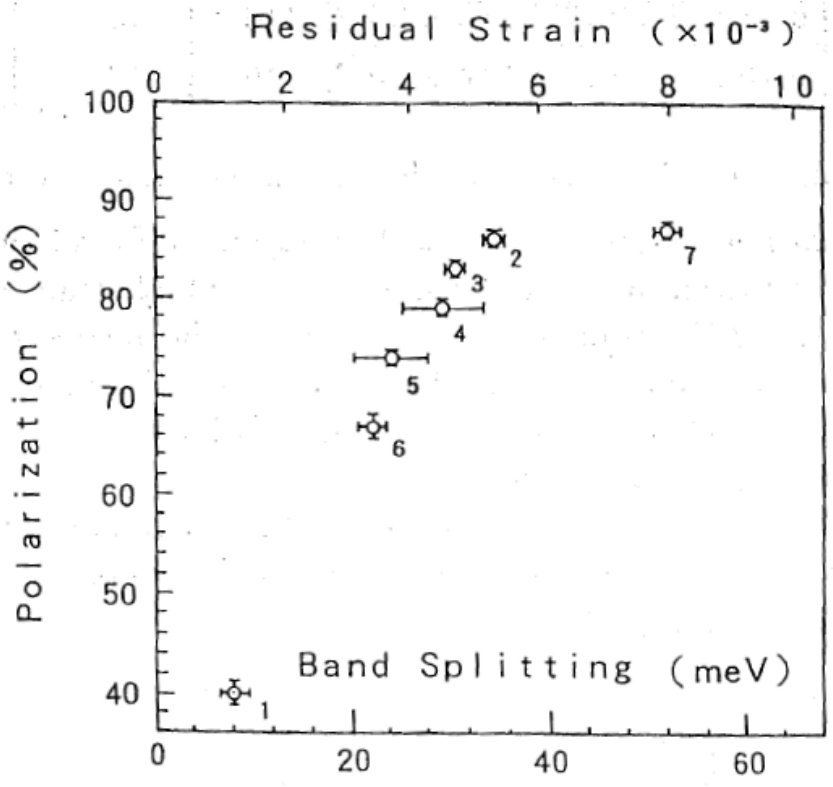


Fig. 1. Strain relaxation in GaAs layers



g. 2. Strain dependence of the maximum polarization

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

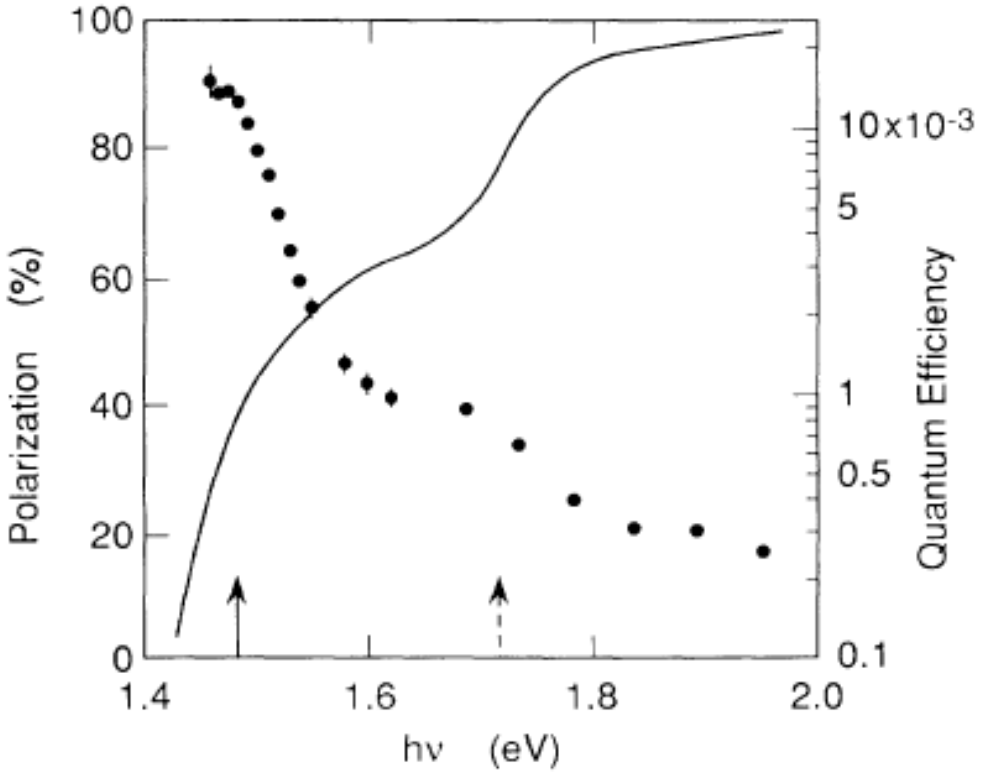
Aoyagi, Nakanishi, et.al., Division of Physics Nagoya University Tech Note 93-14

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%

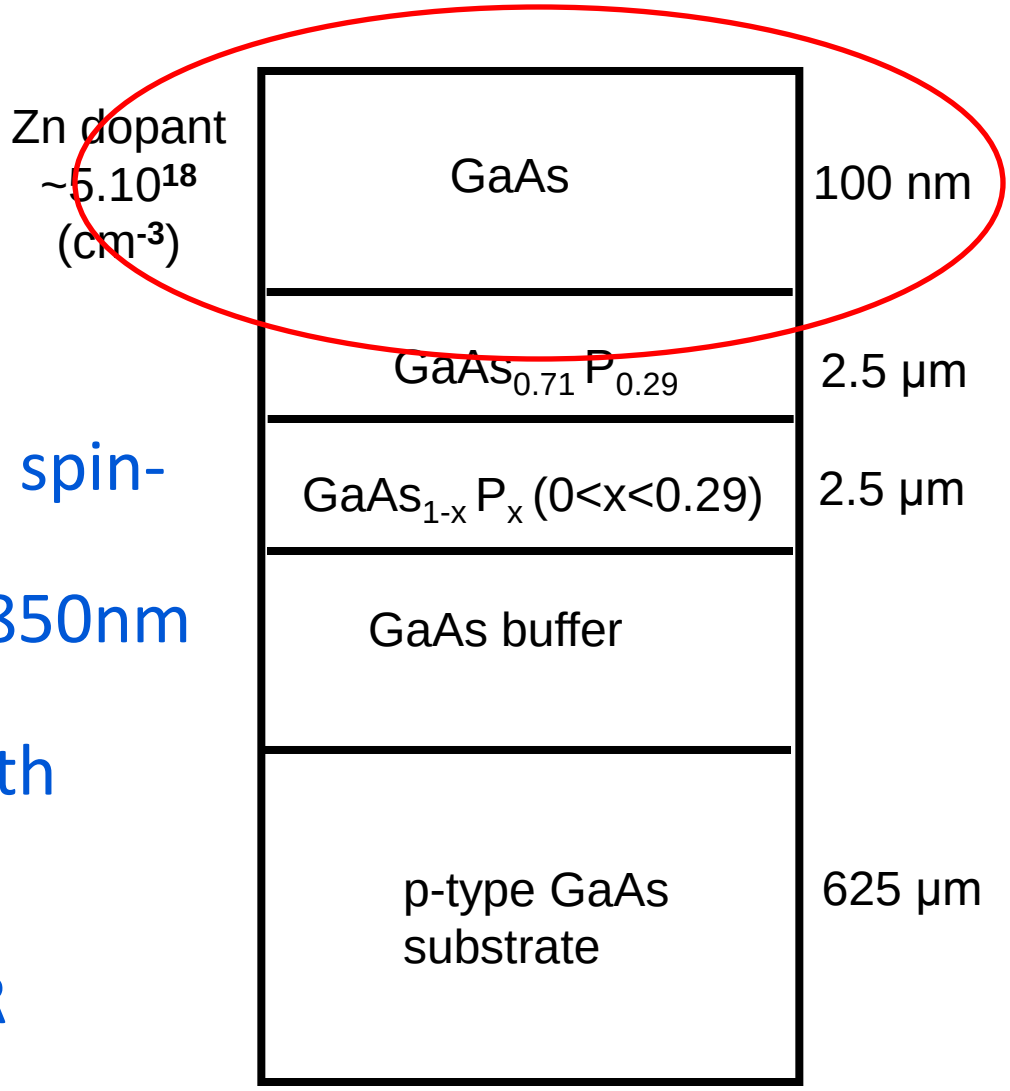
This became the standard SPIN Polarizer wafer sold by SPIRE, now Bandwidth Semiconductor



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

Strained-layer GaAs

- 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



Manufactured by Bandwidth Semiconductor

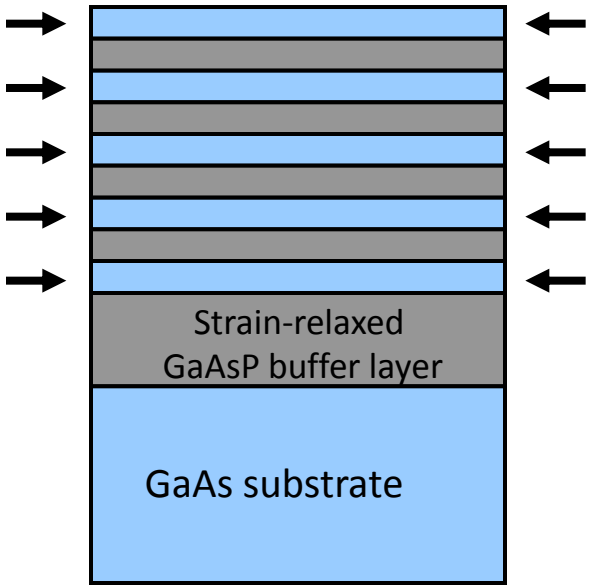
Higher P, Higher QE?

- 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***…

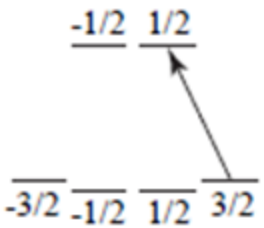
Strained Superlattice Photocathode

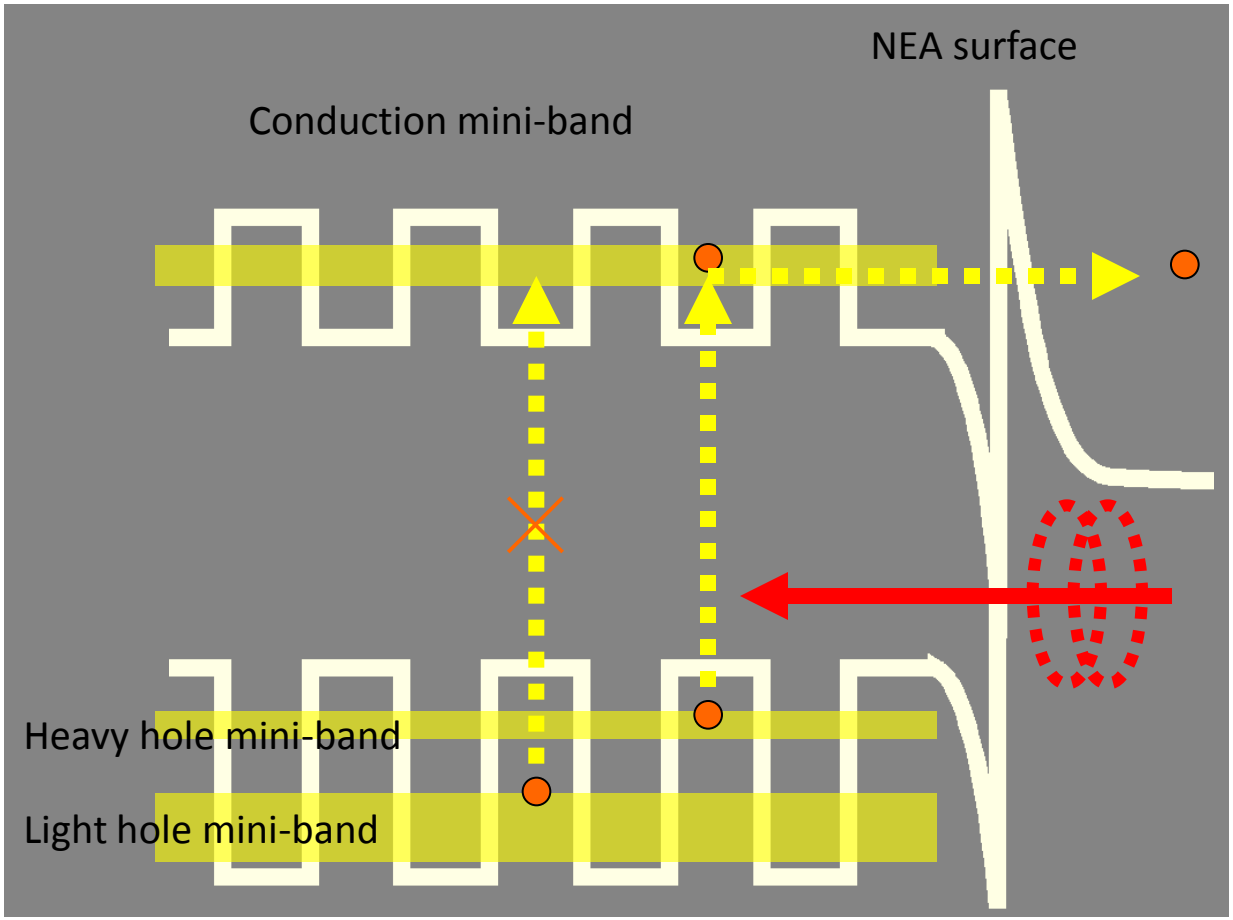
Electrons tunnel through very thin buffer layers!!

Slide courtesy Toru Ujihara, PESP 2008



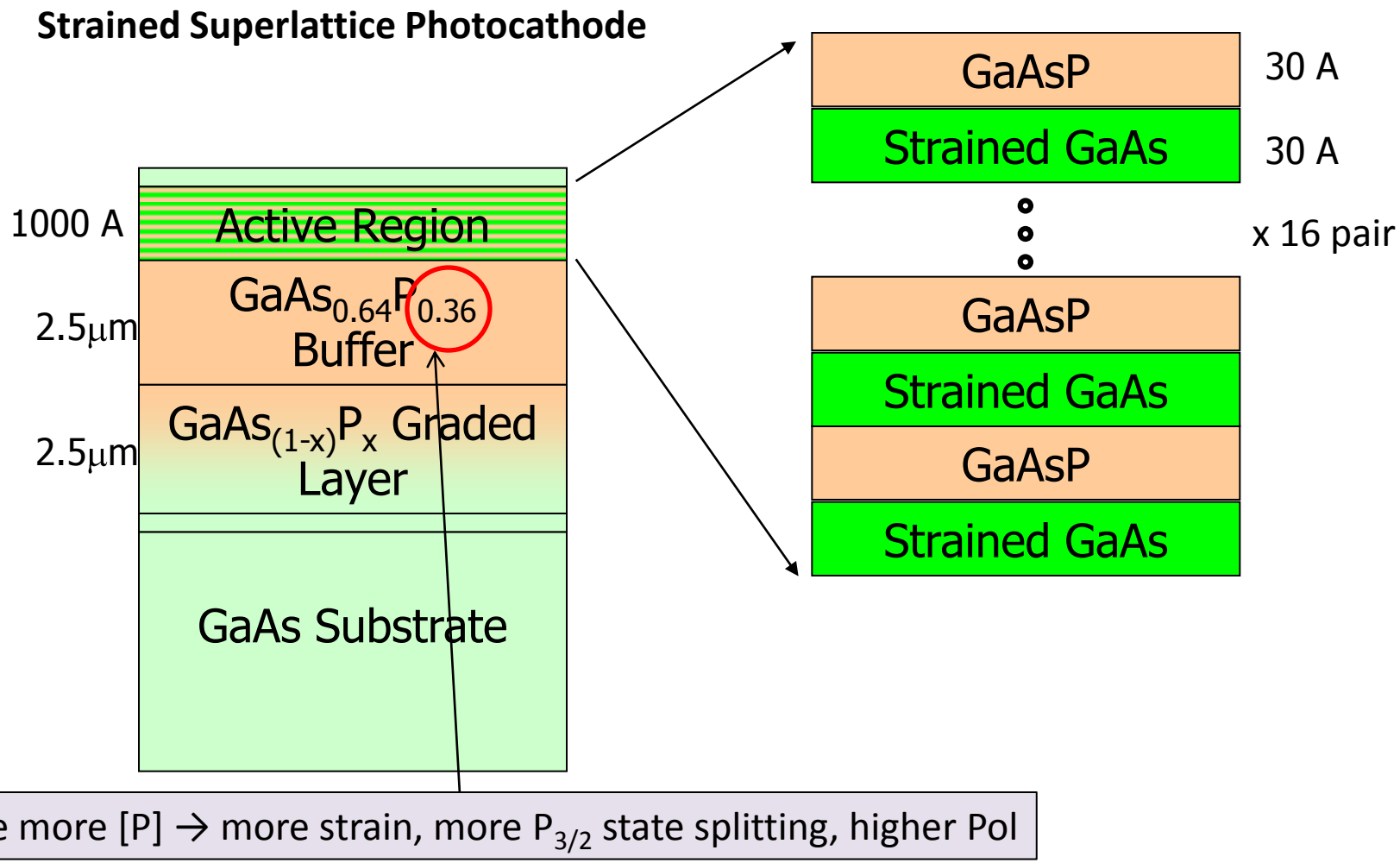
eg., GaAs/GaAsP
strained superlattice





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

Getting the Recipe Right



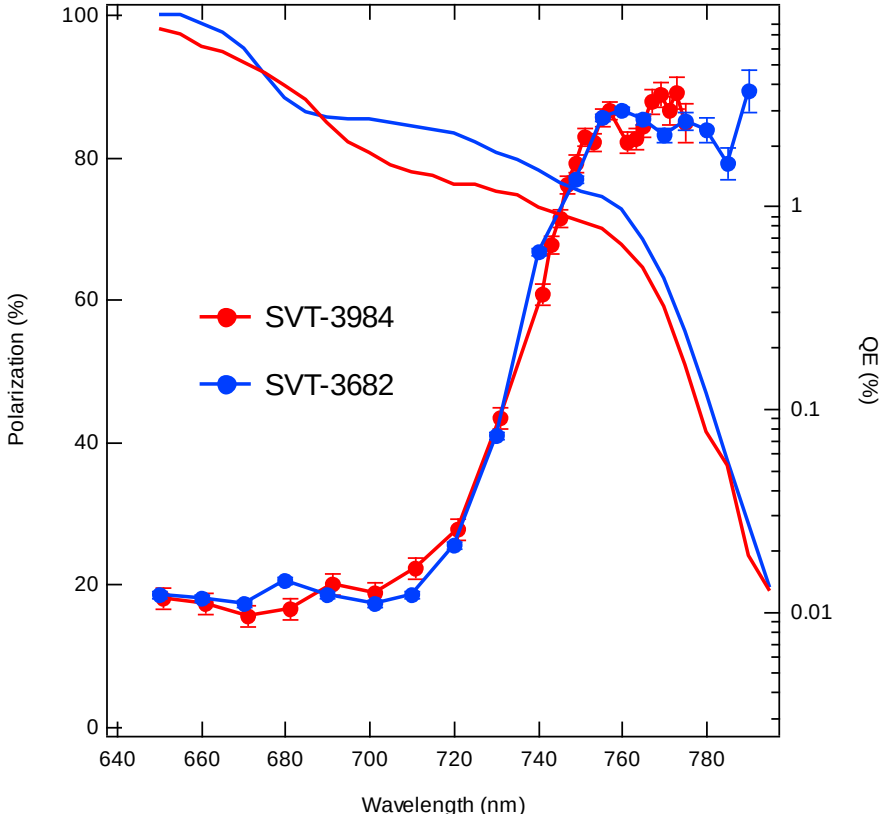
Notice more [P] → more strain, more $P_{3/2}$ state splitting, higher Pol

From Aaron Moy, SVT Assoc and SLAC, PESP2002

SVT ASSOCIATES

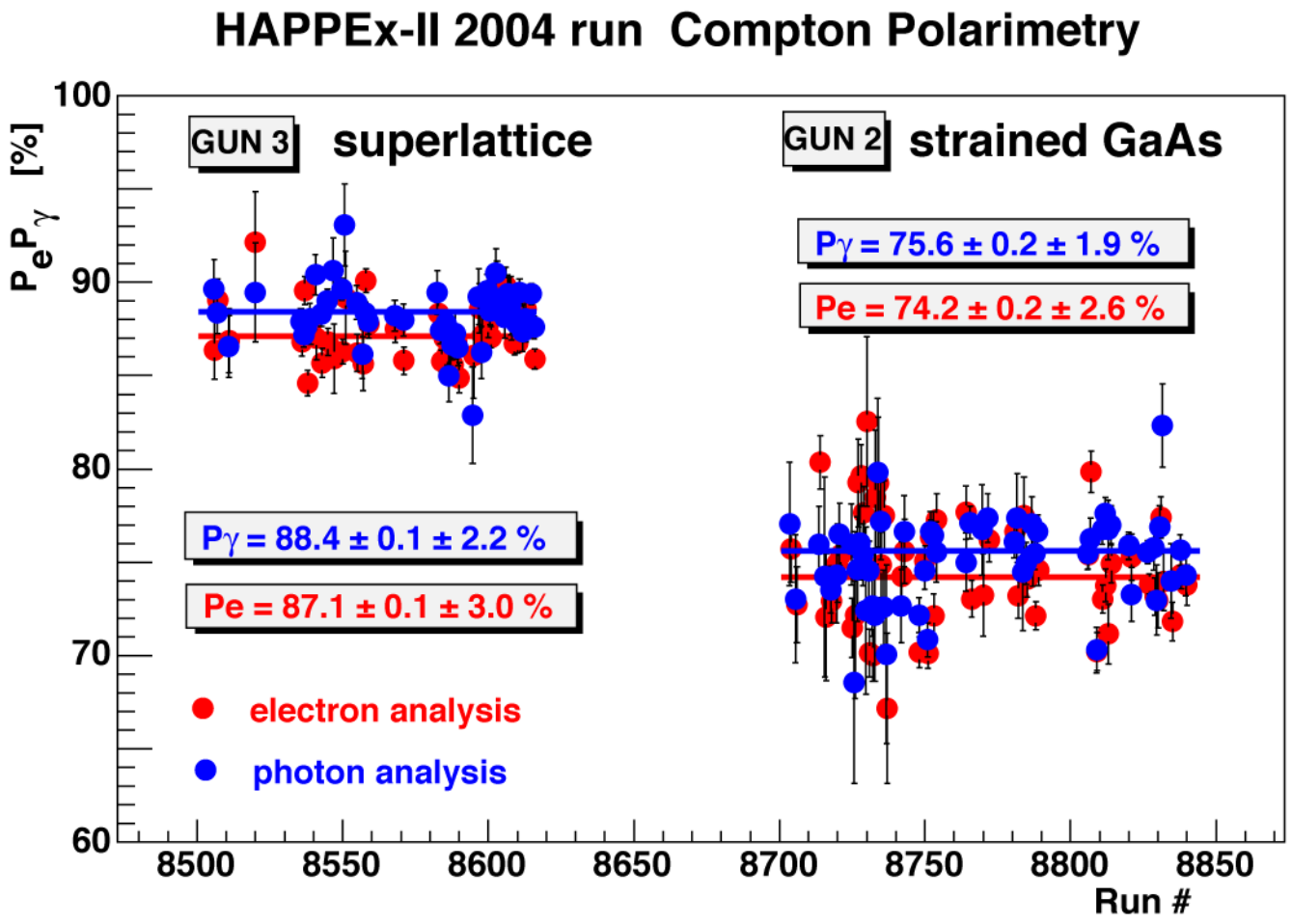
Higher Polarization AND Higher QE

- 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

Significant FOM Improvement



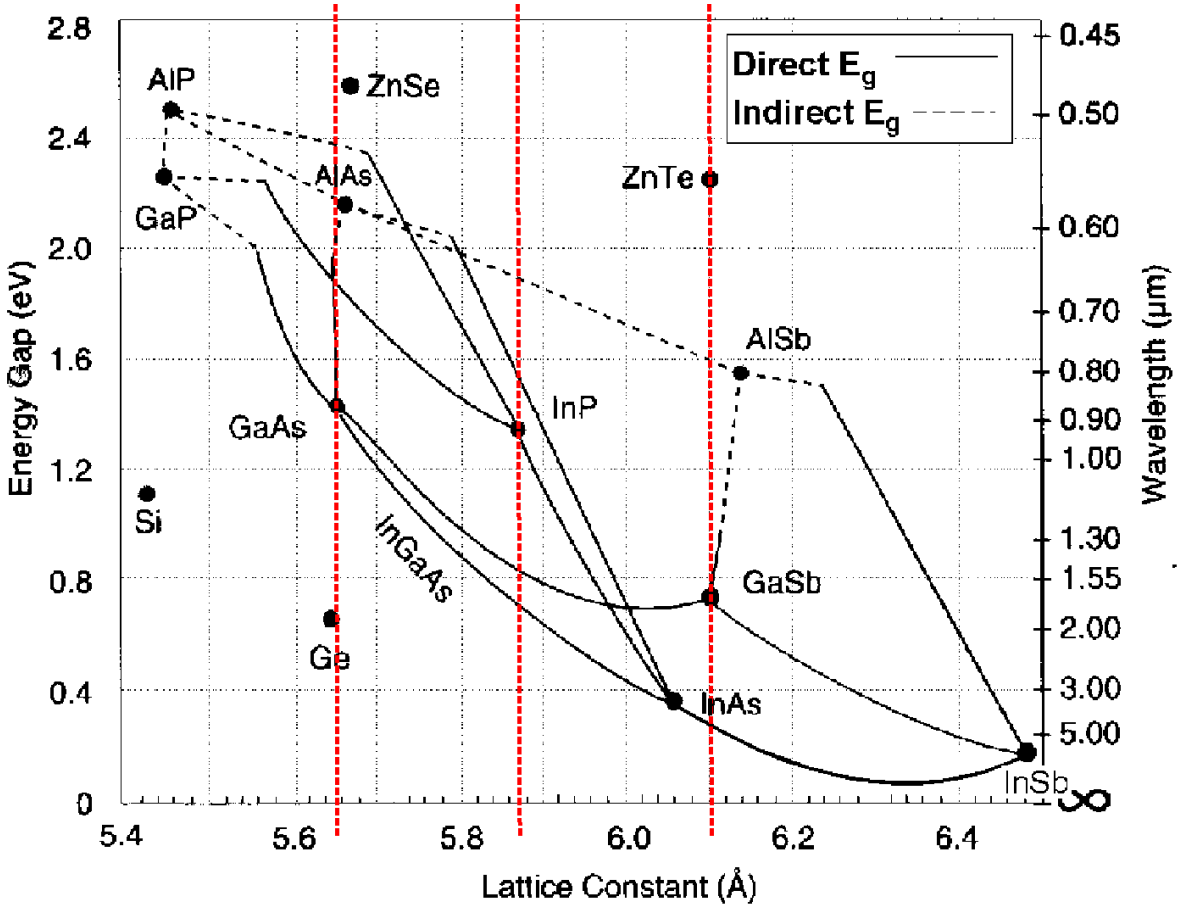
$$FOM\ Improvement = \frac{P_{ssl}^2 I}{P_{sl}^2 I} = 1.38$$

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

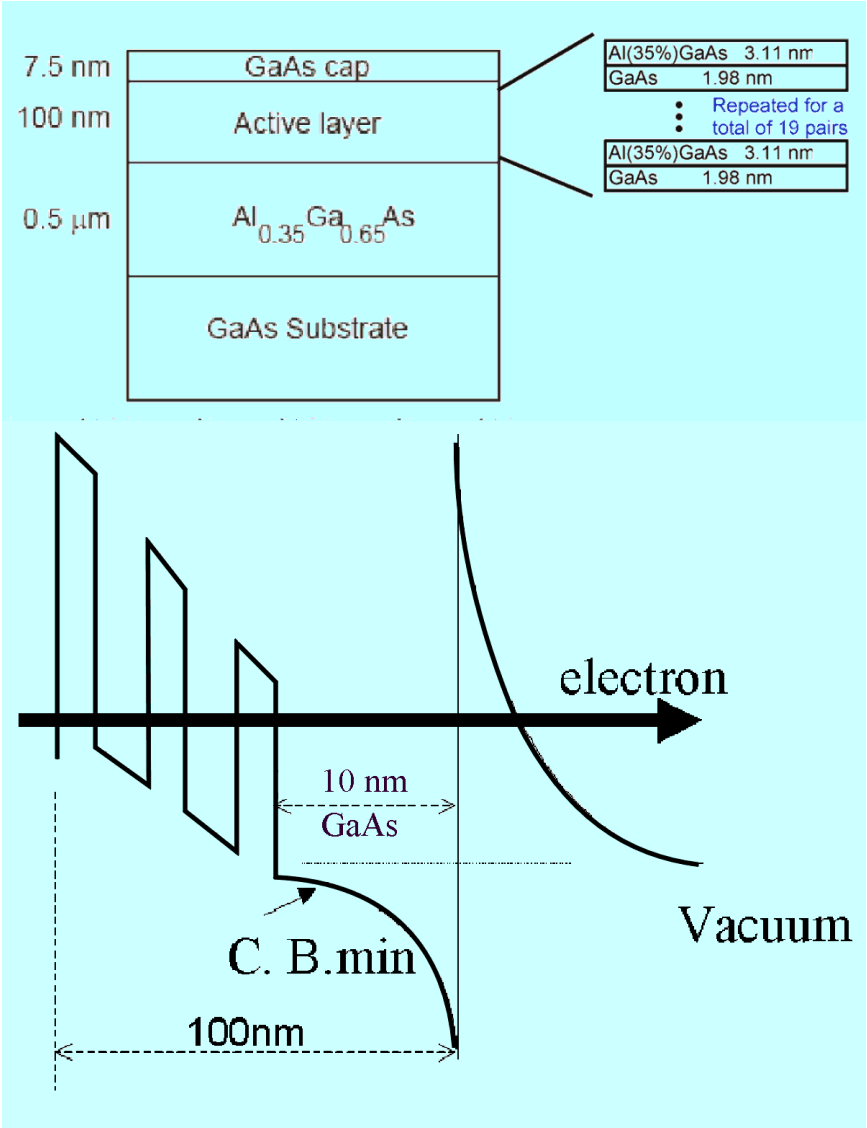


Still looking for combinations that provide Higher Polarization, **Higher QE**, more rugged lifetime

Courtesy Aaron Moy of SVT Associates

Internal Gradient Strained-Superlattice

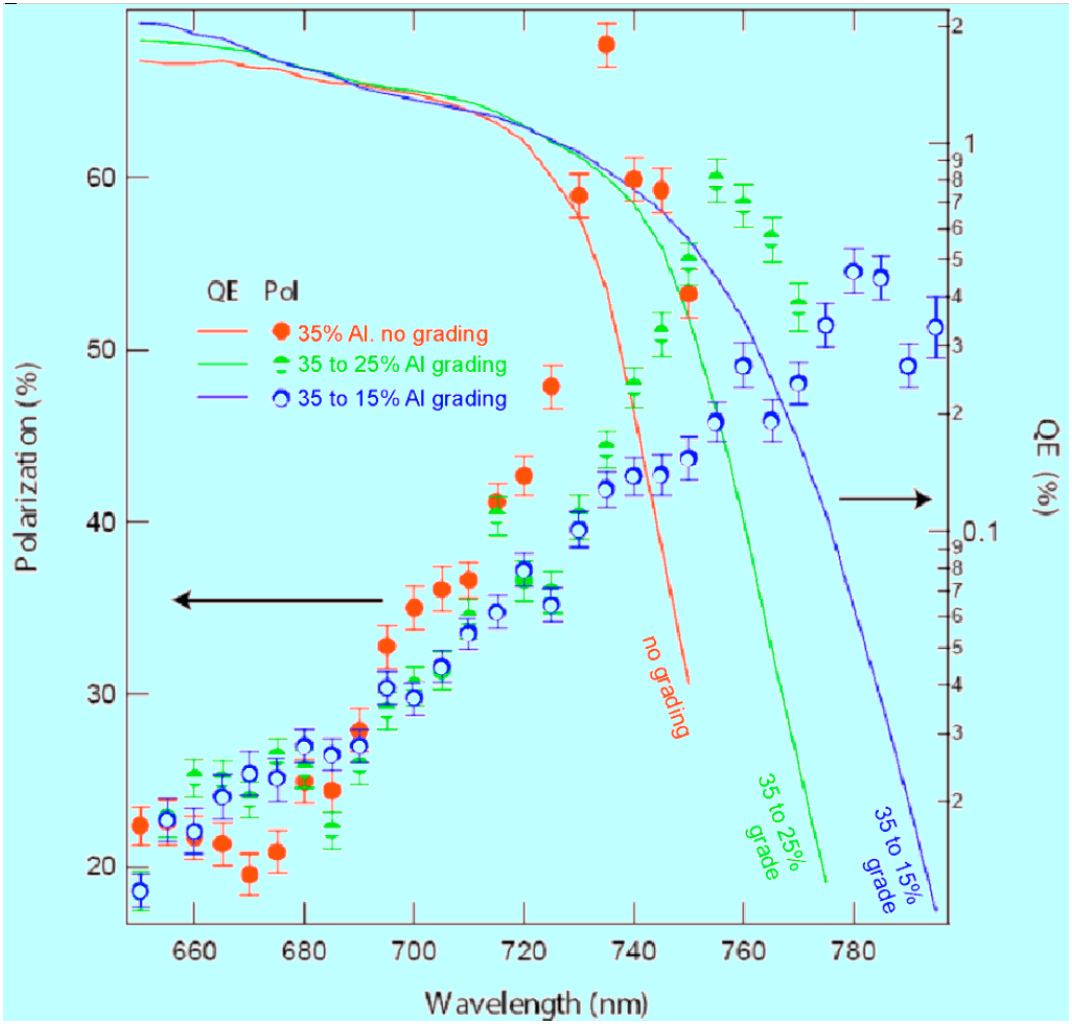
- Photocathode active layers with internal accelerating field
- Internal field enhances electron emission for higher QE
- Less transport time also reduces depolarization mechanisms
- Gradient created by varied alloy composition or dopant profile



Courtesy Aaron Moy of SVT Associates

Internal Gradient GaAs/AlGaAs SLs

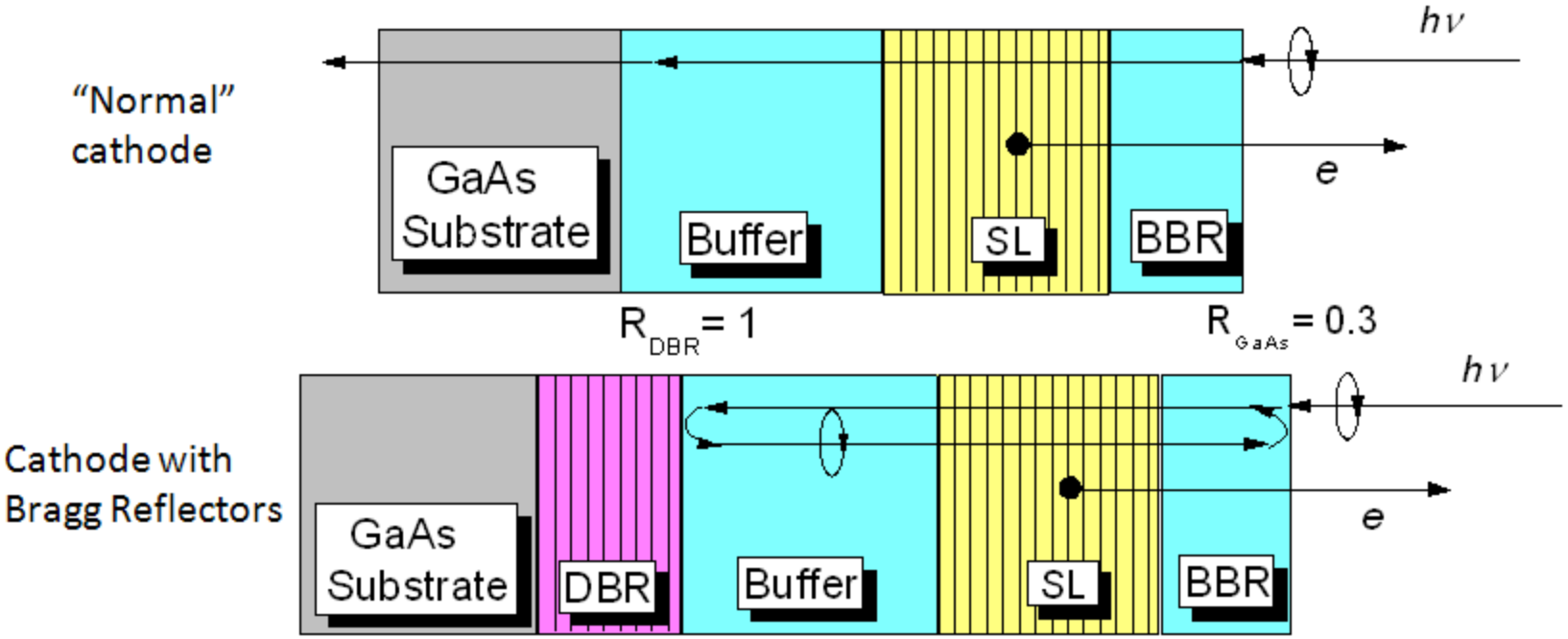
- Polarization decreased as aluminum gradient increased
- Due to less low LH-HH splitting at low aluminum %
- QE increased 25% due to internal gradient field
- Peak polarization of 70 % at 740 nm, shorter than 875 nm of GaAs



Courtesy Aaron Moy of SVT Associates

DBR – Equipped Crystal

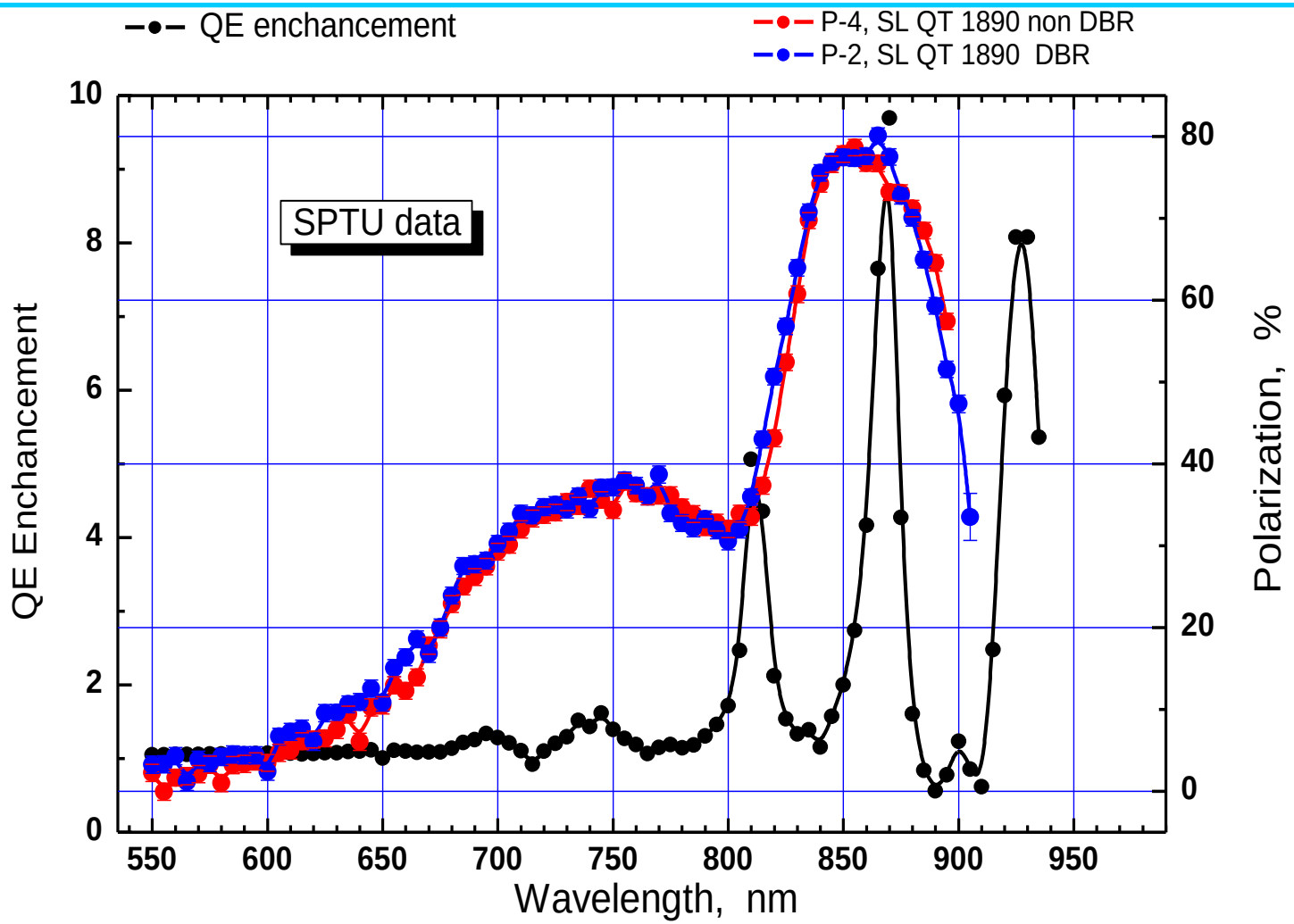
For instance, talk by L. Gerchikov, St. Petersburg, at PESP 2007



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



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