ELECTRON SOURCES

Thermal electron emission : Electron emission from the heated material (typically 1000 -3000K).

Field emission: Emission from the high field gradient surface.

Photo-electron emission: Emission by photoelectron effect.

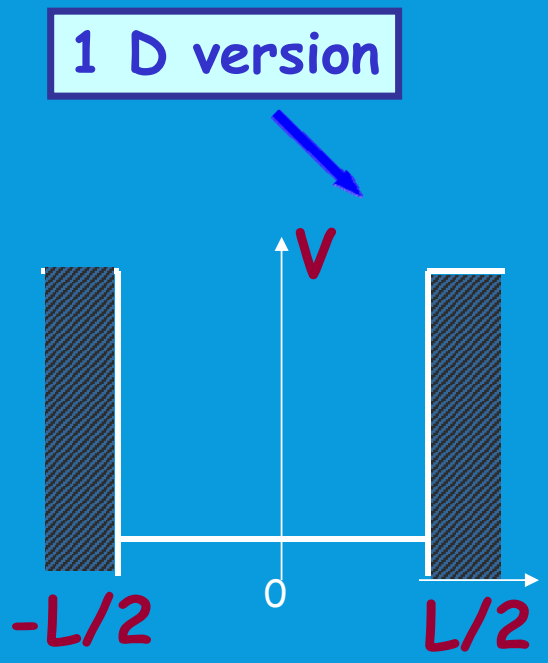
Secondary electron emission: Emission induced by electron absorption.

INTRODUCTION ELECTRON EMISSION METALS - FREE ELECTRON THEORY

- **Conductors** fall into **2** ***main classes***; ***metals*** **& semiconductors.**
- Here, we focus on ***metals***.
- ***A metal*** is loosely ***defined*** as a solid with valence electrons that are not tightly bound to the atoms but are relatively easily able to move through the whole crystal.
- Therefore, these conduction electrons can be considered as moving independently in a square well of finite depth & the edges of the well correspond to the edges of the sample.
- Consider a metal with a cubic shape with edge length L: Ψ & E can be found by solving the Schrödinger equation :

SCHRÖDINGER EQUATION

▪ :



Since $V = 0$ $-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi$

- Use periodic boundary conditions & get **Ψ's** as travelling plane waves.

$$\psi(x+L, y+L, z+L) = \psi(x, y, z)$$

SOLUTIONS

- The solutions to the Schrödinger equation are plane waves,

$$\psi(x,y,z) = \frac{1}{\sqrt{V}} e^{i\vec{k}\vec{r}} = \frac{1}{\sqrt{V}} e^{i(k_x x + k_y y + k_z z)}$$

Normalization constant

V = volume of the cube, $V=L^3$

So the wave vector must be of the form:

$$Na = p\lambda \quad \Rightarrow \quad Na = p\frac{2\pi}{k} \quad \left(where, k = \frac{2\pi}{\lambda}\right) \quad \Rightarrow \quad k = \frac{2\pi}{Na} p = \frac{2\pi}{L} p$$

where p, q, r take any + or - integer values or zero.

$$k_x = \frac{2\pi}{L} p \qquad k_y = \frac{2\pi}{L} q \qquad k_z = \frac{2\pi}{L} r$$

- The wave function **ψ(x,y,z)** corresponds to the energy

$$E = \frac{\hbar^2 k^2}{2m} \qquad E = \frac{\hbar^2}{2m}(k_x{}^2 + k_y{}^2 + k_z{}^2)$$

- The corresponding momentum is:

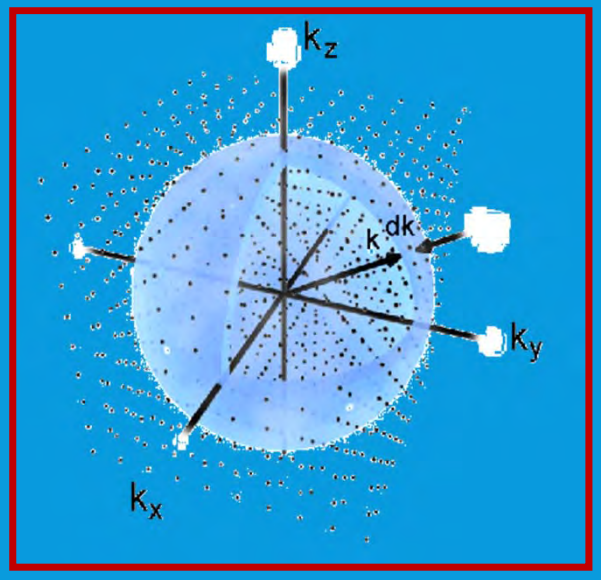
$$p = \hbar(k_x, k_y, k_z)$$

- The energy is completely kinetic:

$$\frac{1}{2}mv^2 = \frac{\hbar^2 k^2}{2m} \rightarrow m^2 v^2 = \hbar^2 k^2 \rightarrow p = \hbar k$$

STATES DISTRIBUTION

- We know that number of allowed **k** values in a spherical shell of **k-space** of radius **k** is:



$$g(k)dk = \frac{Vk^2}{2\pi^2}dk,$$

- **g(k)** is called the density of states per unit magnitude of **k**.

NUMBER OF ALLOWED STATES PER UNIT ENERGY RANGE?

- **Each k state represents two possible electron states**, one for spin up, the other for spin down.

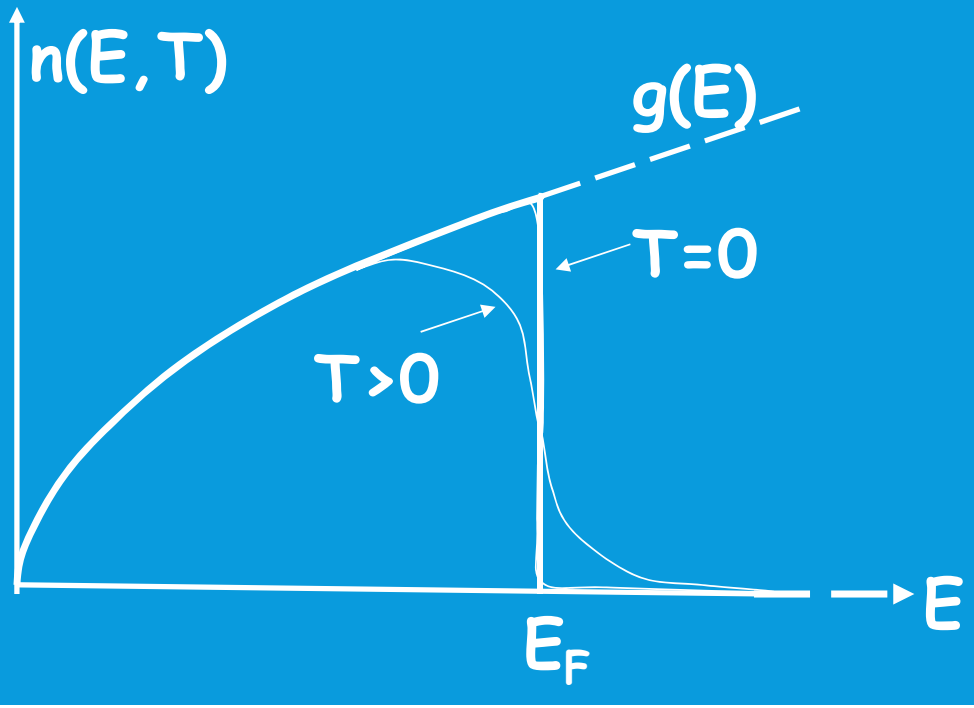
$$g(E)dE = 2g(k)dk \rightarrow g(E) = 2g(k)\frac{dk}{dE}$$

$$E = \frac{\hbar^2 k^2}{2m} \qquad \frac{dE}{dk} = \frac{\hbar^2 k}{m} \qquad k = \sqrt{\frac{2mE}{\hbar^2}}$$

$$g(E) = 2g(k)\frac{dk}{dE} \rightarrow g(E) = 2\frac{V}{2\pi^2}\frac{m}{\hbar^2 k}k$$

$$g(E) = \frac{V}{2\pi^2\hbar^3}(2m)^{3/2}E^{1/2}$$

- What is ***the number of electrons per unit energy*** range according to the free electron model?
- This shows the change in distribution between absolute zero and a finite temperature.



- **n(E, T)** = number of free electrons per unit energy range = area under **n(E, T)** graph.

$$n(E,T) = g(E)\, f_{FD}(E,T)$$

T=0, FERMI ENERGY

- Electrons are **Fermions** ($s = \pm \frac{1}{2}$) & obey the ***Pauli exclusion principle***; each state can accommodate only one electron.
- The lowest-energy state of **N** free electrons is therefore obtained by filling the **N** states of lowest energy.

PILING UP….

- Thus all states are filled up to an energy E_F, ***known as The Fermi energy***, obtained by integrating the density of states between 0 and E_F, The result should equal N. Remember that

$$g(E) = \frac{V}{2\pi^2\hbar^3}(2m)^{3/2}E^{1/2}$$

$$N = \int_0^{E_F} g(E)dE = \int_0^{E_F} \frac{V}{2\pi^2\hbar^3}(2m)^{3/2}E^{1/2}dE = \frac{V}{3\pi^2\hbar^3}(2mE_F)^{3/2}$$

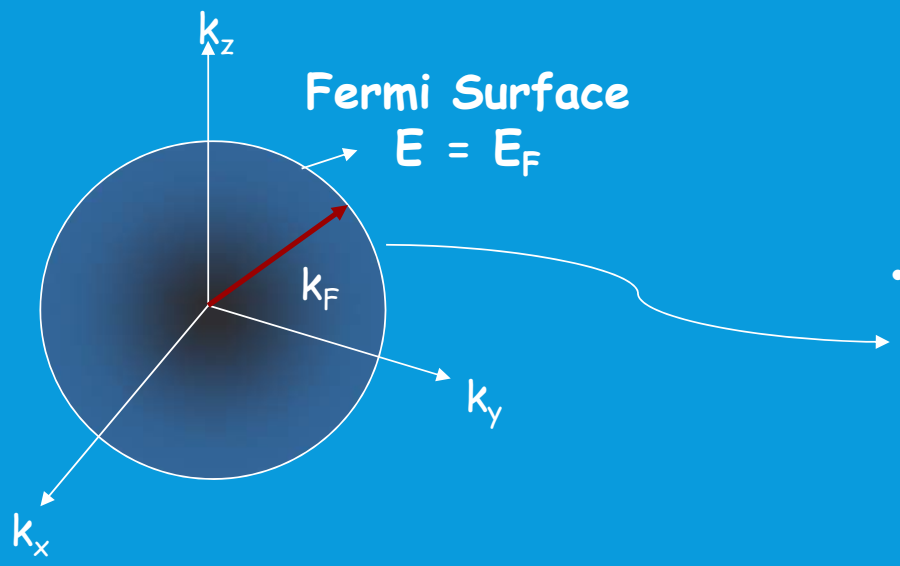
- Solving for E_F (***Fermi energy***):

$$E_F = \frac{\hbar^2}{2m}\left(\frac{3\pi^2 N}{V}\right)^{2/3}$$

- The occupied states are inside the **Fermi sphere in k-space** as shown below; the radius is Fermi wave number k_F.

$$E_F = \frac{\hbar^2}{2m}\left(\frac{3\pi^2 N}{V}\right)^{2/3}$$

$$E_F = \frac{\hbar^2 k_F{}^2}{2m_e}$$



From these two equations, k_F can be found as,

- The ***surface of the Fermi sphere represents the boundary between occupied & unoccupied k states*** at **T = 0** for the free electron gas.

$$k_F = \left(\frac{3\pi^2 N}{V}\right)^{1/3}$$

TEMPERATURE DEPENDENCE

FREE ELECTRON GAS AT NON-ZERO TEMPERATURE

- From Statistical Mechanics, at a temperature T, the probability of occupation of an electron state of energy E is given by the Fermi distribution function
- The Fermi distribution function $f_{FD}(E)$ determines, at temperature T, the probability of finding an electron at energy E.

$$f_{FD} = \frac{1}{1 + e^{(E - E_F)/k_B T}}$$

FERMI-DIRAC DISTRIBUTION & *THE FERMI-LEVEL: MAIN APPLICATION: ELECTRONS IN A CONDUCTOR*

- The Density of States g(E) specifies *how many states exist at a given energy* E.
- The Fermi Function f(E) specifies *how many of the existing states at energy* E *will be filled* with electrons.

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

E_F = Fermi Energy or Fermi Level
k = Boltzmann Constant
T = Absolute Temperature in K

- The Fermi Function f(E) specifies, *under equilibrium conditions*, the *probability* that an available state at an energy E will be occupied by an electron. It is a *probability distribution function*.

Fermi-Dirac Distribution

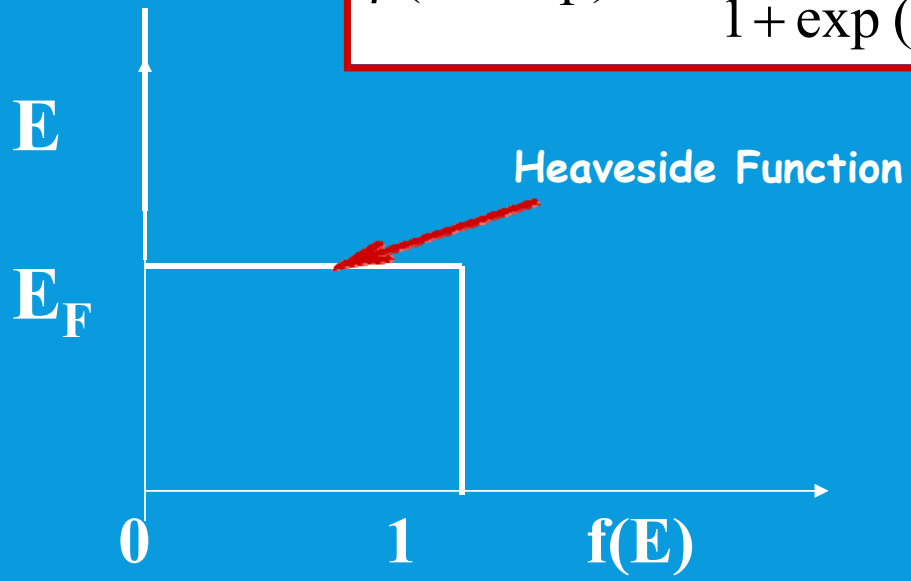
Consider $T \rightarrow 0$ K

For $E > E_F$:

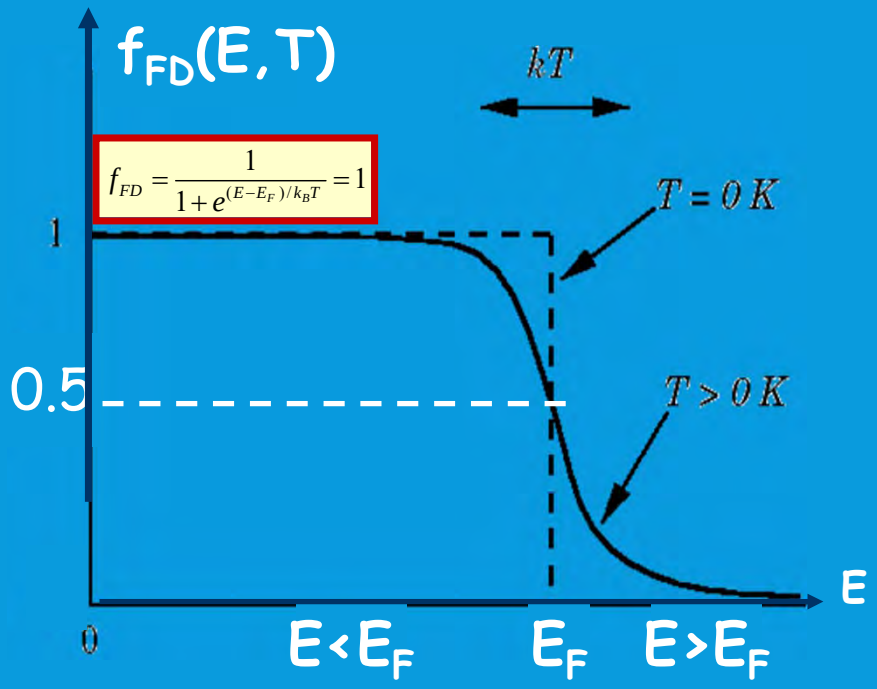
$$f(E > E_F) = \frac{1}{1 + \exp(+\infty)} = 0$$

For $E < E_F$:

$$f(E < E_F) = \frac{1}{1 + \exp(-\infty)} = 1$$



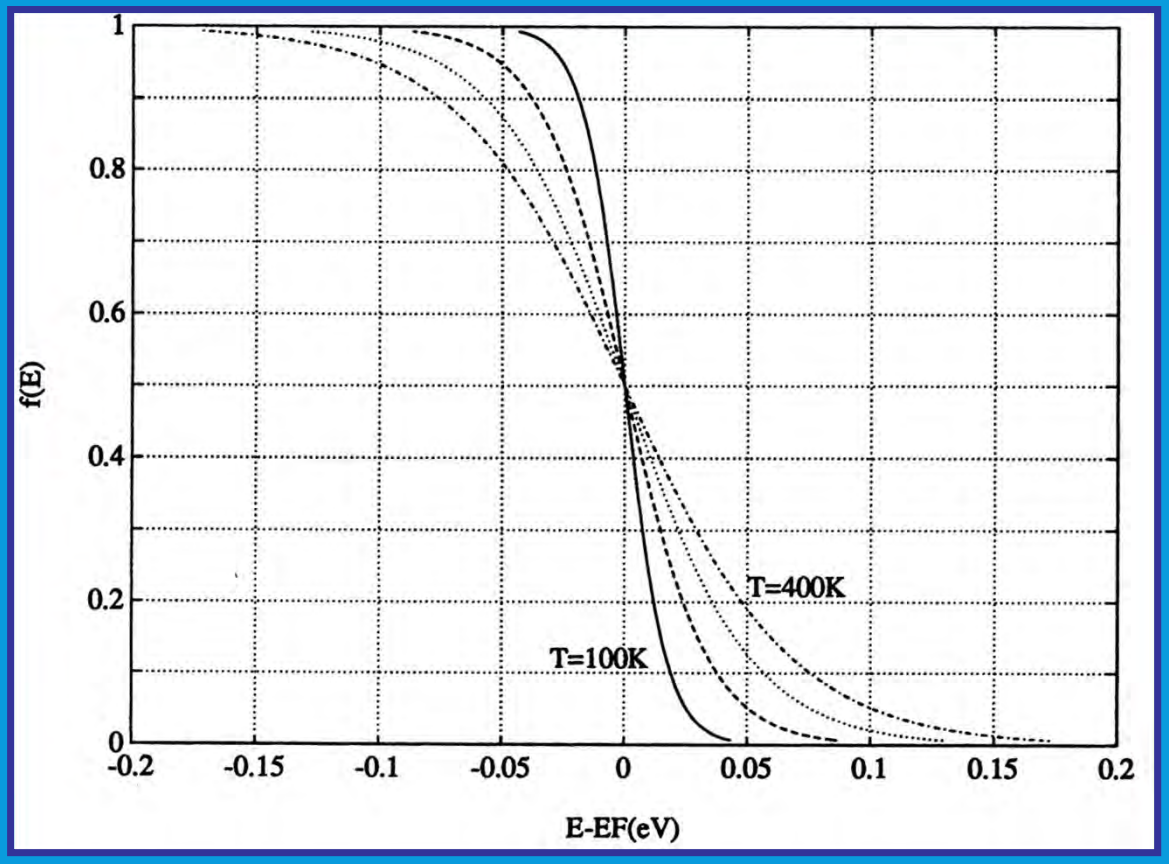
FERMI FUNCTION AT T = 0 & AT A FINITE TEMPERATURE



$$f_{FD} = \frac{1}{1+e^{(E-E_F)/k_BT}}$$

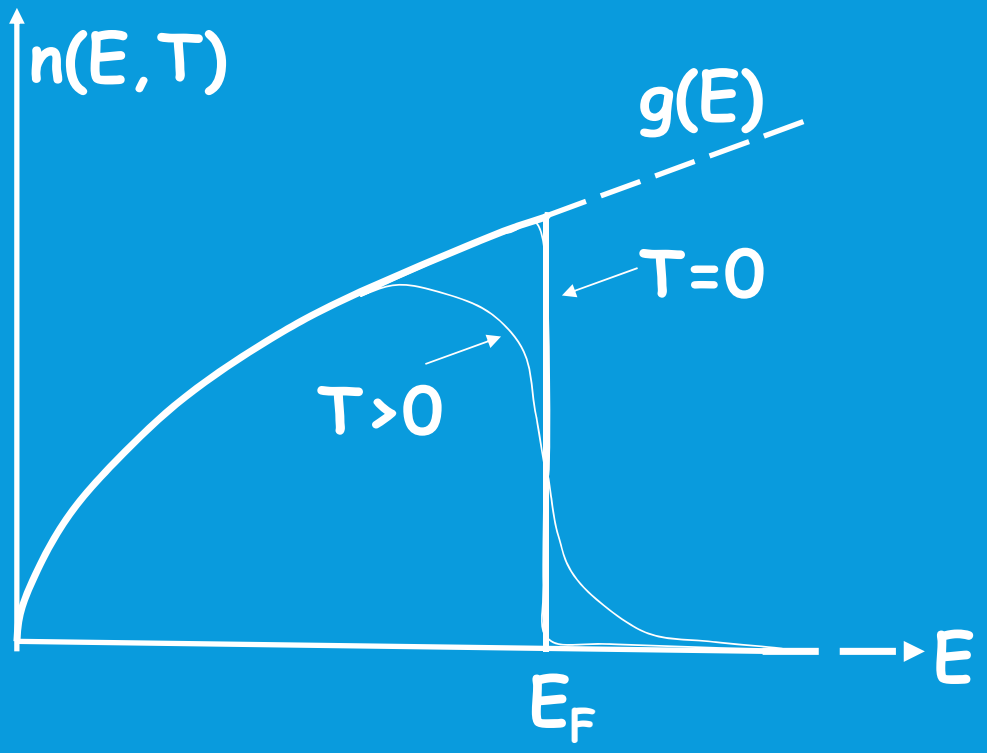
$$f_{FD} = \frac{1}{1+e^{(E-E_F)/k_BT}} = 0$$

Fermi-Dirac Distribution
Temperature Dependence



ELECTRON EMISSION

REMEMBER



- **n(E,T)** = number of free electrons per unit energy range = area under **n(E,T)** graph.

$$n(E,T) = g(E)\, f_{FD}(E,T)$$

Electrons (leptons) in a metal are distributed according to Fermi-Dirac distribution.

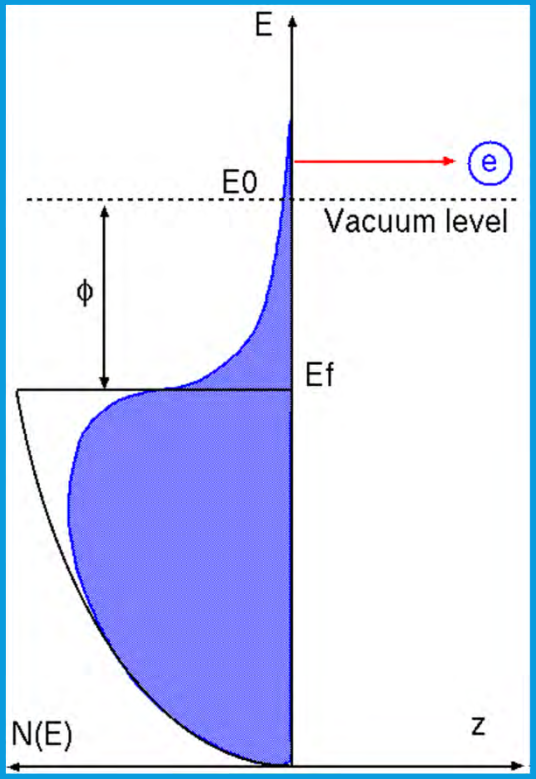
T=0: Electrons occupy the energy states up to Fermi-level (Fermi energy, E_f).

T>0: Electron distribution extends to higher energy state due to the thermal energy.

If the temperature is sufficiently high, so that the electrons are distributed up to the vacuum level (E_0), those electron escapes out to the outside.

The gap between thevacuum level and the Fermi energy is called Work function, ϕ.

To be emitted the electron energy has to be Higher than the vacuum level.



ELECTRON SOURCES - GUNS

GUNS

	CATHODE	EXTRACTION FIELD	
THERMOIONIC DC	Thermal	Static	Conventional
PHOTOCATHODE DC	Photo extraction	Static	Special (polarized, ERL)
PHOTOCATODE RF	Photo extraction	RF	Advanced
THERMOIONIC RF	Thermal	RF	Advanced

EMISSION

- Thermoionic
- Field
- Photo emission

THERMOIONIC

RICHARDSON-LAUE-DUSHMAN EQUATION

- A : thermionic emission constant
- T: Temperature (K)
- k : Boltzmann constant ; 1.38E-23 (J/K)
- e : electronic charge
- m : electron mass
- h : Plank constant ; 6.63E-34 (Js)
- Φ : Work function (fermi level escape potential)

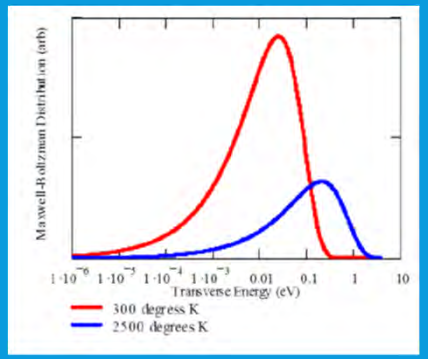
$$J = AT^2 e^{\frac{-\phi}{kT}}$$

$$A = \frac{4\pi emk^2}{h^3} = 1.20 \times 10^6 [A/m^2 K^2]$$

THERMOIONIC EMITTANCE

The velocity distribution for thermally emitted electrons is obtained from the derivative of Maxwell-Boltzmann particle distribution

$$\frac{1}{n_e}\frac{dn(v_x)}{dv_x} = \frac{m}{k_B T} v_x e^{\frac{-mv_x^2}{2k_B T}}$$



Following Lawson, we assume the normalized emittancies evaluated close to the cathode surface where the electron flow is still laminar (no crossing of trajectories) and any correlation between position and angle can be ignored. In this case, normalized cathode emittance is given by,

$$\epsilon_N = \beta\gamma\sigma_x\sigma_{x'}$$

- The root-mean-square (rms) beam size, σx, is given by the transverse beam distribution which for a uniform radial distribution with radius R is R/2. The rms divergence is given by

$$\sigma_{x'} = \frac{\langle p_x \rangle}{p_{total}} = \frac{1}{\beta\gamma}\frac{\sqrt{\langle v_x^2 \rangle}}{c}$$

The normalized, rms thermal emittance is then

$$\epsilon_n = \sigma_x \frac{\sqrt{\langle v_x^2 \rangle}}{c}$$

THERMOIONIC EMITTANCE

The mean squared transverse velocity for a M-B velocity distribution is,

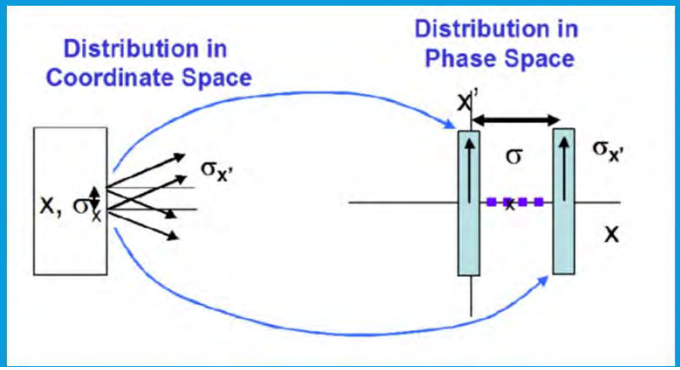
$$\langle v_x^2 \rangle = \frac{\int_0^\infty v_x^2 e^{-\frac{mv_x^2}{2k_BT}} dv_x}{\int_0^\infty e^{-\frac{mv_x^2}{2k_BT}} dv_x} = \frac{k_BT}{m}$$

Therefore the thermionic emittance of a Maxwell-Boltzmann distribution at temperature, T, is

$$\epsilon_{thermionic} = \sigma_x \sqrt{\frac{k_BT}{mc^2}}$$

The divergence part of the cathode emittance contains all the physics of both the emission process and the cathode material properties and as such summarizes much of the interesting physics of the emission process.

The beam size in coordinate space simply traces out the angular distribution to form the transverse phase space distribution as illustrated.

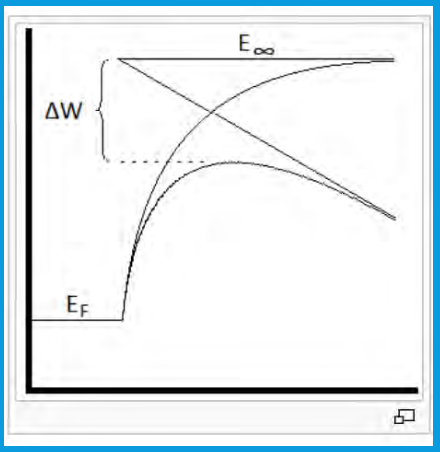


SCHOTTKY EFFECT

- The surface potential barrier seen by an escaping Fermi-level electron has height $\phi = W$ equal to the local work-function
- A thermionic electron emitter is negatively biased in respect to the environment. So we have a E field at the emitter surface.
- The electric field lowers the surface barrier by an amount ΔW, and increases the emission current.
- Substituting W with W-ΔW, and taking F as the Field intensity

$$J(F,T,W) = A_G T^2 e^{\frac{-(W-\Delta W)}{kT}}$$

$$\Delta W = \sqrt{\frac{q_e{}^3 F}{4\pi\epsilon_0}},$$



CATHODES

- For high quality source:

1) Low Work function ϕ
2) High operation Temperature

Cs\ ϕ= 1.9 eV, Te=320K

Metal : Ta\$\phi$ =4,1 eV, Te=2680K, Mo\$\phi$ =4,2 eV, Te=2230K, W\$\phi$ =4,5 eV, Te=2860K

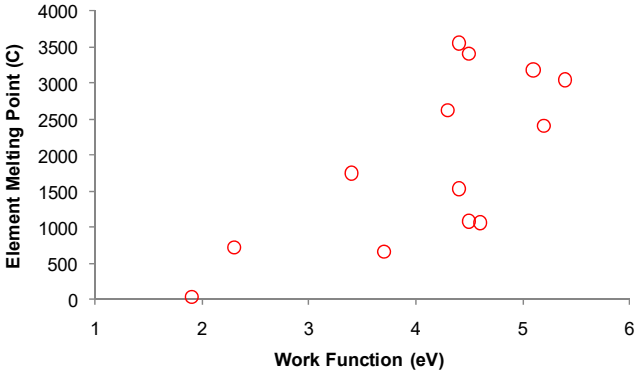
BaO cathode ϕ =1 eV but very delicate to handle due to pollution in air. So impregnated cathodes (W and BaO) are used

CeB6 ϕ =2,5 eV, Te=1800K is very good for high brightness (resistant to poisoning, long lifetime)

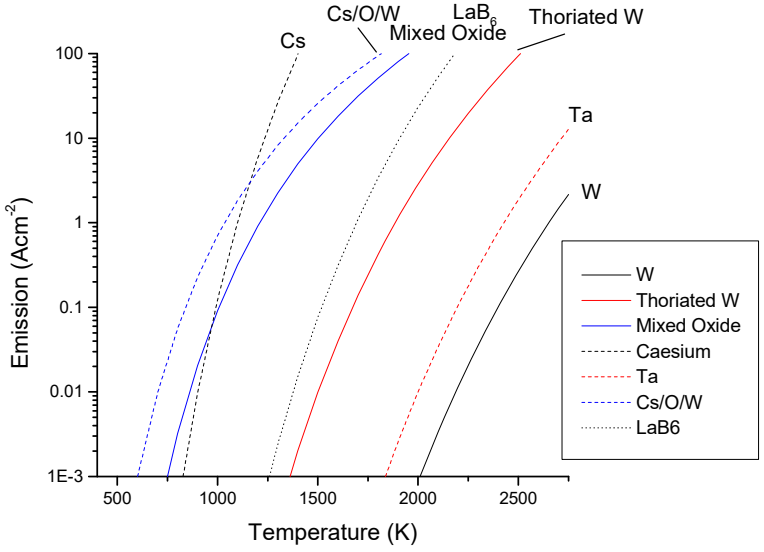
ELECTRONS - THERMIONIC EMISSION

	A $Acm^{-2}K^{-2}$	U_{work} eV
W	60	4.54
W Thoriated	3	2.63
Mixed Oxide	0.01	1
Cesium	162	1.81
Ta	60	4.12
Cs/O/W	0.003*	0.72*
LaB_6	29	2.66

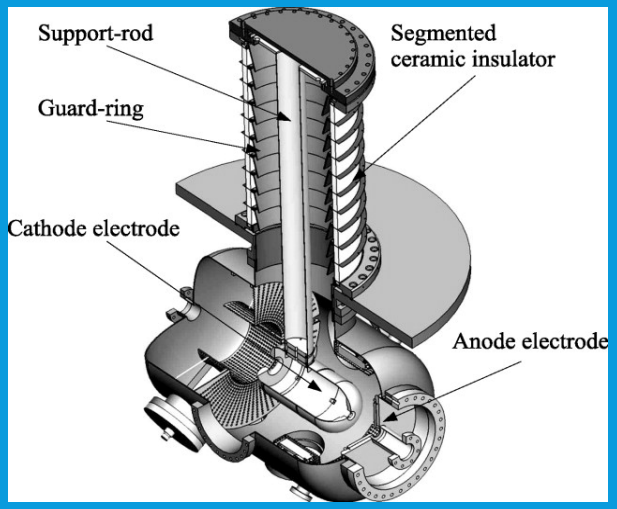
*- A and work function depend on the Cs/O layer thickness and purity



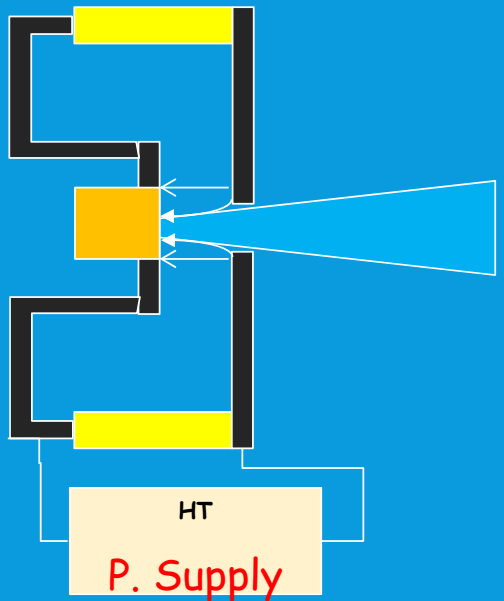
Element melting point v work function for selected metals : Nature does not provide an ideal solution

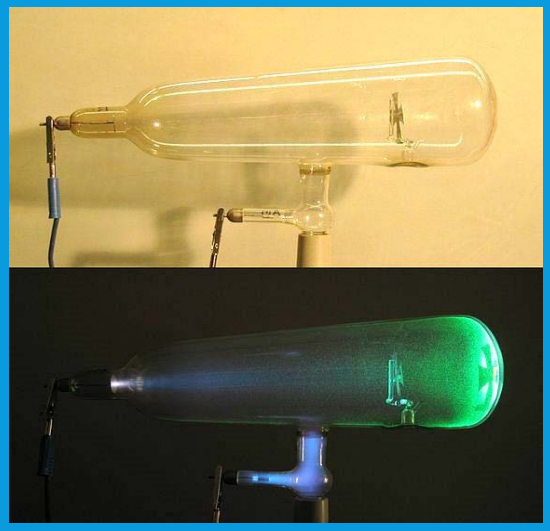


PRINCIPLE

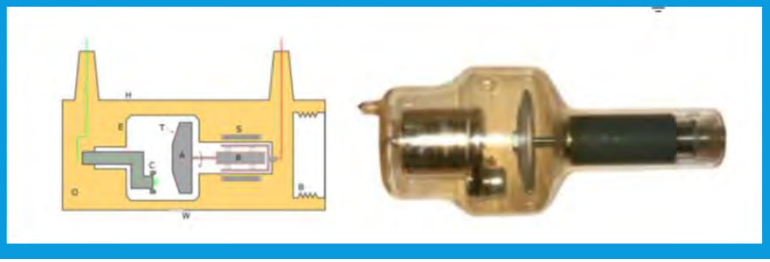


Principles of the electron guns, with thermionic and photo cathodes



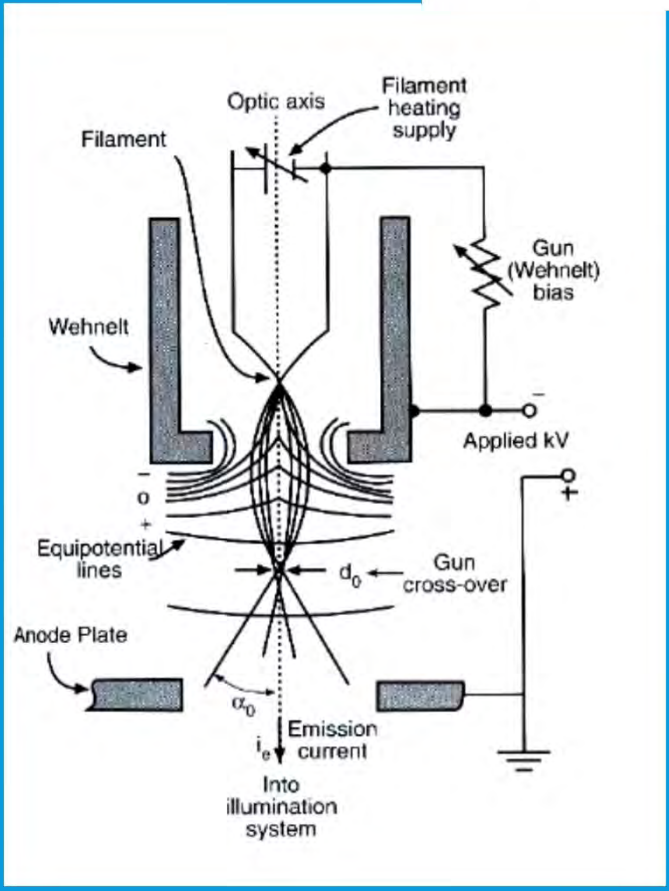


The classic Cathode Ray Experiment Crookes Tube

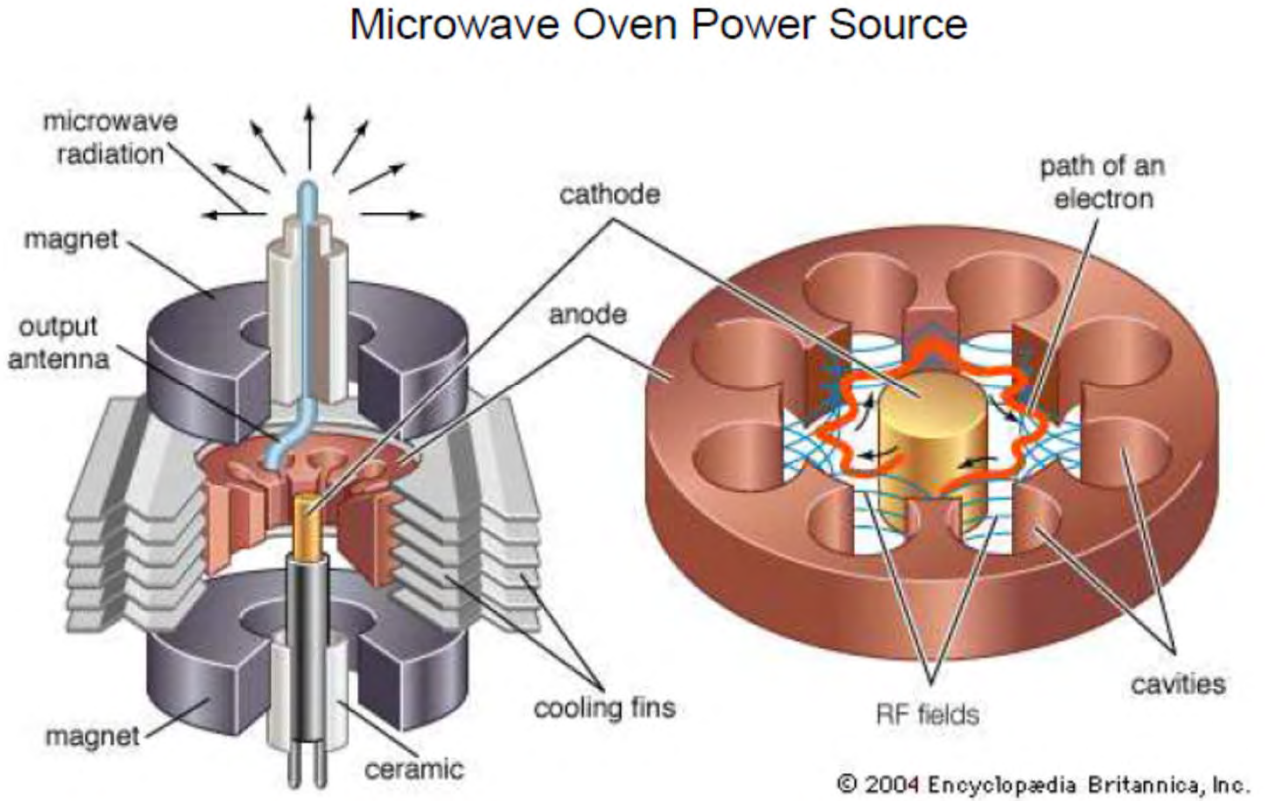


THERMOIONIC GUN FOR IMAGING

- A positive electrical potential is applied to the anode
- The filament (cathode) is heated until a stream of electrons is produced
- The electrons are then accelerated by the positive potential down the column
- A negative electrical potential (~500 V) is applied to the Whenelt Cap
- As the electrons move toward the anode the ones emitted from the filament's side are repelled by the Whenelt Cap toward the optic axis
- A collection of electrons occurs in the space between the filament tip and Wehnelt Cap. This collection is called a space charge
- Those electrons at the bottom of the space charge (nearest to the anode) can exit the gun area through the small (<1 mm) hole in the Whenelt Cap
- These electrons then move down the column to be later used in imaging



MICROWAVE OVEN



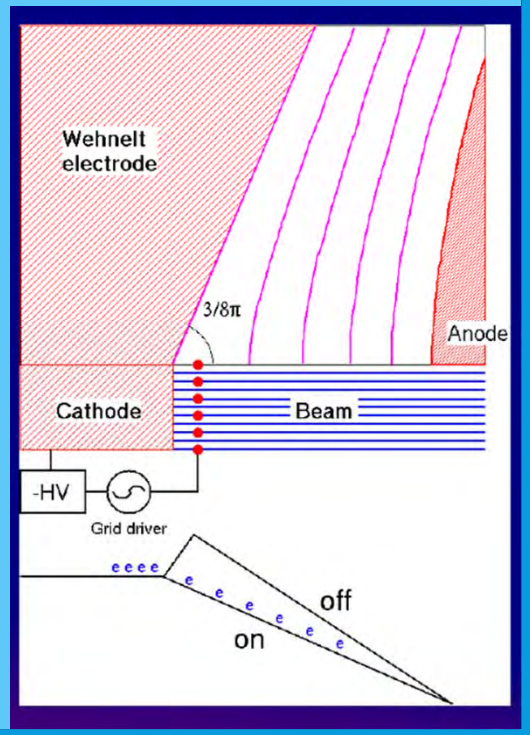
DC GUN

Triode structure: Cathode , anode and grid to tune the emission

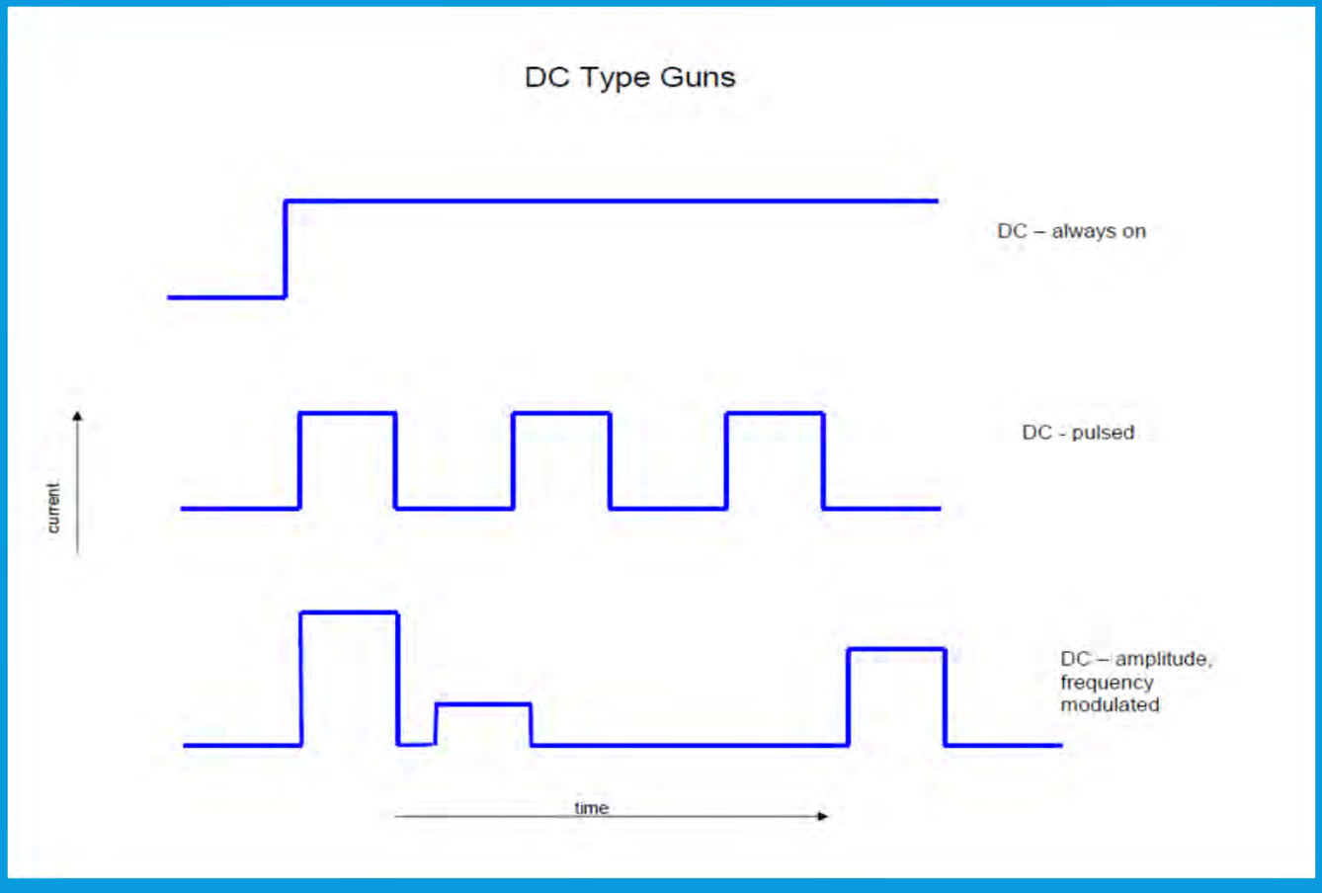
Wehnelt to collimate the space charge flux

Pulse length usually limited by the heater (gun driver) electronics to at least 1 ns

The pulse and te beam are longer….it can be operated in pulsed or CW mode



DC GUN CYCLES



FIELD EMISSION

MECHANISM

- With the larger surface field, the potential barrier to the outside becomes thin.

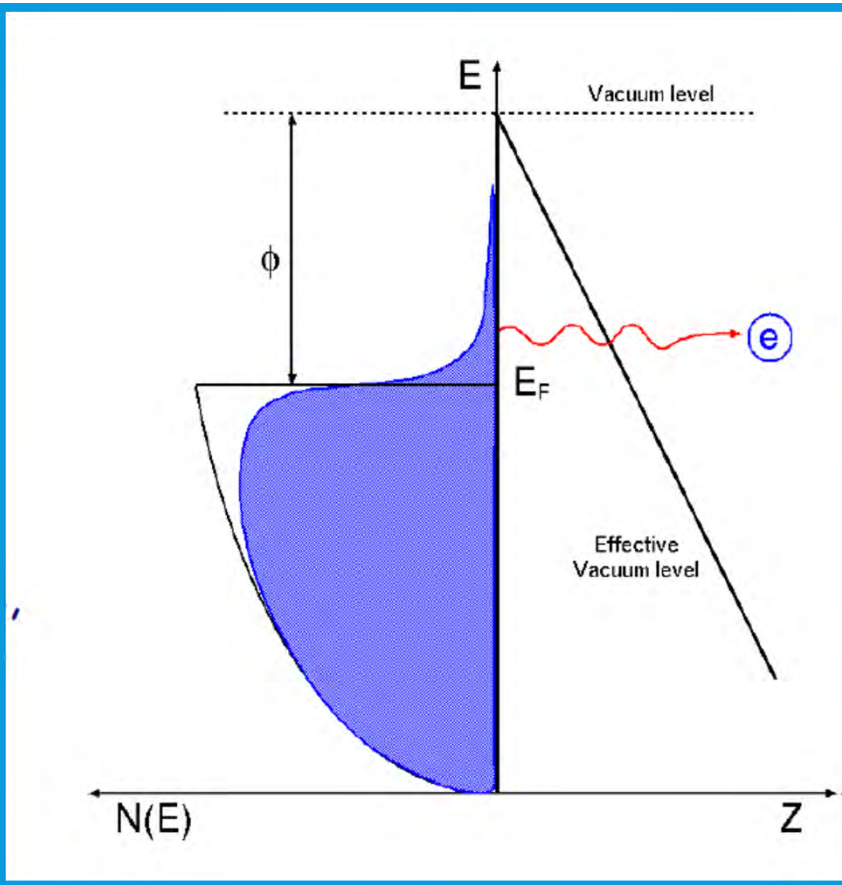
When the field is more than 1Exp8 V/m, the tunnel current becomes significant.

Because of the emission at the cold temperature,it is called sometimes as cold emission.

Fowler Nordheim Equation
F= Surface field
Vacuum potential = E0-Fz

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

$$J = \frac{e^3 F^2}{8h\pi\phi} \exp\left(\frac{4\sqrt{2m}}{3he F}\phi^{3/2}\right)$$



APPLICATION: FIELD EMITTERS….

Work function

$$e\Phi = e\phi_{work} - \frac{e^2}{16\pi\epsilon_0 x} - eE_0 x$$

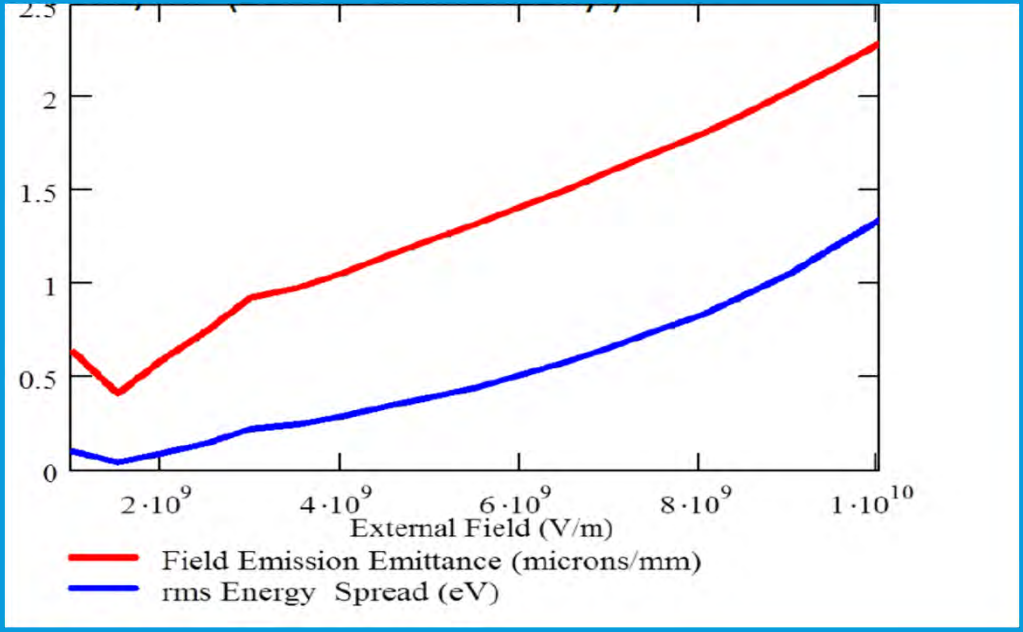
E field potential

Image charge

$$I \approx A \times 1.54 \times 10^{-6} \frac{F^2}{\phi} \exp\left[-6.83 \times 10^9 \frac{\phi^{3/2}}{F}\right]$$

EMITTANCE

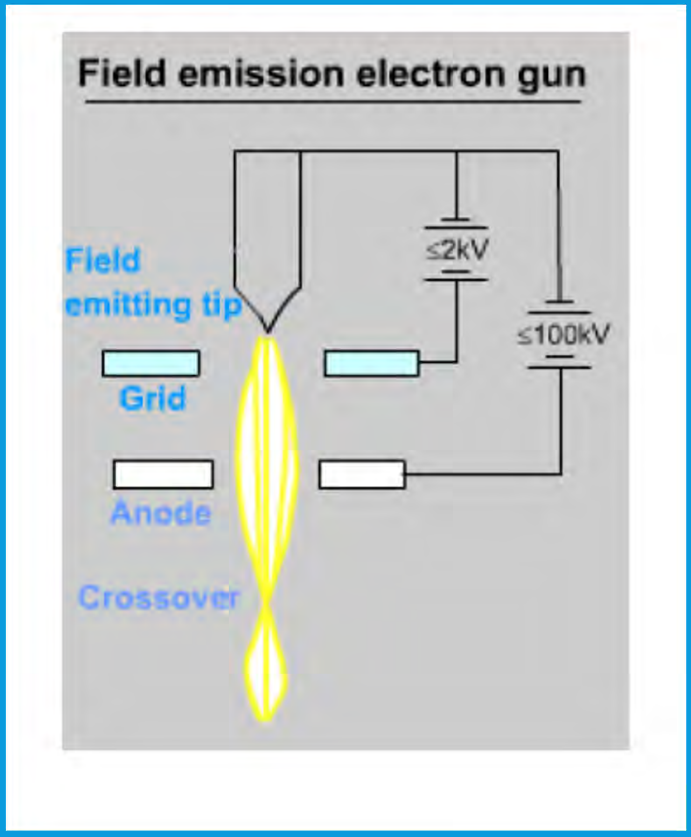
- Armed with the energy spectra the rms energy spread and the field emission emittance are numerically computed for external fields between $10^9$and 10^{10}Volts/m. (Solved numerically.)



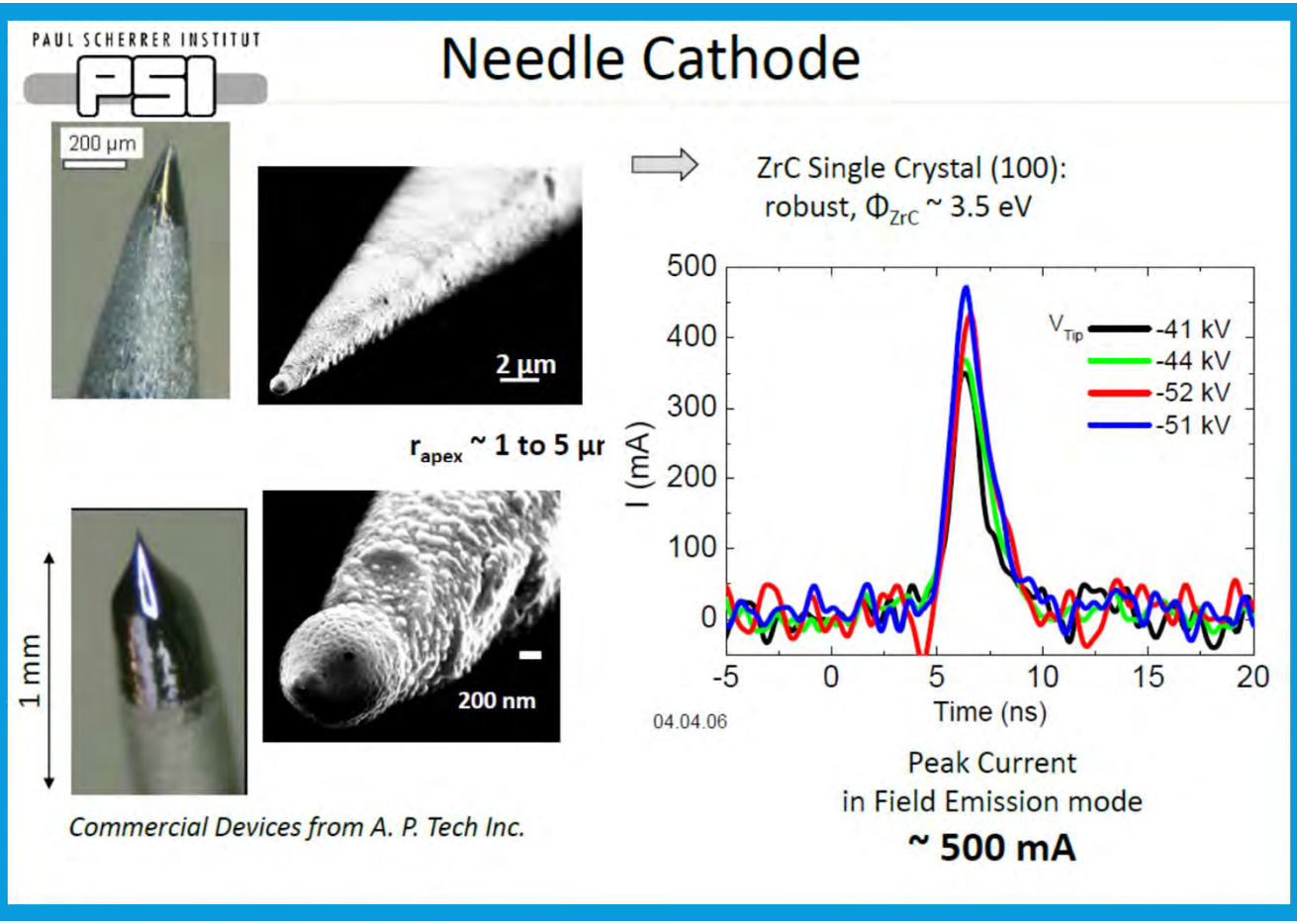
GUN PRINCIPLE....

Grid (First anode):
provides the extraction voltage to pull electrons out of the tip.

Anode (Second anode):
accelerates the electrons to 100 kV or more.



EXAMPLES – NEEDLE CATHODE

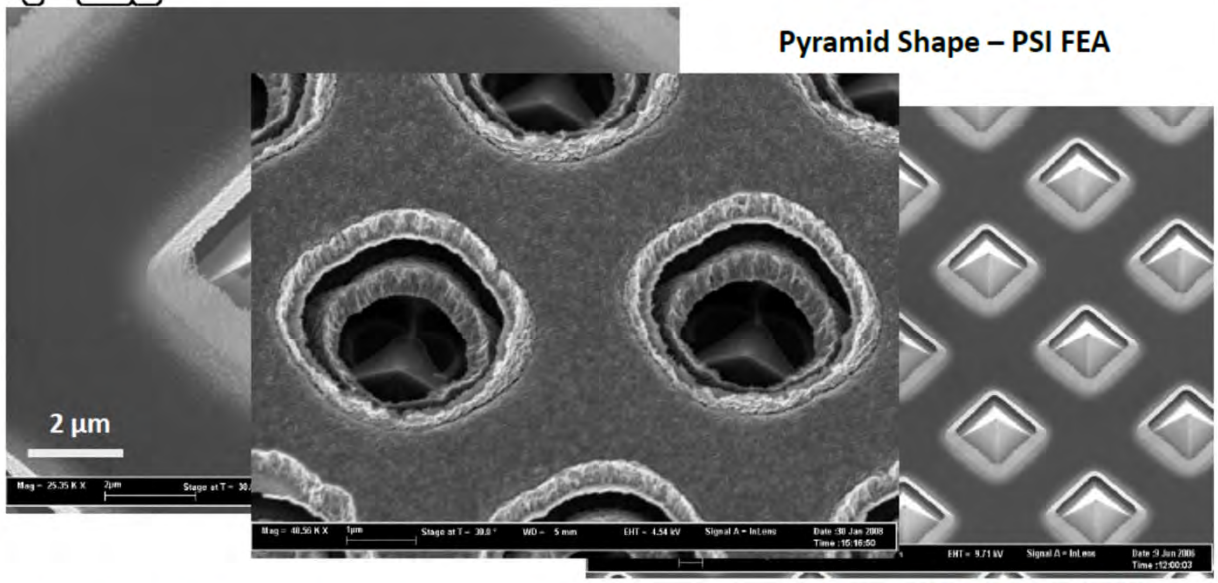


FIELD EMITTER ARRAY

PAUL SCHERRER INSTITUT

PSI

PSI Field Emitter Array



Source: S. Tsujino; E. Kirk

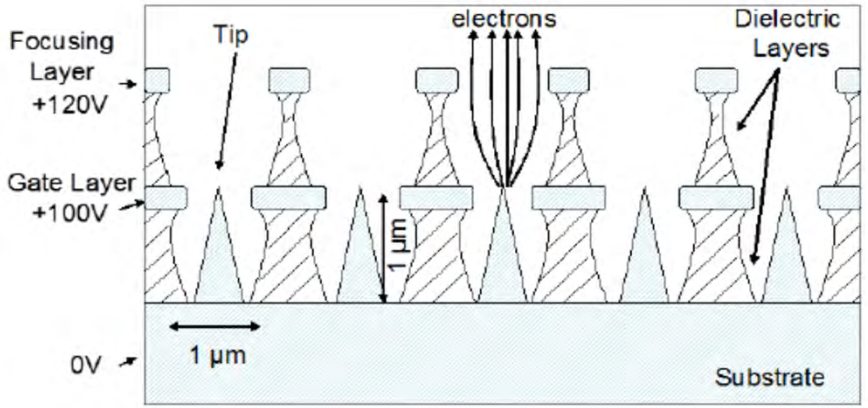
- Mo Tips (Field Enhancement Factor: <β> ~ 90)
- Metallic wafer; Molding Technique
- 10µA per tip DC (gate bias ~200V)

April 2008 PSI: First Double Gated – All Metal FEA

DOUBLE GATED FIELD EMITTER ARRAY

PAUL SCHERRER INSTITUT

Double Gated FEA



$$\varepsilon_{n,rms}(1^{st}\,Gate) \sim \beta\gamma.n.\delta x.\vartheta$$

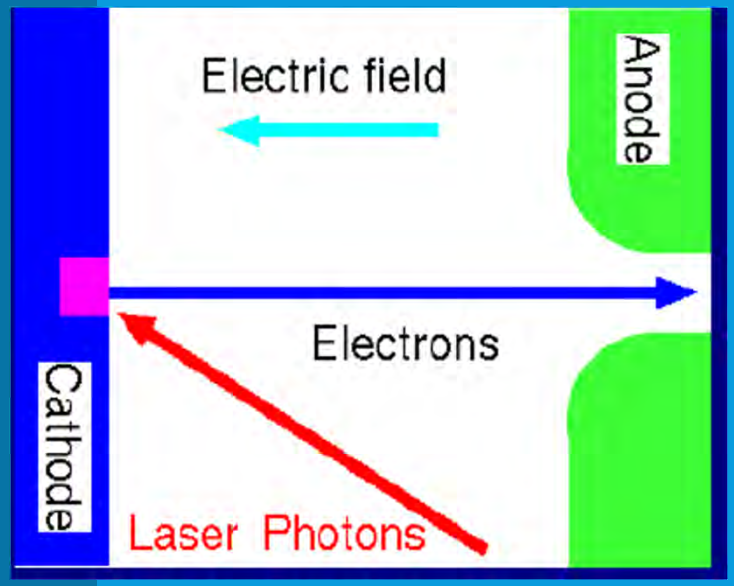
$\beta\gamma.\vartheta = 5mrad$ n=100; δx=2µm

$$\varepsilon_{n,rms}(1^{st}\,Gate) \sim 2\ mm.mrad$$

PHOTO-ELECTRON EMISSION

PHOTOCATHODE DC

- The emitted electrons are extracted by a Dc field - 100 up t 500 kV
- The electron beam is generated by photoemission by laser light impinging on a photocathode
- The temporal response is, at the first order, given by the temporal profile of the laser pulse and by the cathode response
- A lot of design flexibility in respect to the RF gun
- Different cathodes can be used



RF GUN

- Electron beam is generated in the first half-cell cavity
- Accelerating field can attain 150 MV/m, impossible in a DC due

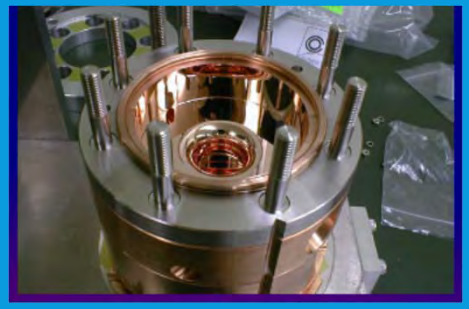
to the discharge limits

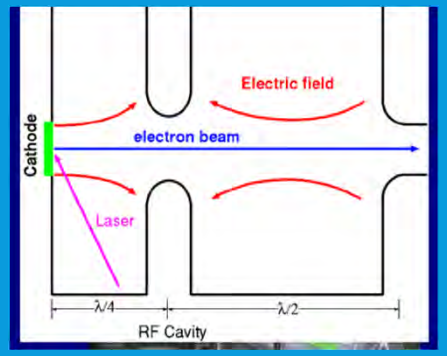
- The beam is immediately accelerated to semi relativistic energies.

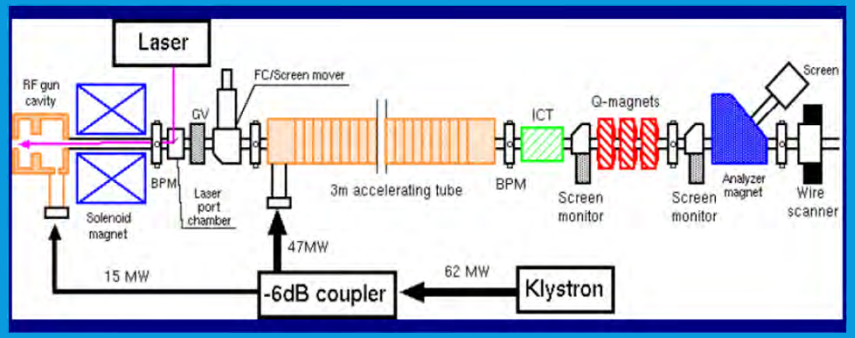
Strong reduction of the space charge effect and of the consequent emittance increase

- Bunch length is short (mainly depends on the laser pulse and on the cathode response).

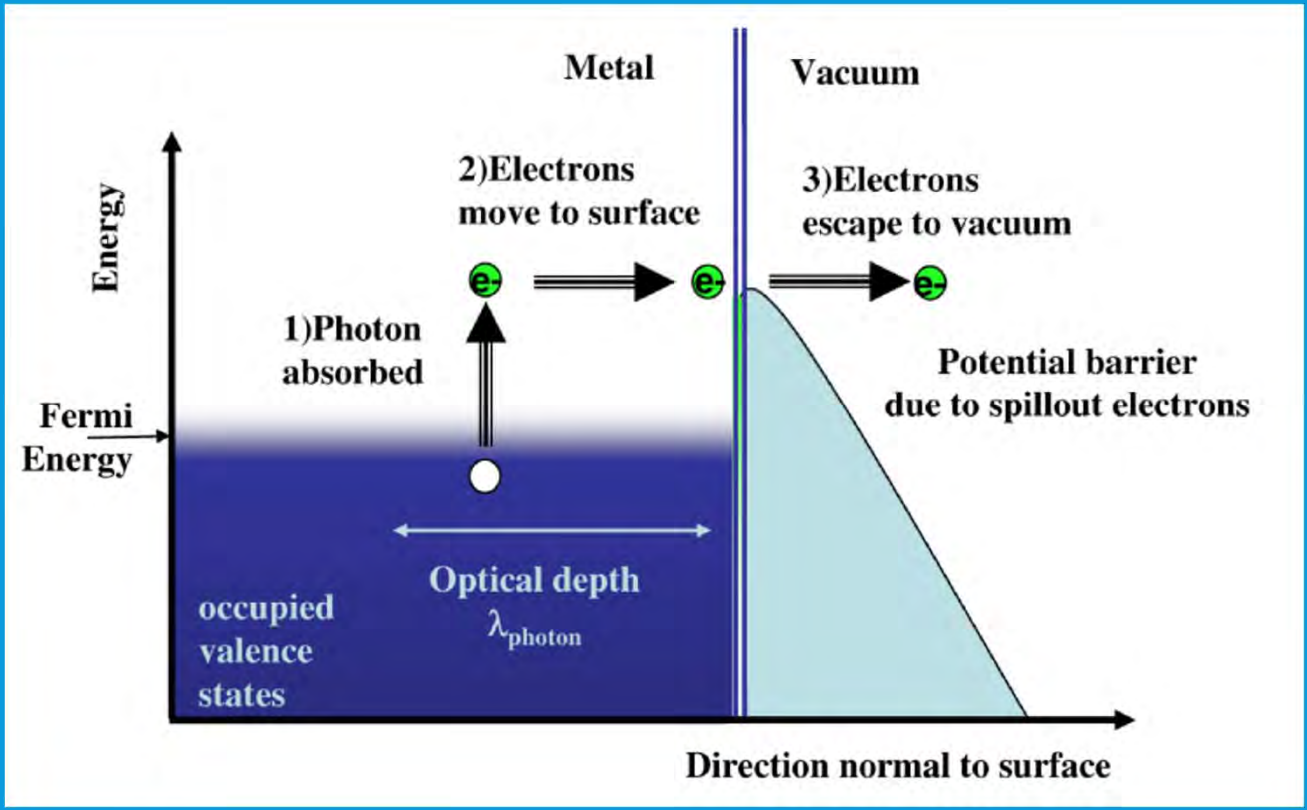
It can attain sub ps regime



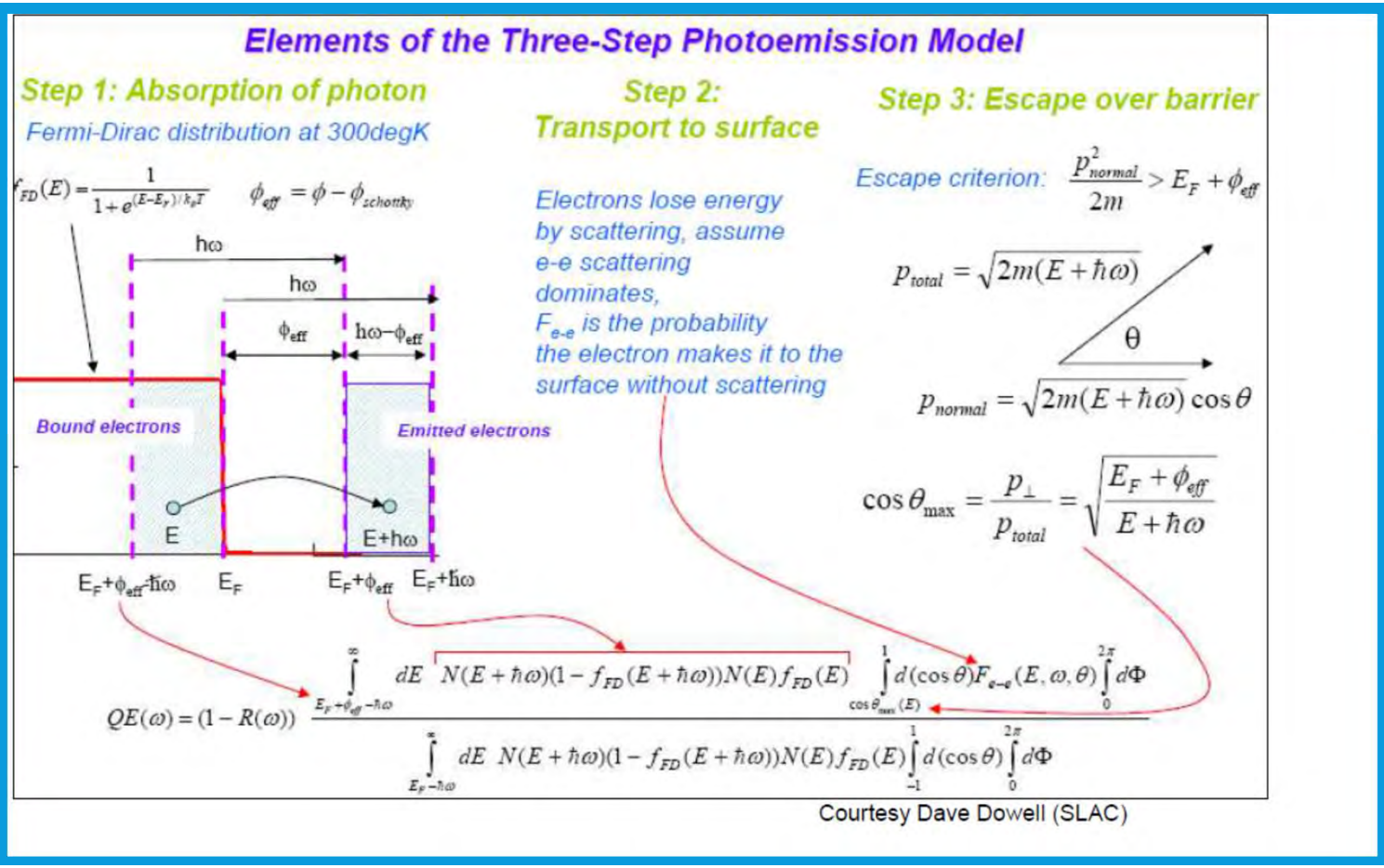




MECHANISM


Metal
Vacuum
Energy
2)Electrons
move to surface
3)Electrons
escape to vacuum
e-
e-
e-
1)Photon
absorbed
Potential barrier
due to spillout electrons
Fermi
Energy
Optical depth
λ_{photon}
occupied
valence
states
Direction normal to surface

MECHANISM



Courtesy Dave Dowell (SLAC)

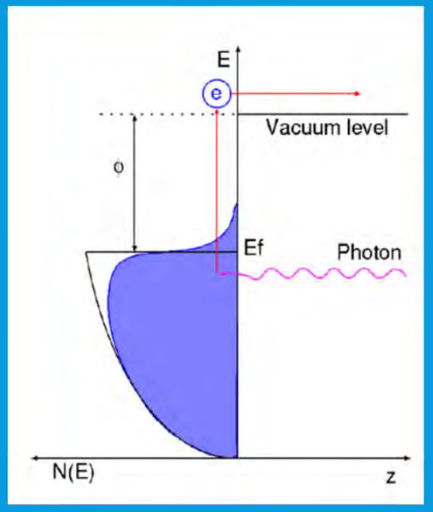
Photons excite electrons into higher energy states.

If the states are higher than the vacuum level, the excited electrons are extracted as the photoelectrons; Photo-electron effect.

Photo-emission condition : $h\nu \geq \phi$

$$J = AT^2 \int_0^{\omega_0} \frac{\log(1+\omega)}{\omega} d\omega$$

$$A = \frac{2\pi e m}{h^3} Pk^2 \qquad \omega_0 = e^{\frac{E_f - E_z}{kT}}$$



QE- Fowler Dubridge Equation

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

R=reflectivity coefficient
Fλ= scattering losses term

P shows the transition probability,
Ez is the kinetic energy of electrons in z direction. Practically,
Quantum Efficiency, η, is defined as

$$\eta = \frac{number\ of\ photo\ electrons}{number\ of\ photons}$$

RULE OF THUMB: $QE[\%] = 123.98 \frac{J[\mathrm{A/cm^2}]}{I_o[\mathrm{W/cm^2}] \times \lambda[\mu\mathrm{m}]}$

SEMICONDUCTOR QE

Cathode Wavelength	λ [nm] , E_{ph} [eV]	QE [%]	$E_a + E_{gap}$ [eV]	Thermal emittance $\left[\frac{\text{mm mrad}}{\text{mm rms}}\right]$	
				Theory (Equ. 7.6)	Experiment
Cs_2Te	262, 4.73	~10	3.5	0.9	1.2 ± 0.1
Cs_3Sb	532, 2.33 473, 2.62 405, 3.06	~4 ~7 ~9	1.6 + 0.45	0.42 0.62 0.82	0.56 ± 0.03 0.66 ± 0.03 0.80 ± 0.04
Na_2KSb	330, 3.76	~10	1 + 1	1.07	N/A
Na_2KSb:Cs	390, 3.18	~20	1 + 0.55	1.03	N/A
K_2CsSb	532, 2.33 473, 2.62 405, 3.06	~4 ~11 ~25	1 + 1.1	0.38 0.58 0.80	0.56 ± 0.03 0.69 ± 0.03 0.87 ± 0.04
GaAs(Cs,F)	532, 2.33	~10	1.4 ± 0.1	0.77	0.47 ± 0.03
GaN(Cs)	260, 4.77	~15	3.4 ± 0.1	0.94	1.35 ± 0.11

Table 7.1. Commonly used high quantum efficiency photocathodes.

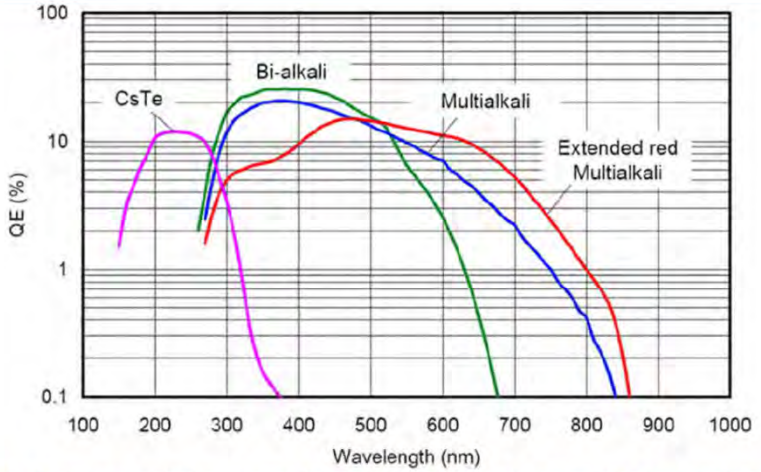


Figure 7.2. Typical spectral response for different types of photocathodes' materials. [7.5]

Work function and associated wavelength for some bulk elements [16,17,18,19,20]

Material	Work Function (eV)	Wavelength λ (nm)
Mg	3.66	339
Al	4.06 - 4.26	310 - 290
Cu	4.53 - 5.10	274 - 245
MgO	2.8	443
Al_2O_3	3.9	318
Cu_2O	5.2	239
CuO	5.3	234
Laser	4.74 / 4.67 / 3.49 / 2.48	262 / 266 / 355 / 500

ADVANTAGES AND PROBLEMS, SEMICONDUCTORS

		E_a+E_g (eV)	(nm)	Advantages	Disadvantages
Alkali-halide	CsI	6.4	209	Air transportable	209nm is impractical satellite bunches and saturation in RF gun
	CsI-Ge	5.0	248		
Alkali-antimonide	Cs_3Sb	2.0	620	Work in visible range	Very sensitive to contamination, short lifetime
	K_3Sb	2.3	539		
	Na_2KSb	2.0	620		
	K_2CsSb				
Alkali-telluride	Cs_2Te	3.5	354	a reliable photocathode material	
				Good QE and life time. Stand high field up to 120MV/m	Need UHV
				Ä Resistance to laser damage: at least 6 W/cm^2 @ 262 nm	
				Rejuvenation partially The dark current@20MV/m is negligible	Need uv laser
	Rb_2Te	4.1	302	Rejuvenated partly, by heating and ion bombardment etching	
	RbCsTe	-			
	K_2Te	-			
Negative Electron Affinity	GaAs (Cs)			polarized electron source	response time is as long as ns
	(111) Diamond		<210nm	Long life time and fast response	A poor response because of NEA

Table1: Properties of semi-conductor photocathodes.

PROPERTIES SEMICONDUCTORS

Material	sub	QE @λ	Life time	Field (MV/m)	working vacuum (mbar)	Dark current	average current density	Response time	damage by Laser
CsI-Ge		0.73 %@213nm 0.13%@266nm	$T_{1/t}$ > One year	70					
		2%@209nm	$T_{1/t}$ > 150 h		10^{-10}~10^{-9}			(>ps)	
Cs_3Sb		2.0%@266nm 0.38%@532nm	very short (from 1 to few hours)						
		4%@527nm	$T_{½}$ <4 hours	>20	10^{-10}~10^{-9}			~ps	
K_3Sb		1.6%@266nm 0.023%@532nm							
		1~3%@262nm	robust						
K_2CsSb		8%@527nm	$T_{½}$ <4 hours	>20	10^{-10}~10^{-9}			~ps	
		1.2%@541nm	daily						
Cs_2Te		13%@266nm							
	Cu,Au	0.2-0.5 %		22		Very small			
		16%@262nm	~450 hrs QE>1.5%	100					
	Cu-Au	2~8%@262nm	Few week QE>1.5%	120	1~5×10^{-9}				
	Cu		>300 hrs	100	7×10^{-9}	Several mA			
		10% at 262nm	drops during the first 50 hours with a τ~40 hours, followed by a slower decrease with a τ~350 hours.	127	10^{-9}			<2ps	

Material		QE @λ	Life time	Field (MV/m)	working vacuum (mbar)	Dark current	average current density	Response time	damage by Laser
		> 1.5 %	QE > 1.5 % during 460 h @ 750 μA		1.4x10-9		21 mA/cm^2		6 W/cm^2 @ 262 nm
	Mo	5.6%@262nm		35~40	10^{-10}	16μA			
		0.2-0.5 %		22		Very small			
		8%@263nm	More than one month QE>1%		5×10^{-8}				
	Mo	16~18% @ 251nm 8~12% @ 263nm	over 1% for 100h	20~25	10^{-10}	<0.4mA/cm^2			
		13%@266nm	$T_{1/t}$>100 hrs	>20	10^{-10}~10^{-9}			<3ps	
KCsTe		Same as Cs_2Te							
GaAs (Cs)		3~5%@ HeNe		30		Larger than PEA carhodes			
			20 hours of CW beam with an average current of 3.1mA, $T_{1/t}$~58 hrs	3.9 DC gun					
		1.5~6%@750nm	short		10^{-11}			<ns	

PROPERTIES METALS

Material	QE @λ	Life time	Field (MV/m)	working vacuum (mbar)	Dark current	average current density	Response time	damage by Laser
Cu	4×10^{-5}@248nm		75					
	1.4×10^{-4}@266nm	Almost indefinite	>100	10^{-7}			<ps	
Mg	1.3×10^{-4}@248nm		75					
	6×10^{-4}@266nm	>5000hours		10^{-7}			<ps	
	0.2 ~ 0.3% @266nm.		100	10^{-9}	thermal emittance is 0.4 mm-mrad/mm			
	1.3×10^{-4}@265nm			10^{-10}				
Y	1×10^{-5}@248nm		75					
	5×10^{-4}@266nm	long	~100	$<10^{-7}$			<ps	
Ca	4×10^{-5}@248nm		75					
Sm	7×10^{-4}@266nm	long	~100	$<10^{-7}$			<ps	
Ba	0.1%@337nm			$<10^{-7}$			<ps	
Nb	10^{-4}@266nm							0.3 mJ/mm² for 15ps, 266nm 3.5 mJ/mm² for 20ns, 248nm

SEMICONDUCTORS - VALENCE, CONDUCTION AND VACUUM LEVEL (POSITIVE AND NEGATIVE) ELECTRON AFFINITY

Electron affinity χ is the
Energy gap between E_0 and
E_c (some eV). Work potential is the difference
Beteween E_0 and E_f

NEA -> $E_0 > E_c$ in the BULK

The Positive EA electrons in the bulk are loosing energy
by collisions...only surface electrons are emitted
For Negative EA electrons in Conduction Band are thermalized
and their free mean path is much bigger...
also bulk electrons (microns) are emitted

Increased efficiency. Photon has to have the GAP energy

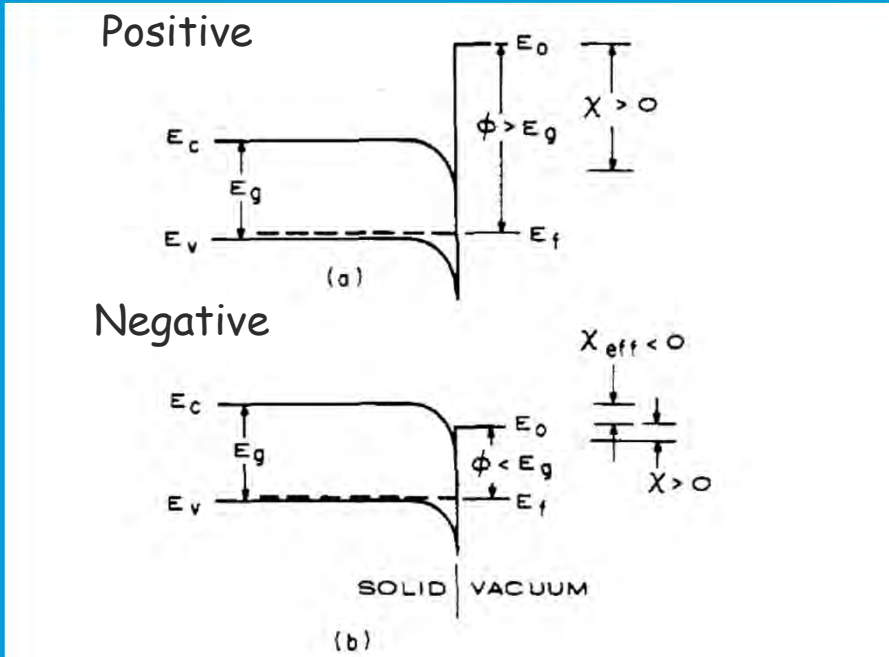


Fig. 1. Band diagrams showing (a) positive electron affinity and (b) negative electron affinity conditions in relation to band-gap energy E_g and work function ϕ.

EMITTANCE

- Schottky effect (external field lower the work potential). Take into account

$\phi_{eff} = \phi - \phi_{schottky}$

Total momentum is $\sqrt{2m(E+\hbar\omega)}$

and the electron perpendicular have $\frac{p_z^2}{2m} > E_{Fermi} + \phi_{work} - \phi_{Schottky}.$

So $cos\theta_{max} = \sqrt{\frac{E_F + \phi_{work} - \phi_{Schottky}}{E+\hbar\omega}}$

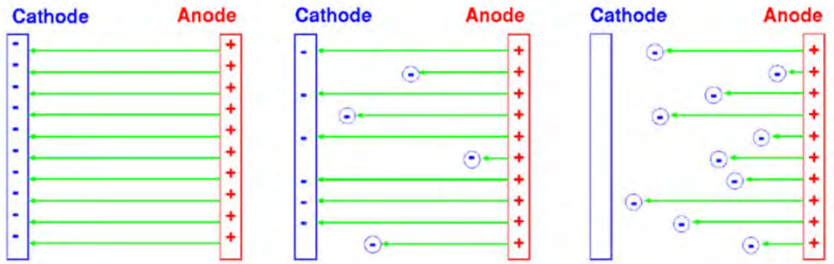
Emittance ->rms of the transverse momentum $p_x = \sqrt{2m(E+\hbar\omega)}sin\theta cos\phi$ obtaining

$$\Delta_{photo} = \beta\gamma\sigma_{x',photo} = \sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}.$$

Averaging in both planes

$$\epsilon_{photo} = \sigma_x\sqrt{\frac{2(\hbar\omega - \phi_{eff})}{3mc^2}}.$$

SPACE CHARGE LIMIT



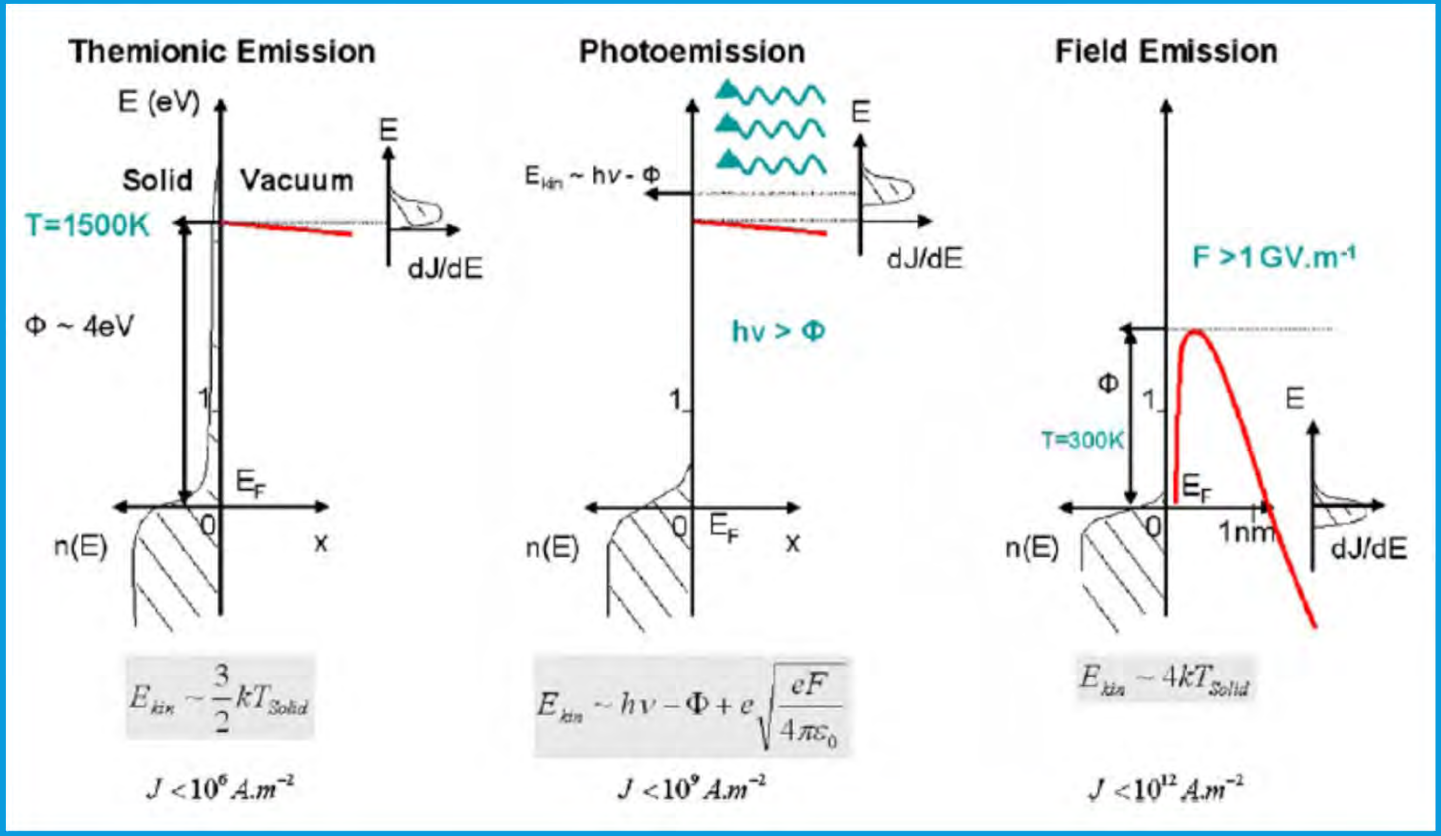
- Electron terminate the electric flux (remember Gauss's law).
- Electric field is weakened by the space charge.
- At some limit, the field at the cathode surface is disappeared; the space charge limit.
- In the space charge limit, the dynamics of the electron cluster decides the electron current, rather than the emission from the cathode.
- In diode geometry - two electrodes and one dimension – the current is

$$J = 2.33\times10^{-6} S \frac{V^{3/2}}{d^2} = PV^{3/2} \left(A/m^2\right)$$

V and d : voltage and distance between two electrodes.

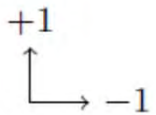
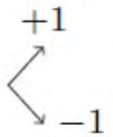
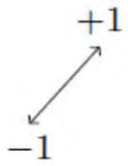
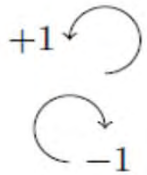
- – S : area size
- – P : perveance defined as; $P = 2.33\times10^{-6} \frac{S}{d^2} \left(A V^{-3/2}\right)$

SUMMARY


Themionic Emission
E (eV)
E
Solid
Vacuum
T=1500K
dJ/dE
Φ ~ 4eV
1
E_F
0
n(E)
x
$E_{kin} \sim \frac{3}{2} kT_{Solid}$
$J < 10^{6} A.m^{-2}$
Photoemission
$E_{kin} \sim h\nu - \Phi$
E
dJ/dE
hν > Φ
1
0
E_F
n(E)
x
$E_{kin} \sim h\nu - \Phi + e\sqrt{\frac{eF}{4\pi\varepsilon_0}}$
$J < 10^{9} A.m^{-2}$
Field Emission
F >1 GV.m⁻¹
Φ
1
E
T=300K
E_F
0
1nm
n(E)
dJ/dE
$E_{kin} \sim 4kT_{Solid}$
$J < 10^{12} A.m^{-2}$

POLARIZED SOURCES

POLARIZATION - STOKES PARAMETERS

Stokes parameters	Photon		Electron
I_0	Intensity		Intensity
P_1 or ξ_1	 Plane polarization along $\vec{\epsilon_1}$ (+1) and $\vec{\epsilon_2}$ (−1)	$-1 \longleftrightarrow +1$	Transverse polarization ζ_1 orthogonal to the momentum direction
P_2 or ξ_2	 Plane polarization at 45° to the right of $\vec{\epsilon_1}$ and $\vec{\epsilon_2}$		Transverse polarization ζ_2 orthogonal to the momentum direction
P_3 or ξ_3	 Left (+1) and Right (−1) circular polarization		Longitudinal polarization ζ_3 parallel (+1) or antiparallel (−1) to the momentum direction

POLARISED ELECTRONS

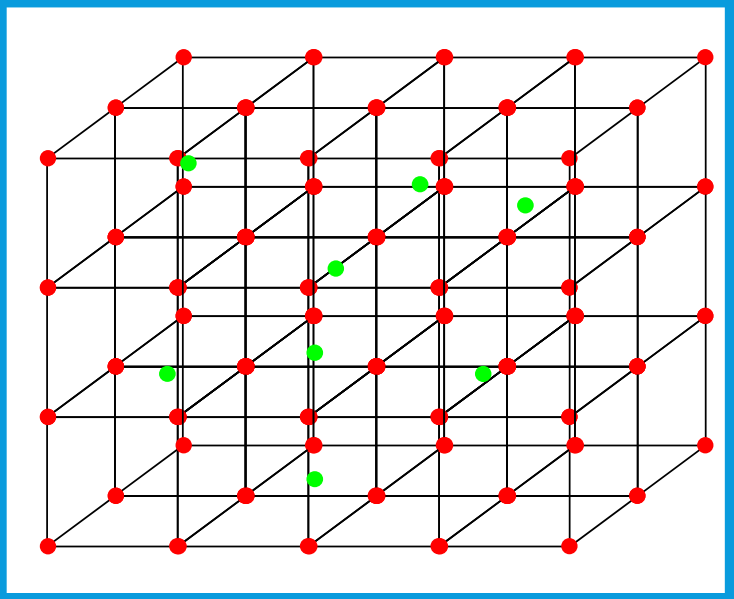
Projecting the spin on the three axis the polarization vector is given by :

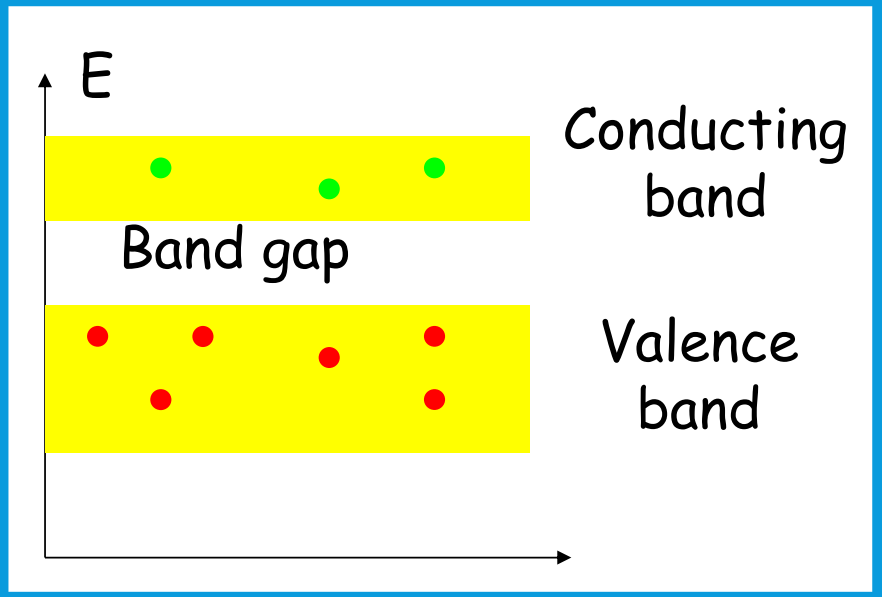
$$\vec{\zeta} = \begin{pmatrix} \zeta_1 \\ \zeta_2 \\ \zeta_3 \end{pmatrix} = \frac{1}{N} \sum_{i=1}^{N} \vec{\zeta}_i$$

Considering the longitudinal polarization in respect to the propagation vector (momentum) we can have parallel or Antiparallel states:

$$P_e = \frac{\zeta_3}{I_0} = \frac{i(c_2^* c_1 - c_1^* c_2)}{c_1^* c_1 + c_2^* c_2} = \frac{N_+ - N_-}{N_+ + N_-}$$

SEMICONDUCTOR BAND STRUCTURE





Doping (Z, Be) is used to control the concentration of carriers:

$10^{17}\,\mathrm{cm}^{-3}$ - low

$10^{18}\,\mathrm{cm}^{-3}$ - medium

$10^{19}\,\mathrm{cm}^{-3}$ - high

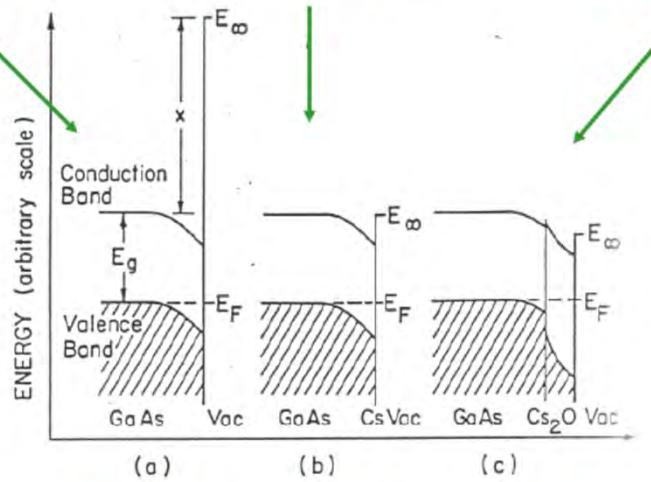
POLARIZED CATHODE - GAAS

Photo-Emission from GaAs

Bare GaAs surface;
Large work function.
No electrons

Alkalai (Cs) reduces
work function.
Some electrons.

Cesium + Oxidant (O or NF3)
"Negative Electron Affinity".
Many electrons



$$QE = \frac{\#\ e^-\text{'s}}{\#\ \gamma\text{'s}}$$

$E_a > 0$ $E_a \approx 0$ $E_a < 0$

POLARISED ELECTRONS

- Main principle : electrons with definite spin occupies separate states.
- Exciting electrons form Valence to Conduction the spin is preserved
- Electron SPIN – ORBIT coupling separate P1/2 and P3/2 levels…
- It is possible so to excite states selecting spin numbers

PHOTOEMISSION FROM P-TYPE SEMICONDUCTORS

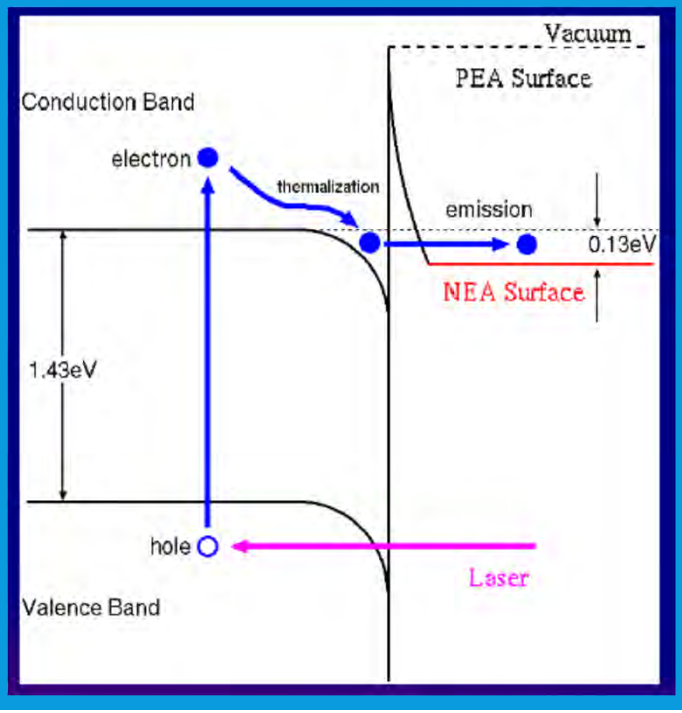
In GaAs cathodes 50% polarization is possible but little current density , limited by the small QE (Large energy jump…) -> SOLUTION NEA cathodes. Electrons are excited to the conduction band, and go easily at the vacuum level . By increasing the QE it is possible to optimize the laser wavelength and intensity

Φ for GaAs a few eV, reduced to ~1 eV with Cs,O

Bands bend down with p doping, ~0.75 eV for GaAs

Net result: Vacuum level below CBM in bulk (negative electron affinity)

This increase the emitted current



TRANSITIONS

- angular momentum conservation gives the allowed transition from the four initial states mj= +- 3/2 and +-1/2 and the two final mj=+-1/2 depending on the initial helicity of the photon (+-1).

The rules for absorption of the photon (and consequent electron transition) are for right or left hand helicity respectively -> Δmj=+1, Δmj=-1

Example , for a right hand helicity ->

$$-|3/2,-3/2\rangle_{Valence} \rightarrow |1/2,-1/2\rangle_{Conduction} \qquad with\ \Delta m_j = -\frac{1}{2} - \left(-\frac{3}{2}\right) = +1$$

$$-|3/2,-1/2\rangle_{Valence} \rightarrow |1/2,+1/2\rangle_{Conduction} \qquad with\ \Delta m_j = \frac{1}{2} - \left(-\frac{1}{2}\right) = +1$$

For the allowed transitions the transition probability amplitudes are given by the Clebsh Gordon coefficents

$$P(|3/2,-3/2\rangle_{Valence} \rightarrow |1/2,-1/2\rangle_{Conduction}) = 1 \ , P(|3/2,-1/2\rangle_{Valence} \rightarrow |1/2,+1/2\rangle_{Conduction}) = \frac{1}{3}$$

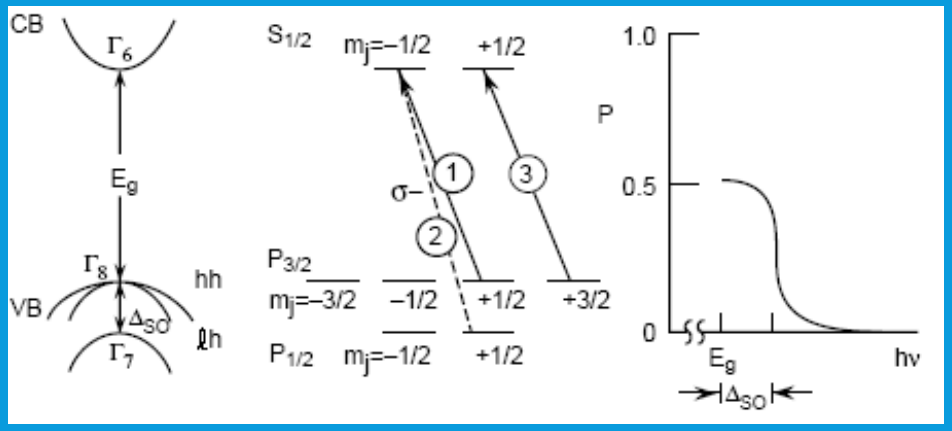
$$P(|3/2,+3/2\rangle_{Valence} \rightarrow |1/2,+1/2\rangle_{Conduction}) = 1 \ , P(|3/2,+1/2\rangle_{Valence} \rightarrow |1/2,-1/2\rangle_{Conduction}) = \frac{1}{3}$$

POLARIZATION FOR BULK GAAS

Calculated the probabilities of transition
the polarization is limited to 50%, given
by the Clebsh Gordon coefficients.
The transition from P1/2
is supressed by the laser tuning
In the degenerate P3/2 states the different
probabilities between 3/2 and $\frac{1}{2}$ states gives
the final polarization

Energy
vs
Momentum

Polarization
vs excitation photon
energy



Spin-orbit split-off band below VBM by Δ_{SO}=0.35 eV
->P_{max} = (3-1)/(3+1)=0.5…see next slide

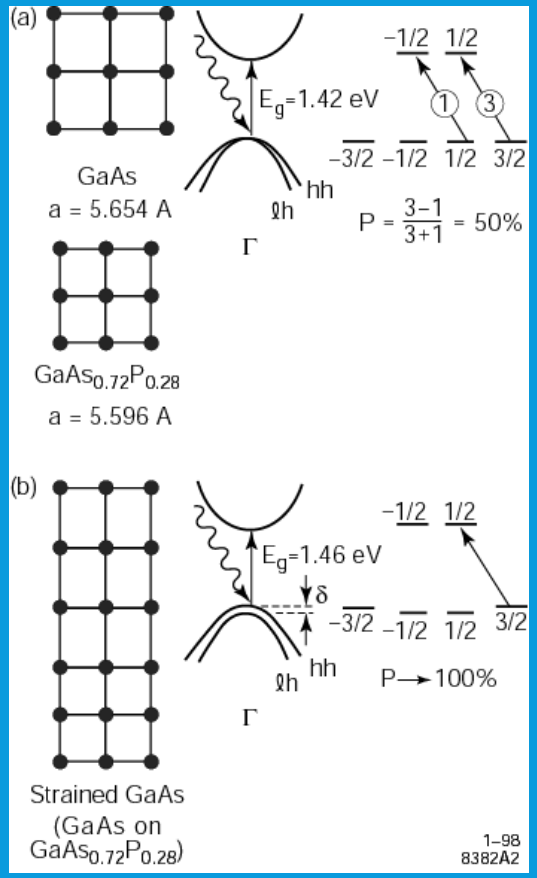
Needs photons in the range Eg < Eγ < Eg+Δso

Single-layer Strained GaAsP/GaAs Canceling the degeneracy

Transition from mj=+- 3/2 is selected by untying the degenerecence of the states with strained and superlattice structure

The laser has to match the good transition, 1.46 eV

With this wavelength QE is reasonable

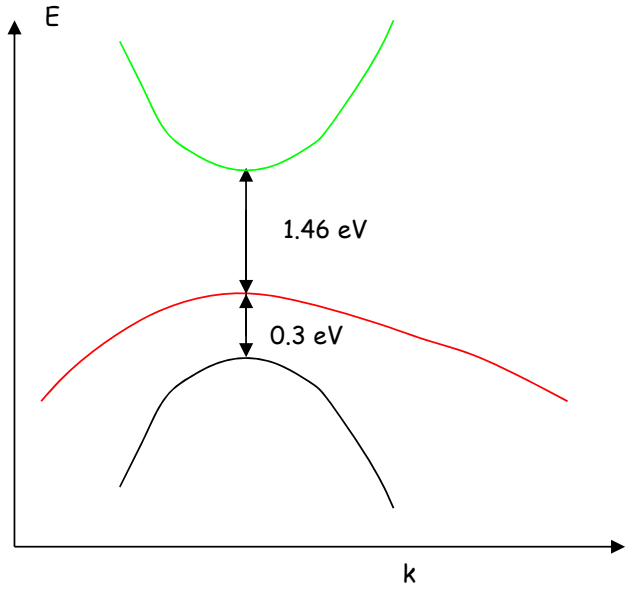


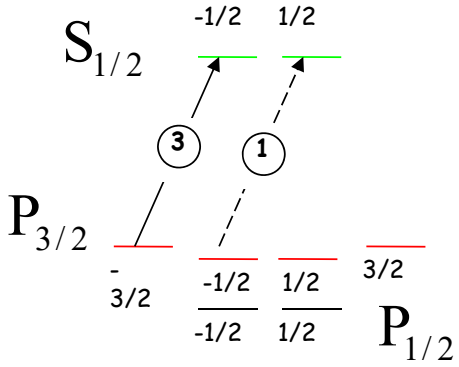
Bi-axial compressive strain lifts the degeneracy of the hh and lh bands at Γ

δa~1% yields δ of 50-80 meV

STRAINED CRYSTAL

With this technique it is possible to separate the levels at the degeneracy Tuning the laser light it is possible to select only the appropriate spins





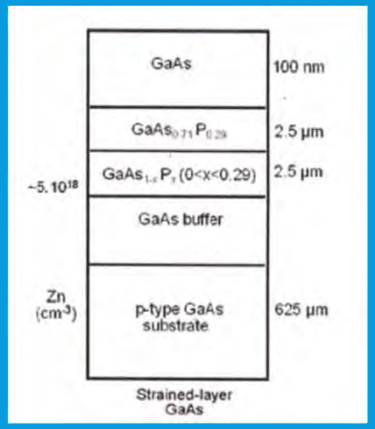
$$\sigma^{+}\text{light} \Rightarrow \Delta m_j = +1$$

$$P_{max} = 100\%$$

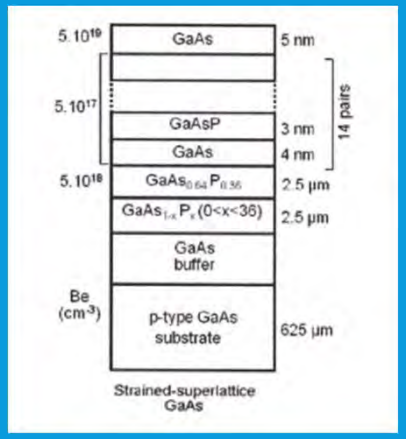
STRAINED CRYSTAL

- How to do it
- Growing a layer of GaAsP on GaAs
- The strain is introduced by the mismatch between the two different lattice structures
- Improved by GsAs and GsAsP supelattices

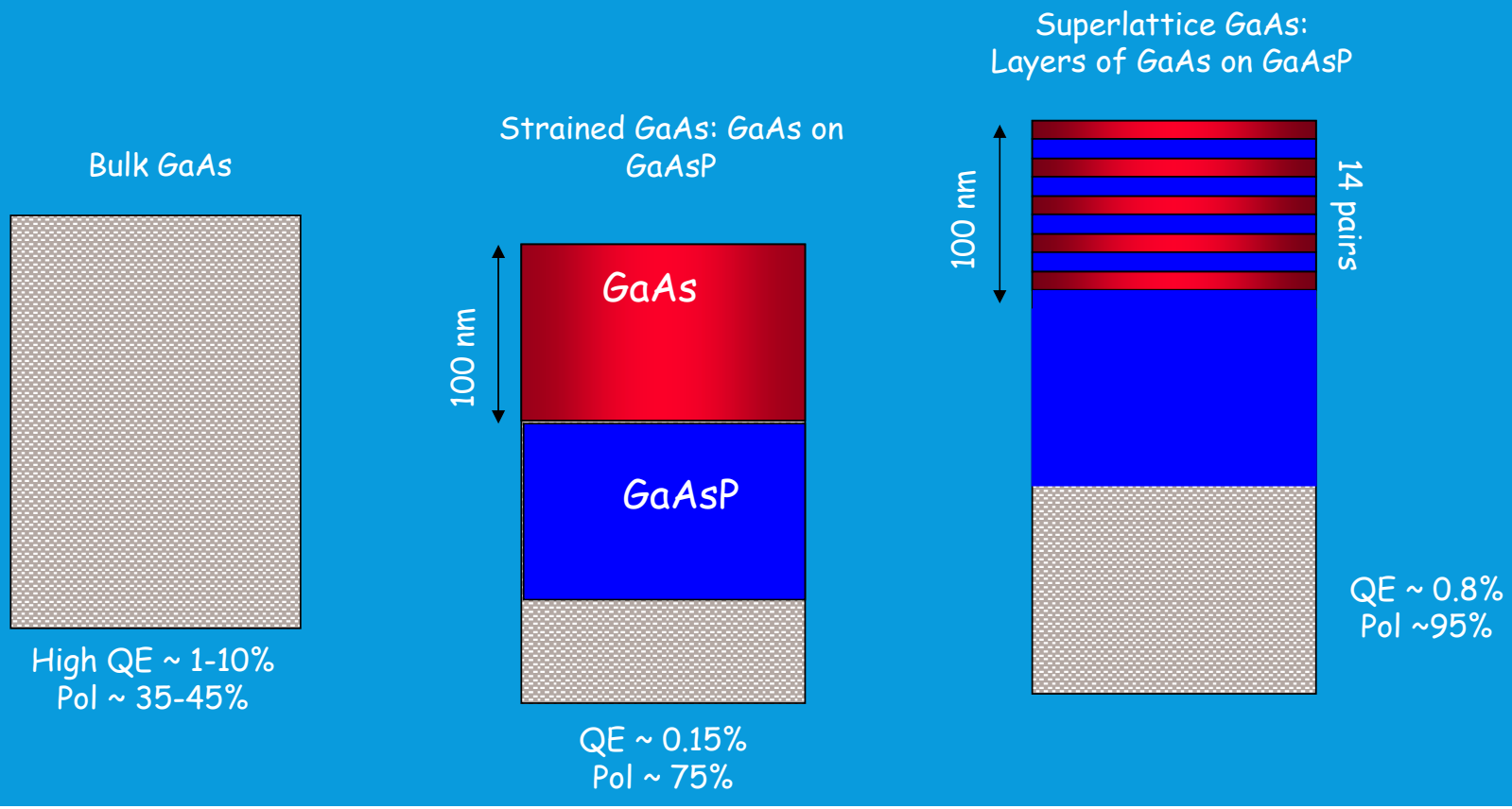
Strained



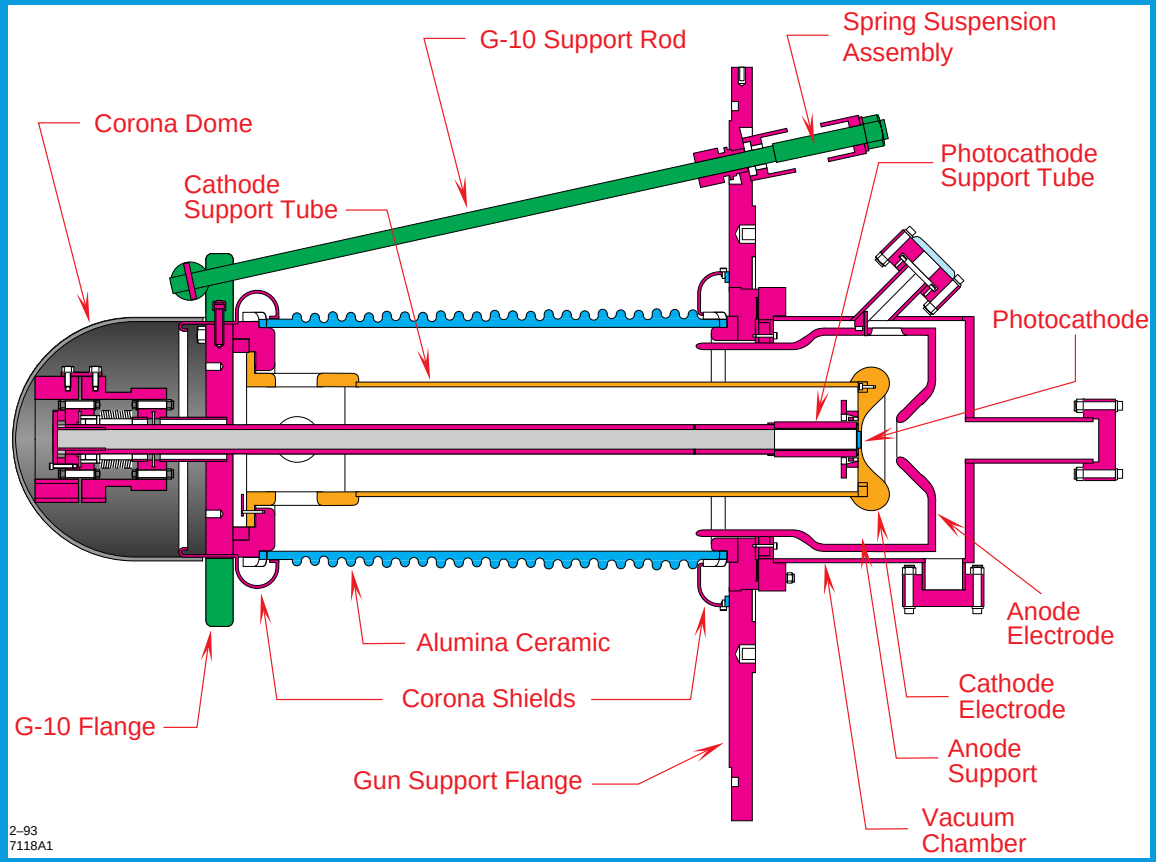
Superlattice



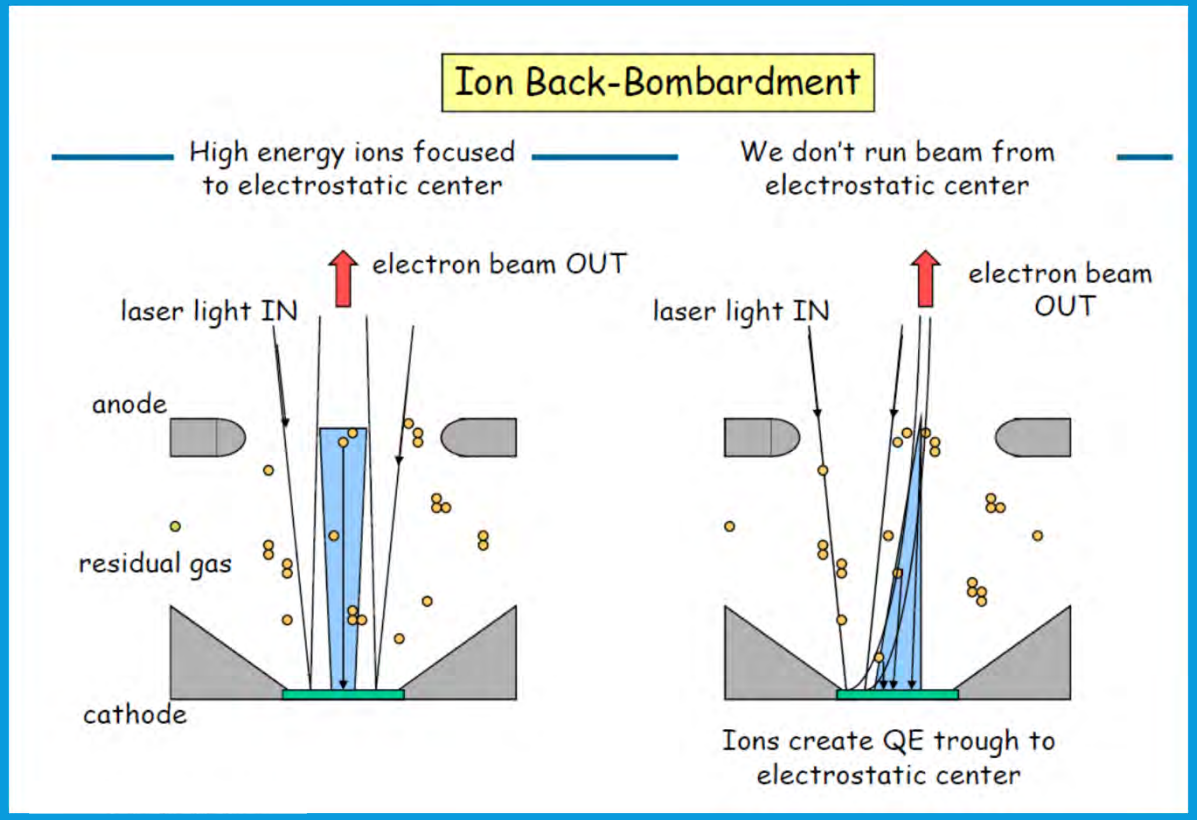
GAAS-BASED PHOTOCATHODES



POLARIZED GUN

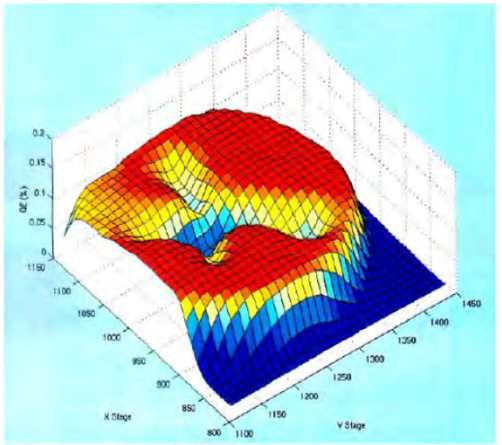


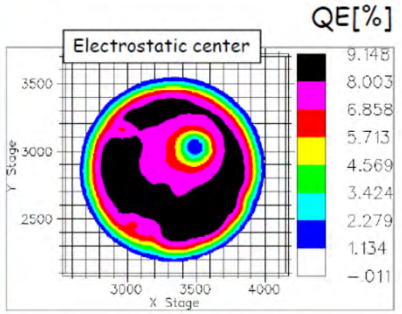
MAIN TECHNOLOGY CHALLENGE - VACUUM



Bad, bad ions...

Imperfect vacuum => QE degrades via ion backbombardment





VACUUM AND LIFETIME

Better Vacuum = Longer Lifetime