Photodetectors and their Spectral Ranges

	SINGLE ELEMENT	IMAGE
- *photoemission devices (or external photoelectric devices)*	vacuum photodiode gas photodiode photomultiplier	pickup tubes image intensifiers and converters
- *internal photoelectric devices*	semiconductor photodiode avalanche photodiode phototransistor (BJT, FET) photoresistance	CCDs vidicon
- *thermal detectors*	thermocouple (or photopile) thermistor (or bolometer) pyroelectric	 uncooled IR FPA IR vidicon
- *weak interaction detectors*	photon drag, Golay cell photoelectromagnetic point contact diode	

0.1μm | 1μm | 10μm | 100μm | (λ)

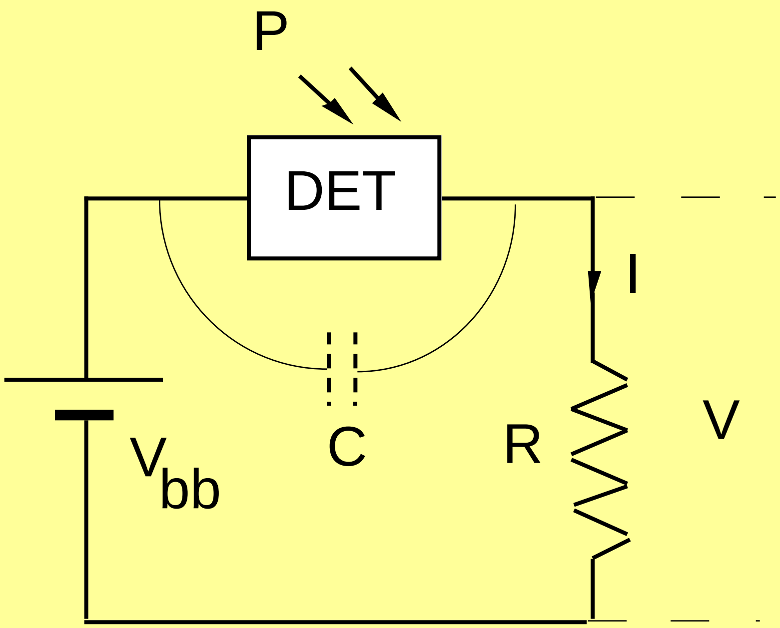
—*photoemission* —

—*internal photoelectric effect* —

—*thermal*—

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Detectors based on Photoelectric effect



Power collected $P = h\nu\ F$

is a flux F of photons of energy $h\nu$

Output current $I = e\ F'$

is a flux F' of electrons of charge e

Then, current is proportional to power,

$$I/P = \sigma = e\ F' / h\nu\ F = \eta\ (e / h\nu)$$

where $\eta = F'/F$ is quantum efficiency (electrons-to-photons)

and $\sigma = I/P = \eta\ (\lambda e / hc) = \eta\ (\lambda / 1.24)$ [A/W]

is spectral sensitivity (current out -to-power in)

Detectors based on Photoelectric effect 2

To trade photons for electrons we need a material requiring an energy not larger than the photon energy, so $h\nu \geq E_{cc}$, where energy E_{cc} for the charge carrier generation is E_W (work function) in external and E_G (bandgap) in internal photoemission.
This is the threshold condition: $hc/\lambda \geq E_{cc}$ or

$$\lambda \leq \lambda_t = hc/eE_{cc} = 1.24 / E_{cc} \, (eV)$$

In alkaline antimonides, $E_W \approx 1.2\text{-}3.0$ eV,
and $\lambda_t \approx 1\text{-}0.4$ μm (blue to NIR)

ternaries (InGaAs) $E_G \approx 0.75$ eV, $\lambda_t \approx 1.8$ μm

InSb $E_G \approx 0.25$ eV, $\lambda_t \approx 5$ μm (MIR)

HgCdTe $E_G \approx 0.08$ eV, $\lambda_t \approx 16$ μm (FIR)

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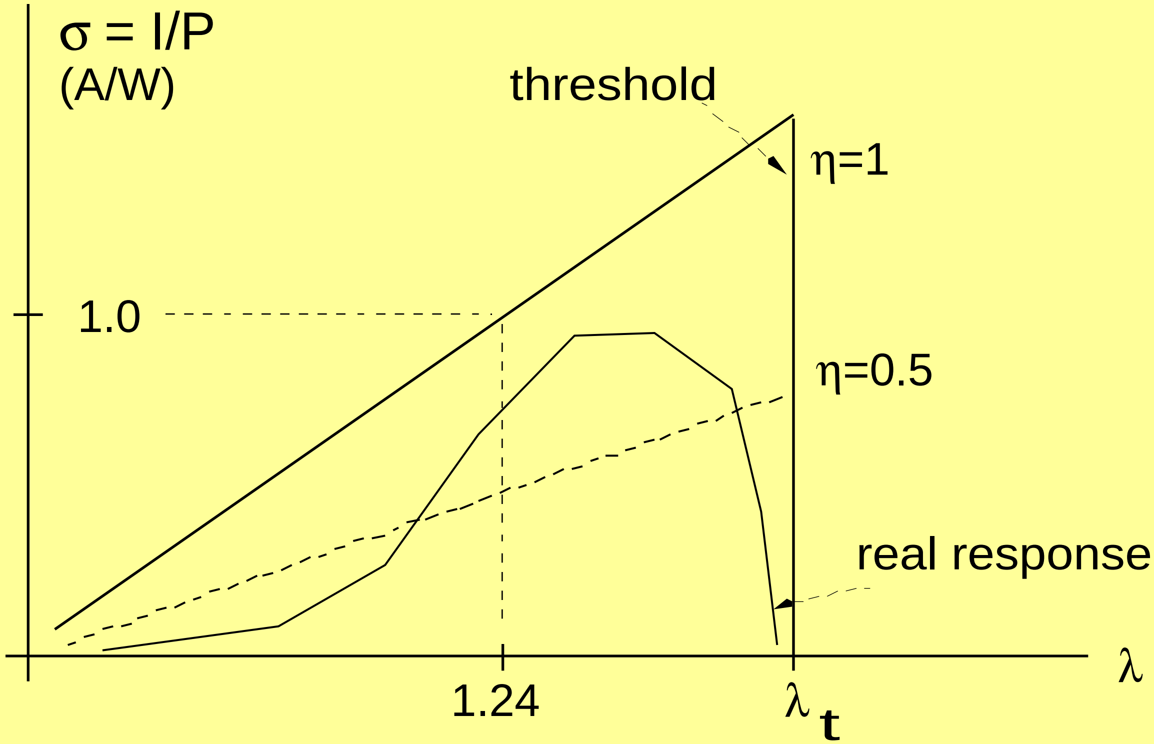
Detectors based on Photoelectric effect 3



general response curve of a quantum detector:
at P=cons, current increases linearly with λ, then sharply decreases to 0 at the photoelectric threshold
a real detector has a curve rather than a triangle

Detectors based on Photoelectric effect 4

Once produced, we shall remove charge carriers fast, so we need very thin layers to cross or a favorable electric field helping collection

photocathodes

pn junction in a diode

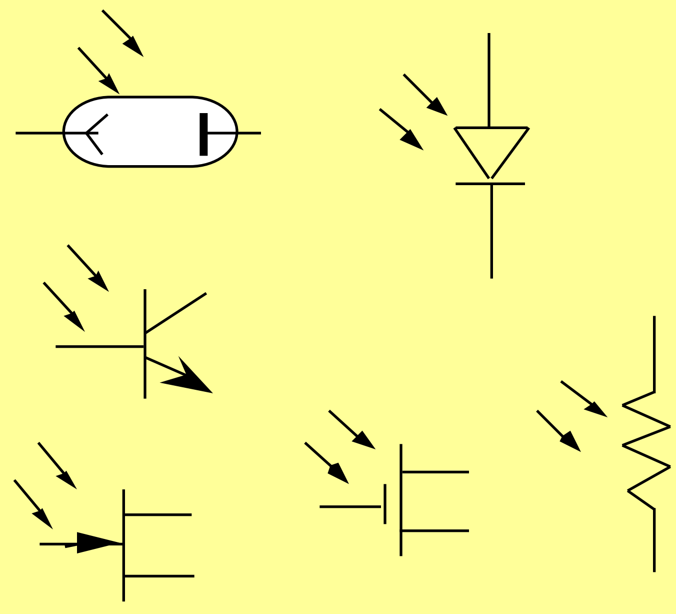
base-collector junct.of BJT

gate-drain junct in a FET

depleted layer in a MOS

3rd junct in a SCR

applied field in a resistance



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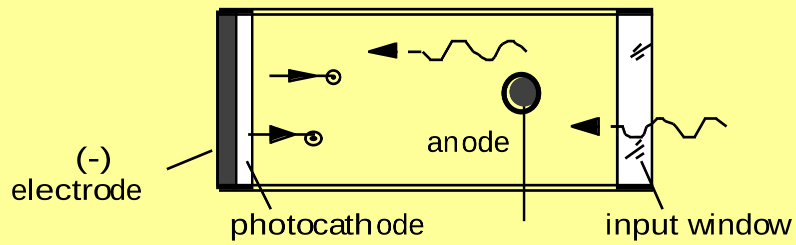
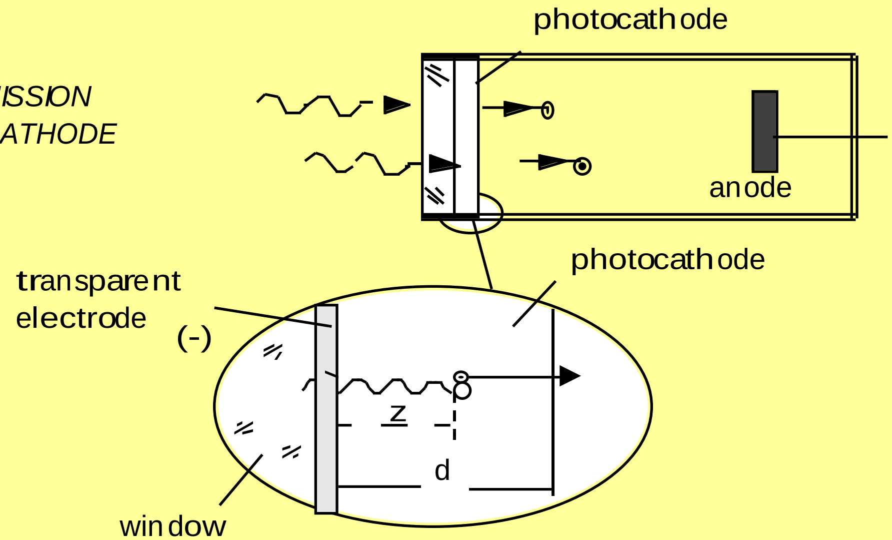
TYPES OF PHOTOCATHODES

REFLECTION PHOTOCATHODE



TRANSMISSION PHOTOCATHODE



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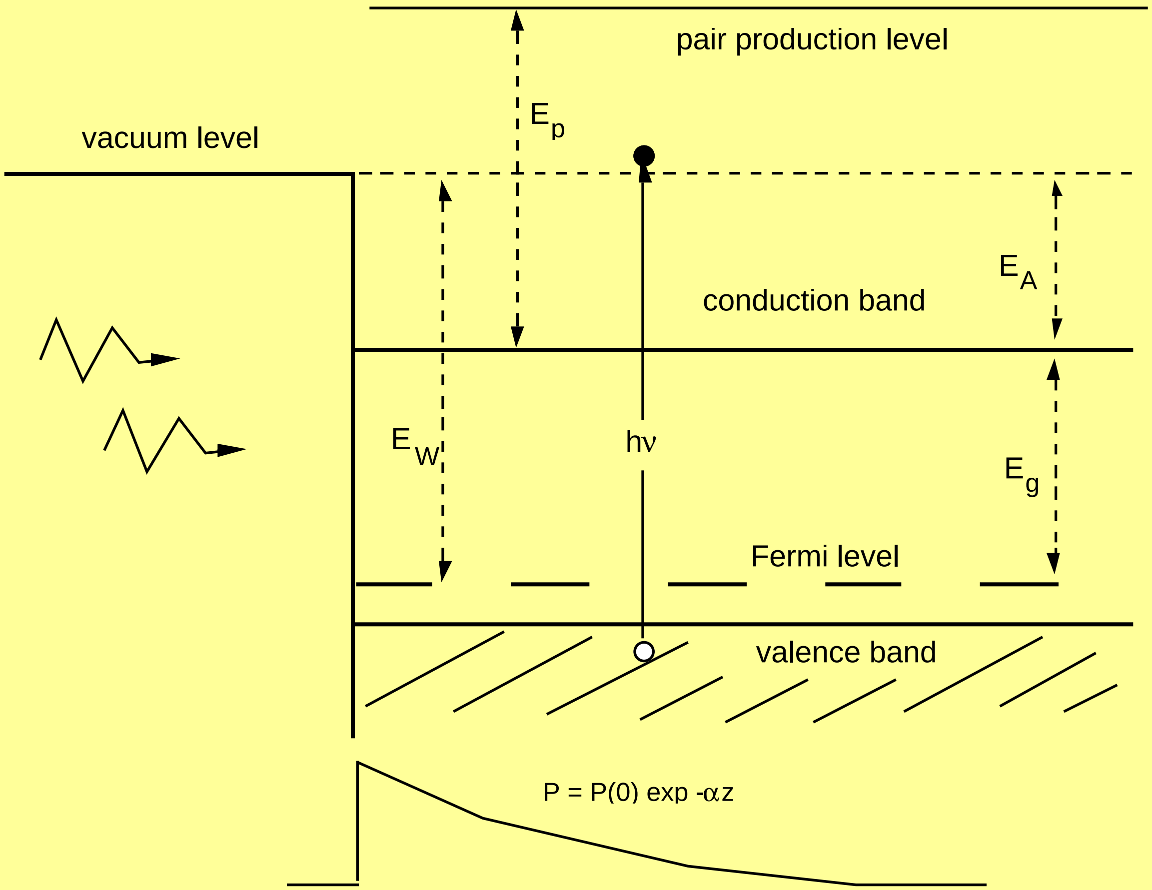
PHOTOEMISSION PROCESS

i) photon absorption and generation of an electron-hole pair
ii) diffusion of the electron to the surface
iii) emission of the electron in the vacuum



$h\nu \geq E_g + E_A$

$\lambda_t = hc/(E_g+E_A)$

$\lambda_{t\ [\mu m]} = 1.24/E_{[eV]}$

$E_p >> E_A$

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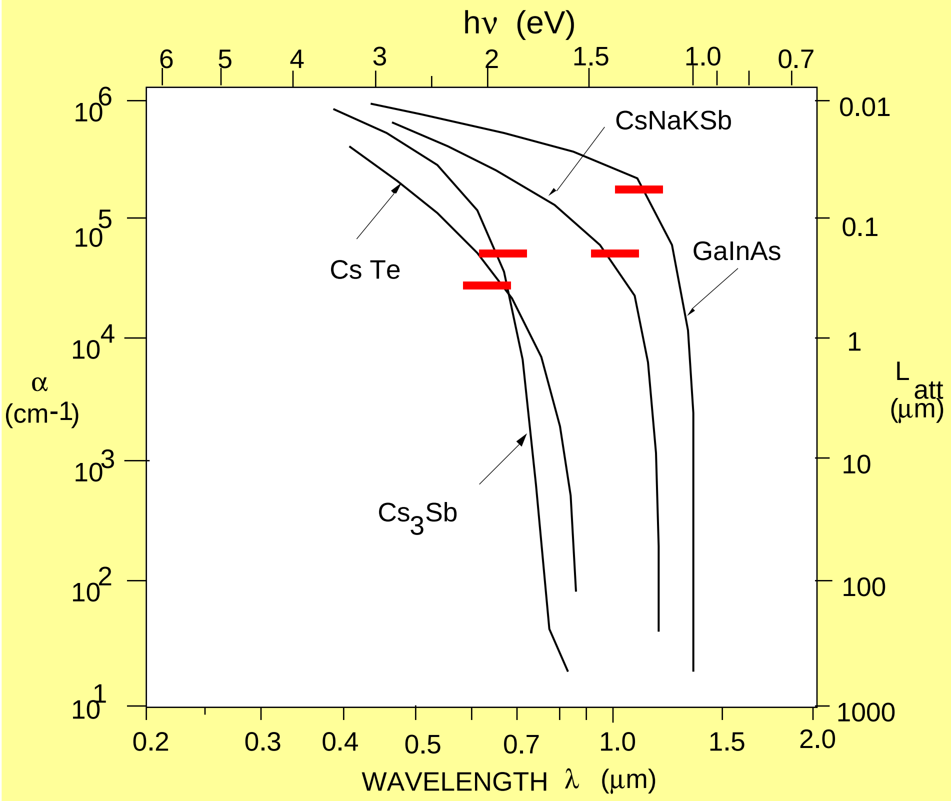
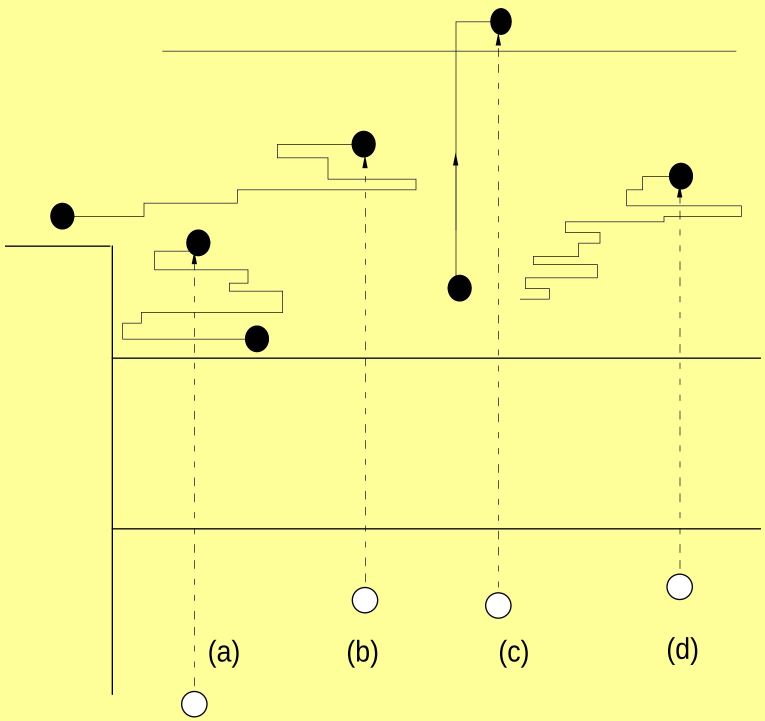
ABSORPTION and DIFFUSION

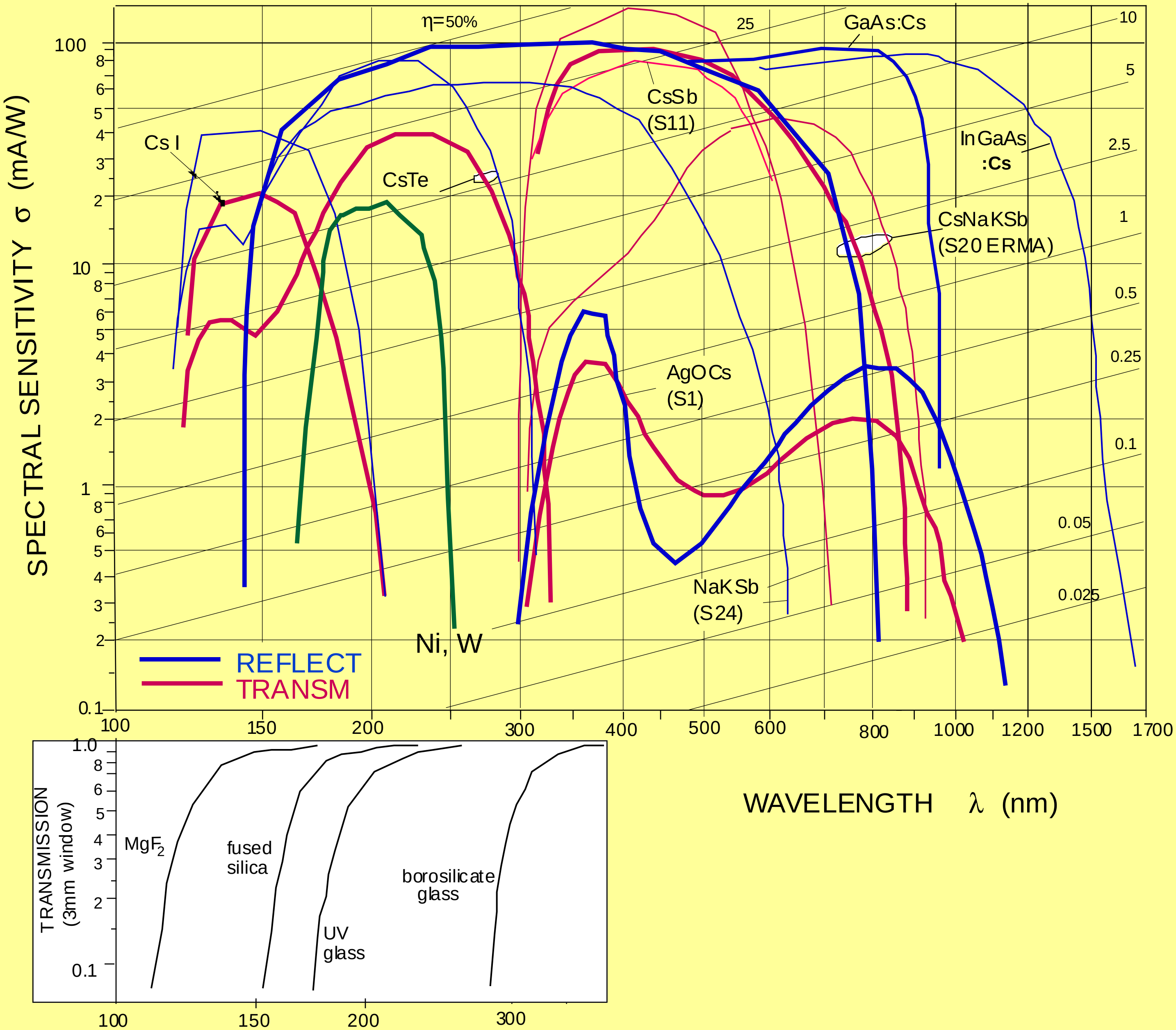


absorption



diffusion to the surface

Photocathode responses



EFFICIENCY CALCULATION

$p(L) = (1/\Lambda) \exp -L/\Lambda$; $p(\theta)= 1/2\pi$ $p(z) = \text{gauss}(z,\Lambda) = [1/\sqrt{(2\pi)}\Lambda] \exp -z^2/2\Lambda^2$

$\langle l \rangle = l_f \sqrt{(\Delta E/\Delta e_f)}$

$p_1(E,z) = p(E-\Delta e)\ \text{gauss}(z,\Lambda)$

$p_2(E,z) = p(E-k\Delta e)\ \text{gauss}(z,\sqrt{2}\Lambda)$

…………...

$p_k(E,z) = p(E-k\Delta e)\ \text{gauss}(z,\sqrt{k}\Lambda)$

$\Pi(z)$ = escape probability

$$\eta_e = \int_{0-\infty} \Pi(z)\ \alpha \exp -\alpha z\ dz,$$

$$\Pi(z) = \int_{EA-\infty} dE \int_{z-\infty} [\Sigma_{k=0-\infty} p_k(E,z')]\ dz'$$ (reflection photocathode)

$$\Pi(d-z) = \int_{EA-\infty} dE \int_{(d-z)-\infty} [\Sigma_{k=0-\infty} p_k(E,z')]\ dz'$$ (transmission photocathode)

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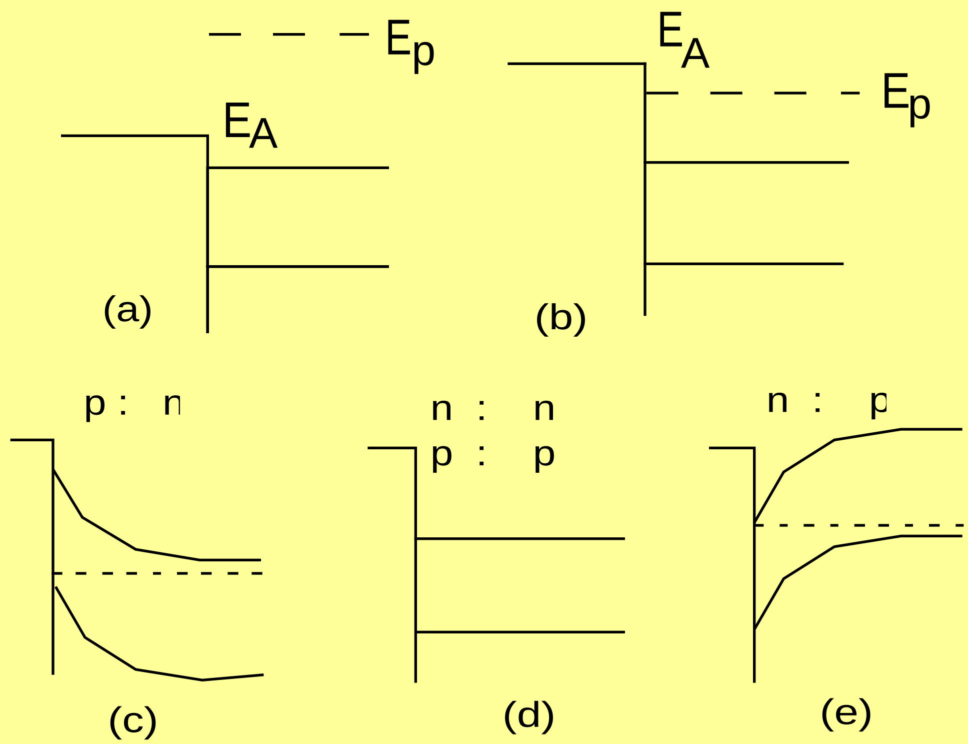
BAND BENDING AT THE SURFACE



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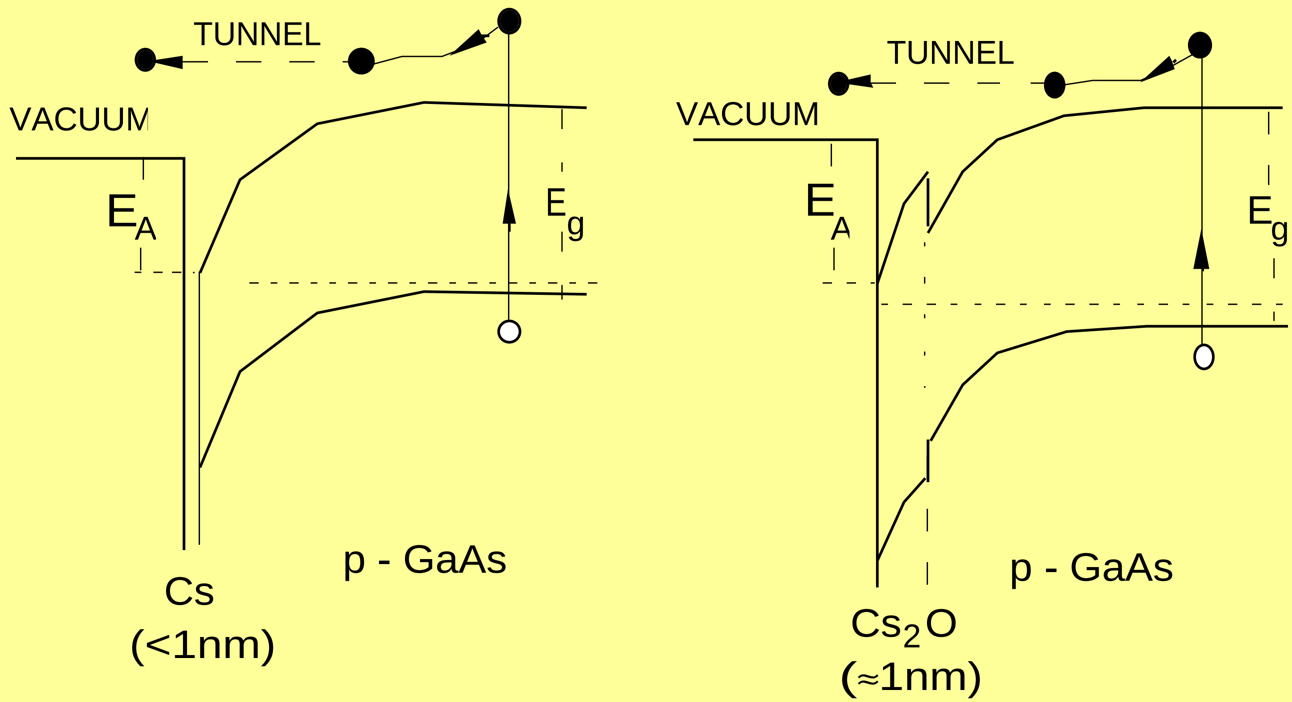
NEGATIVE AFFINITY



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PHOTOCATHODE PARAMETERS

material	SD	E_g (eV)	E_A (eV)	E (eV)	E_p (eV)	λ_s (μm)	α (μm^{-1})	η_{max} (%)	J_{dark} (A/cm^2)
Na_3Sb		1.1	2.2	3.3	<4.3	.37	60	2	
K_3Sb		1.1	1.5	2.6	<3.7	.48	30	7	
Rb_3Sb		1.0	1.2	2.2	3.0	.57	30	10	
Cs_3Sb	S-11	1.6	0.45	2.05	2.0	.60	50	25	1 f
Na_2KSb	S-24	1.0	1.0	2.0	3.0	.62	100	30	<0.1f
[Cs]Na_2KSb	S-20	1.0	0.55	1.55	3.0	.80	100	35	1 f
Ag-O-Cs	S-1			≈ 1		1.2		1	1 p
Cs_2Te				3.7	5.0	.31		30	
GaAs [Cs_2O]		1.42	<0	1.4		.87		25	0.3 f
$Ga_xIn_{1-x}As$ [Cs]		1.1	<0	1.1		1.1		10	5 f
other semiconductors:									
Si		1.1	4.1	5.2	1.8			0.04	
Ge		0.7	4.5	5.2	1.5-2			0.08	

Notes: SD = standard international (EIA) designation of spectral response and window type;
η_{max} = quantum peak efficiency (at $\lambda=\lambda_{max}$) for reflection photocathodes;
α = optical absorp-tion coefficient at $\lambda=\lambda_{max}$; J = dark current density,
in pico- or femto-ampere per cm^2 of photocathode surface (at 300 K).

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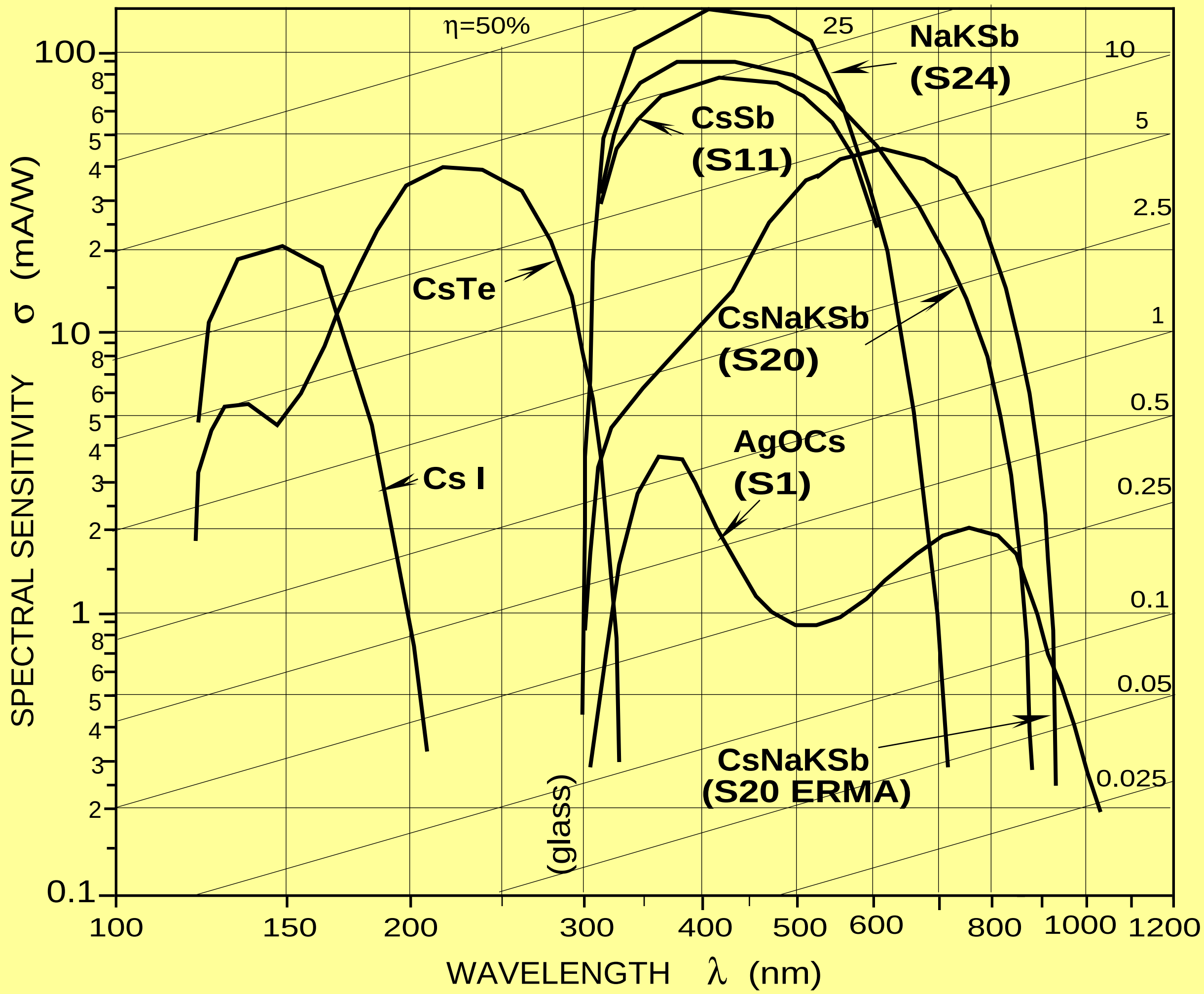
TRANSMISSION PHOTOCATHODES



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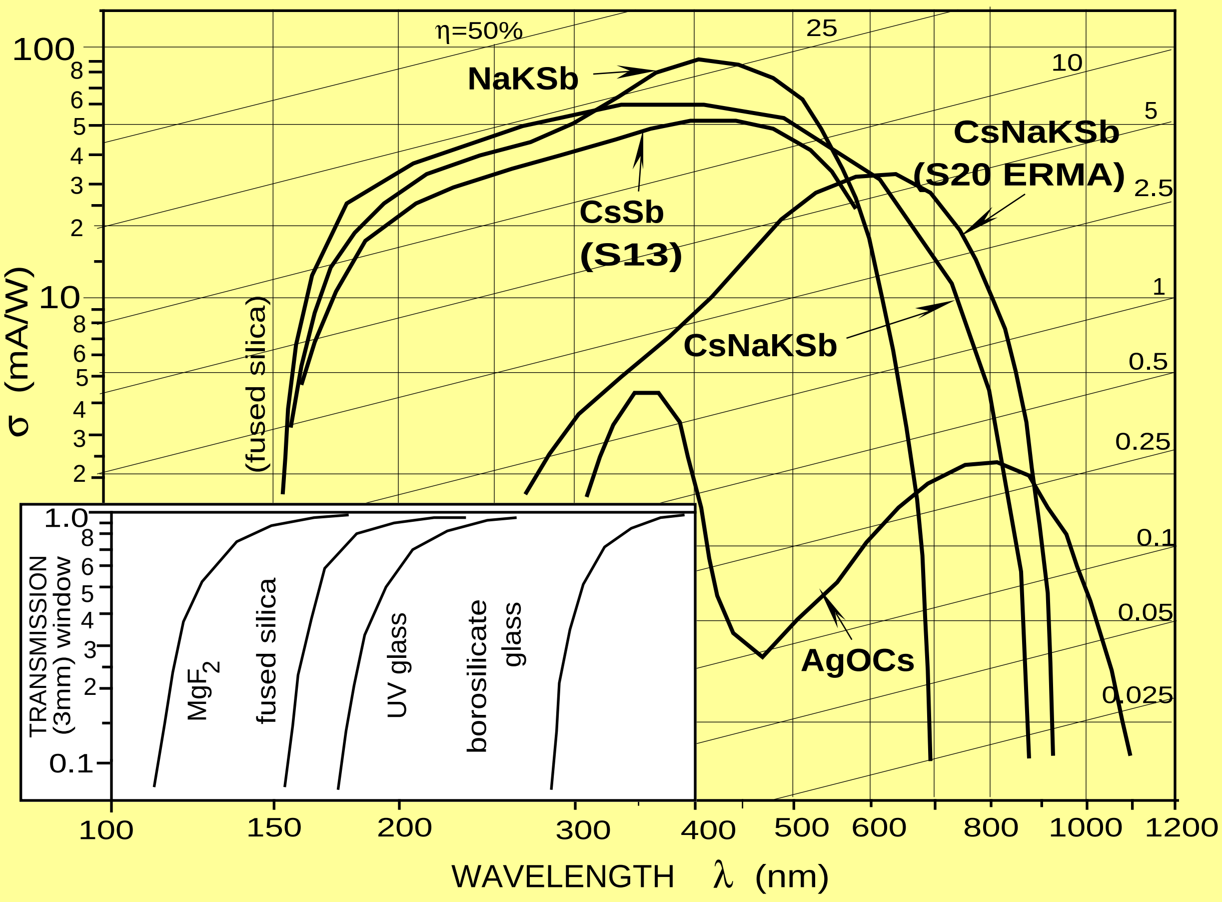
REFLECTION PHOTOCATHODES:
UV-cutoff of a 3-mm thick window



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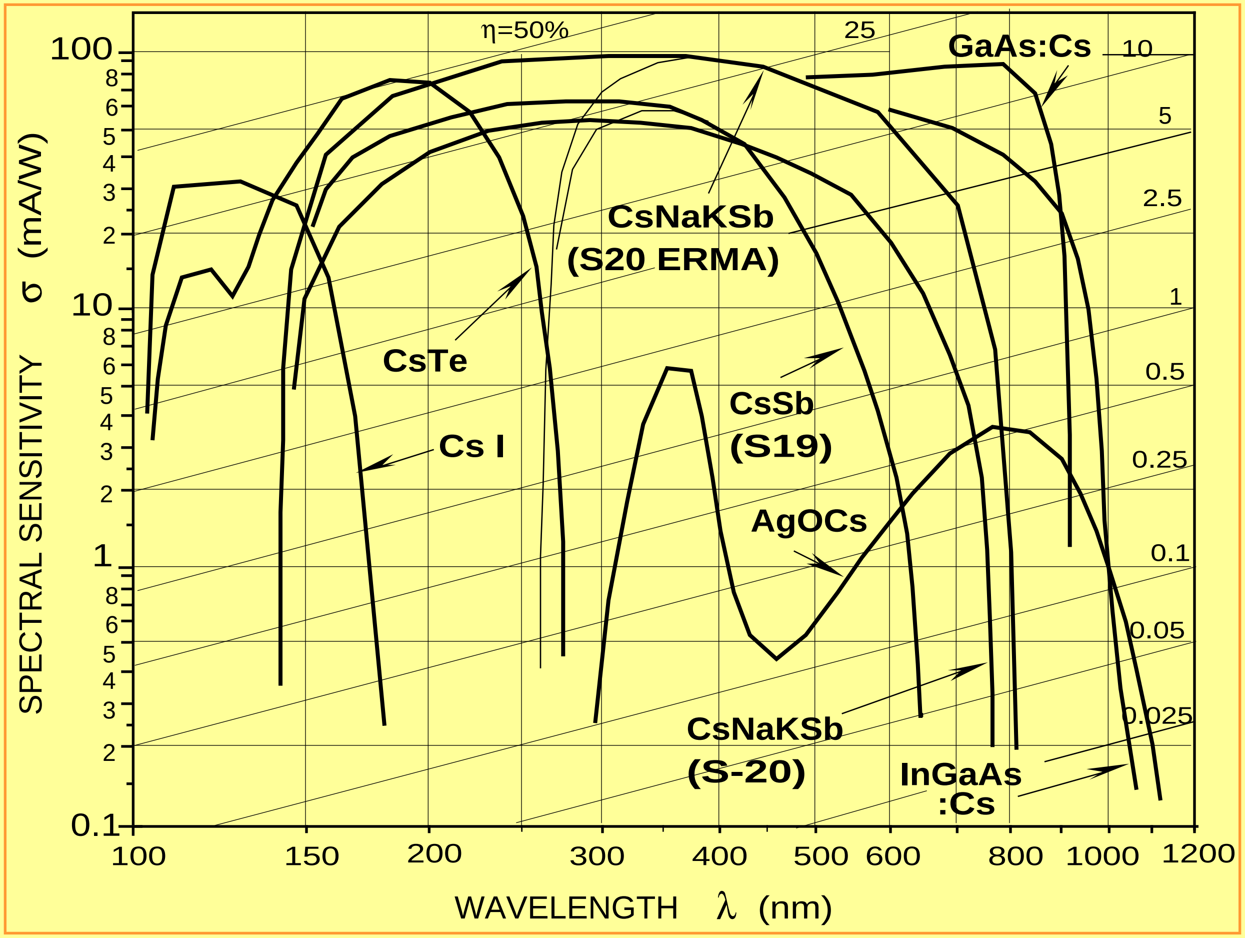
REFLECTION PHOTOCATHODES



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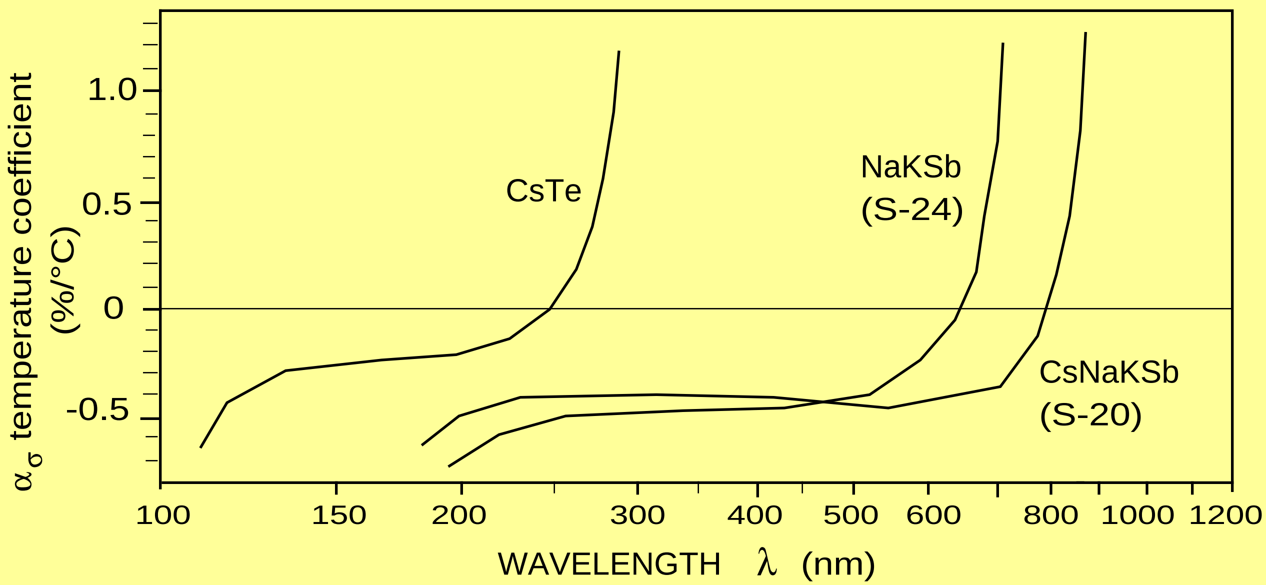
TEMPERATURE COEFFICIENT OF SPECTRAL SENSITIVITY

$$\alpha_\sigma = (1/\sigma)\, d\sigma/dT$$



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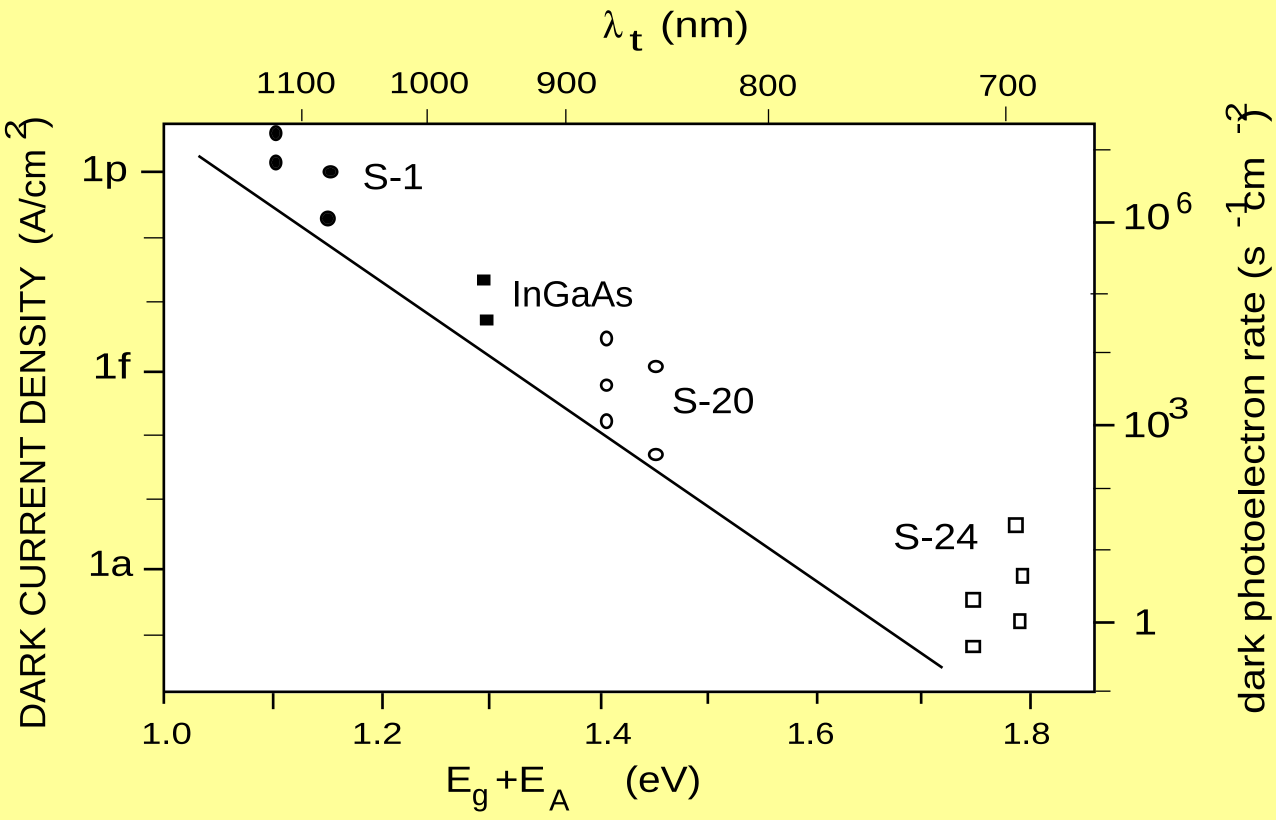
DARK CURRENT vs WORKFUNCTION



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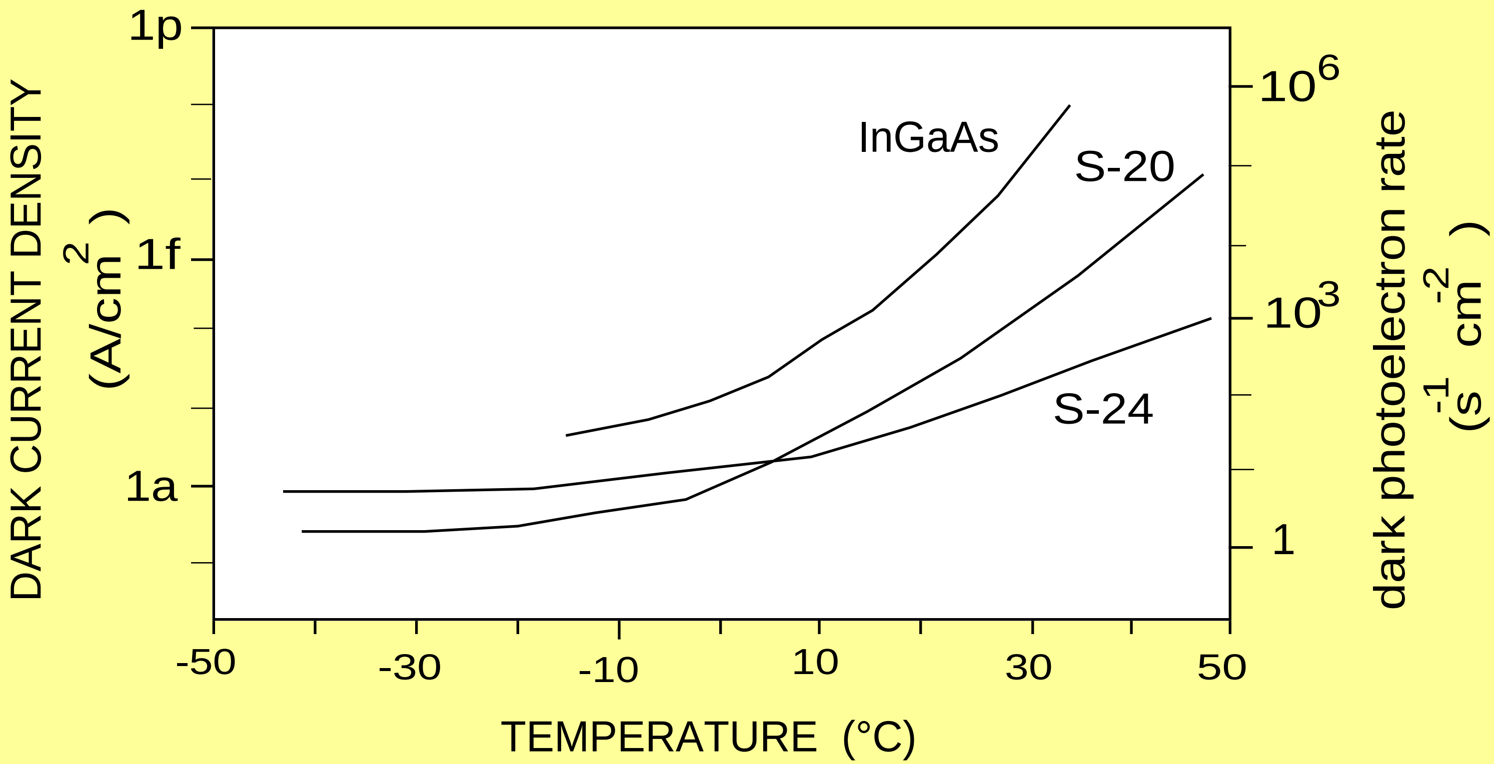
DARK CURRENT TEMPERATURE COEFFICIENT



$$\alpha_J = (1/J_d)\ dJ_d/dT$$

$$= (2+ E_W/kT)/T \approx 0.34\ (2+ E_W/kT)\ [\%/°C]$$

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PHOTOCATHODE FABRICATION

Common features:

a high-vacuum process (10^{-6} torr)
surface contaminants control very critical
medium-temperature thin film deposition

Bi- and tri-alkaline fabrication:

Sb evaporated first, (6 nm in transm. photocath),
K in the stoichiometric ratio (K_3SB) **
then Na adding K and Sb in turn to have Na_2KSb **
last Cs or Cs-O **

** = maximizing photoresponse

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PHOTOCATHODE FABRICATION

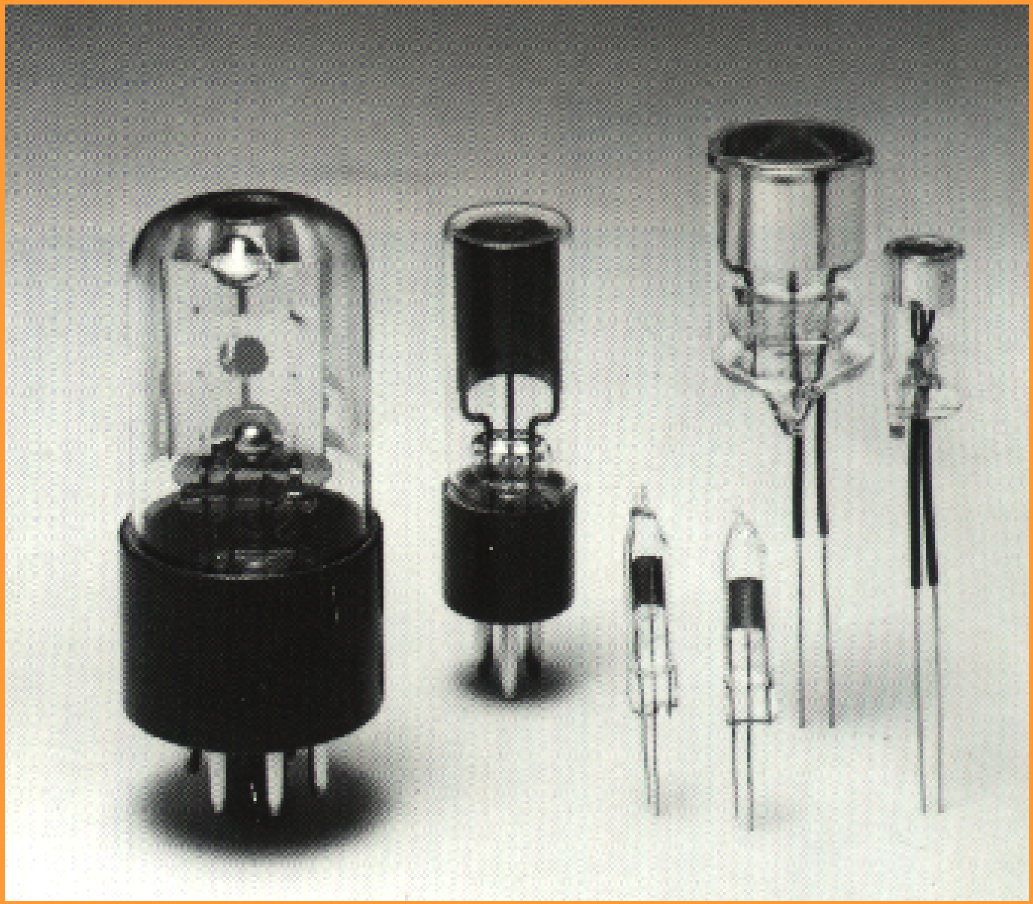
Typical apparatus for photocatode fabrication

Picture

to be

added

PHOTOTUBES (or vacuum photodiodes)



PT with hemicylindrical reflection photocathode (left) and with transmission photocathode on a plane input window

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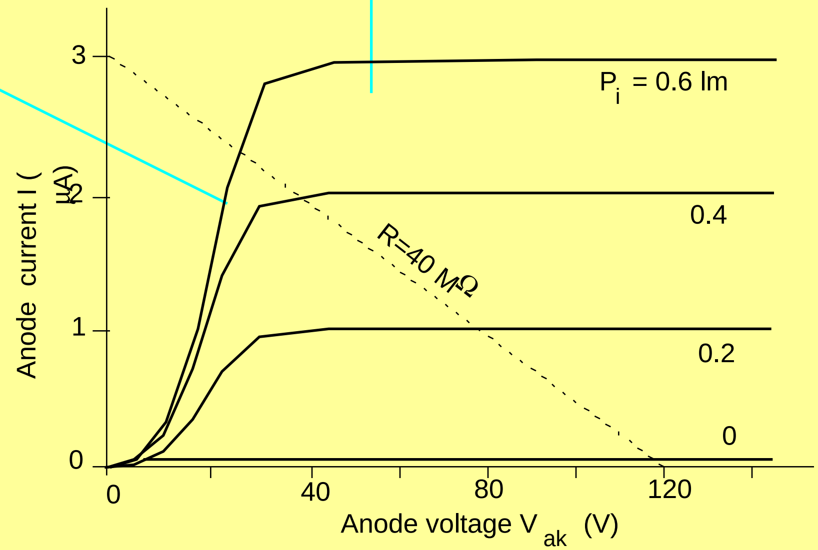
PHOTOTUBES

saturation regime

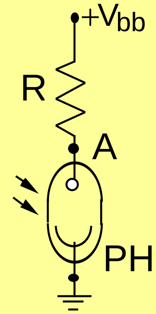
space charge regime

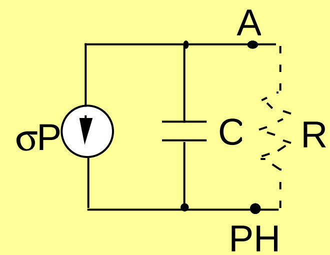
$J_a = (4\varepsilon_0/9d^2)\,(2e/m)^{1/2}\,V_{ak}^{3/2}$

V/I characteristics



bias and eqv circuit





PHOTOTUBES: speed of response

Transit time:

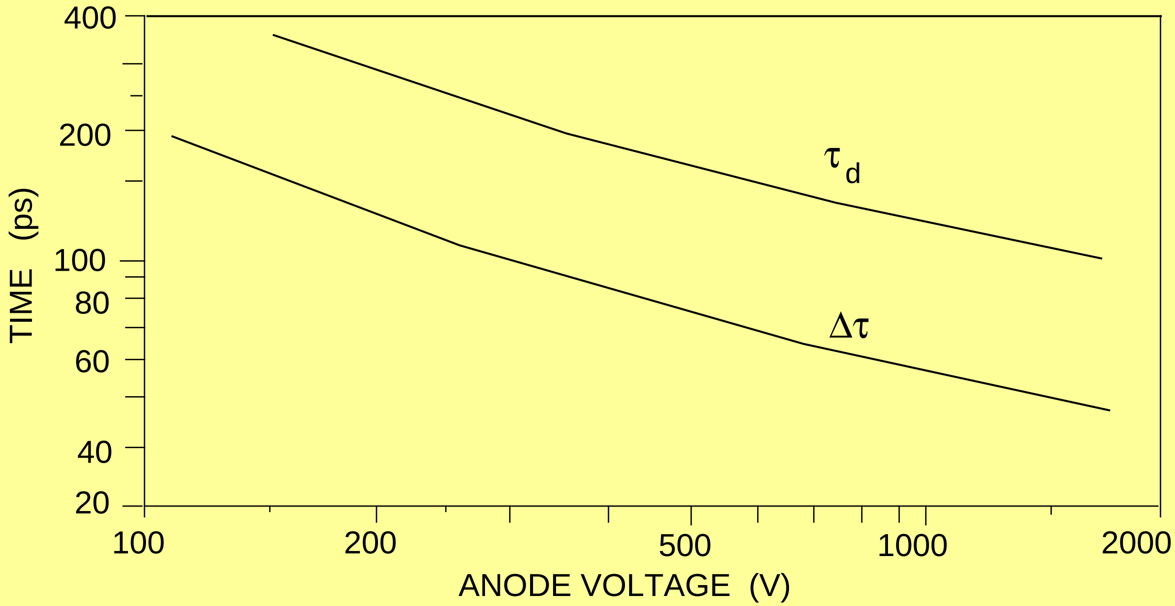
$\tau_d = d\,(2m/eV_{ak})^{1/2} = 33.7\text{ ns } d_{[cm]}\,(V_{ak})^{-1/2}$

Dispersion: $\Delta\tau$ is a fraction of τ_d

Frequency cutoff:

$f_2 = 0.44/\Delta\tau$ (intrinsic cutoff), or

$f_2 = 1/2\pi RC_a$ (extrinsic cutoff)



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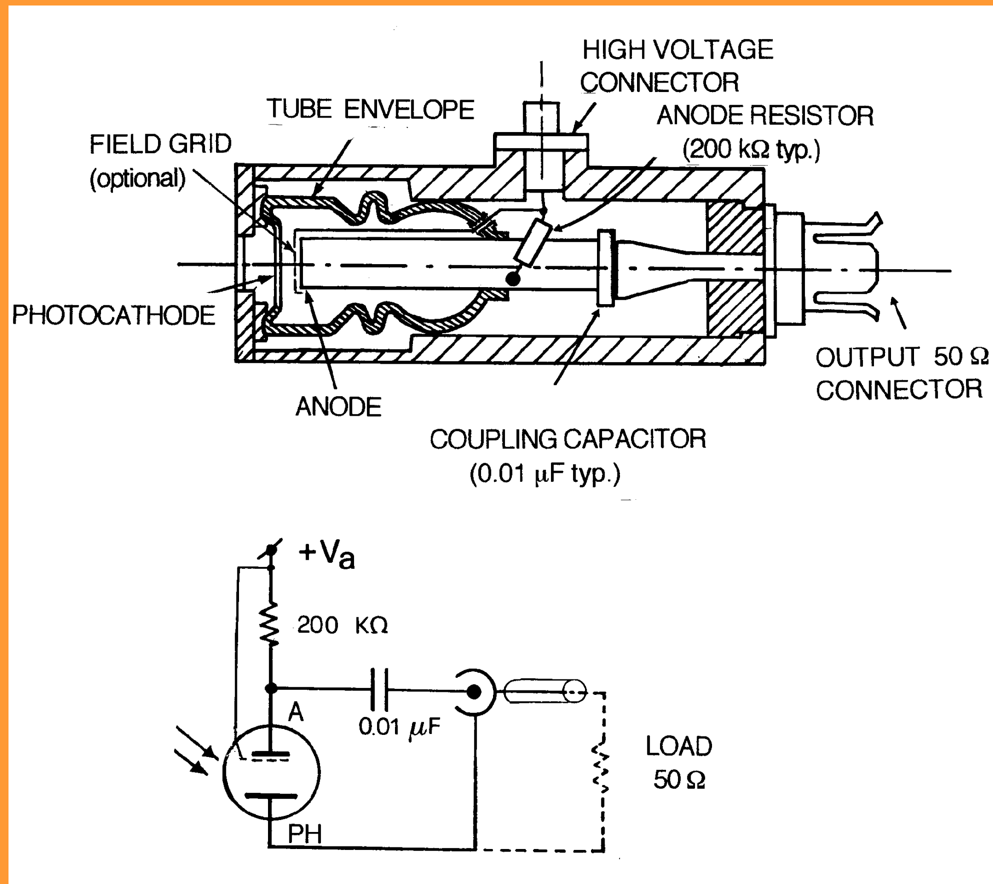
TYPICAL FAST PHOTOTUBE



A fast phototube (rise time 100 ps or bandwidth 3 GHz) with transmission photo-cathode (S-1, S-11 or S-20) on a glass or quartz window and 50-Ohm output electrode. Top: device structure; bottom: bias circuit. With the field grid, speed of response is limited by the dispersion Δt rather than by the transit time τ_d

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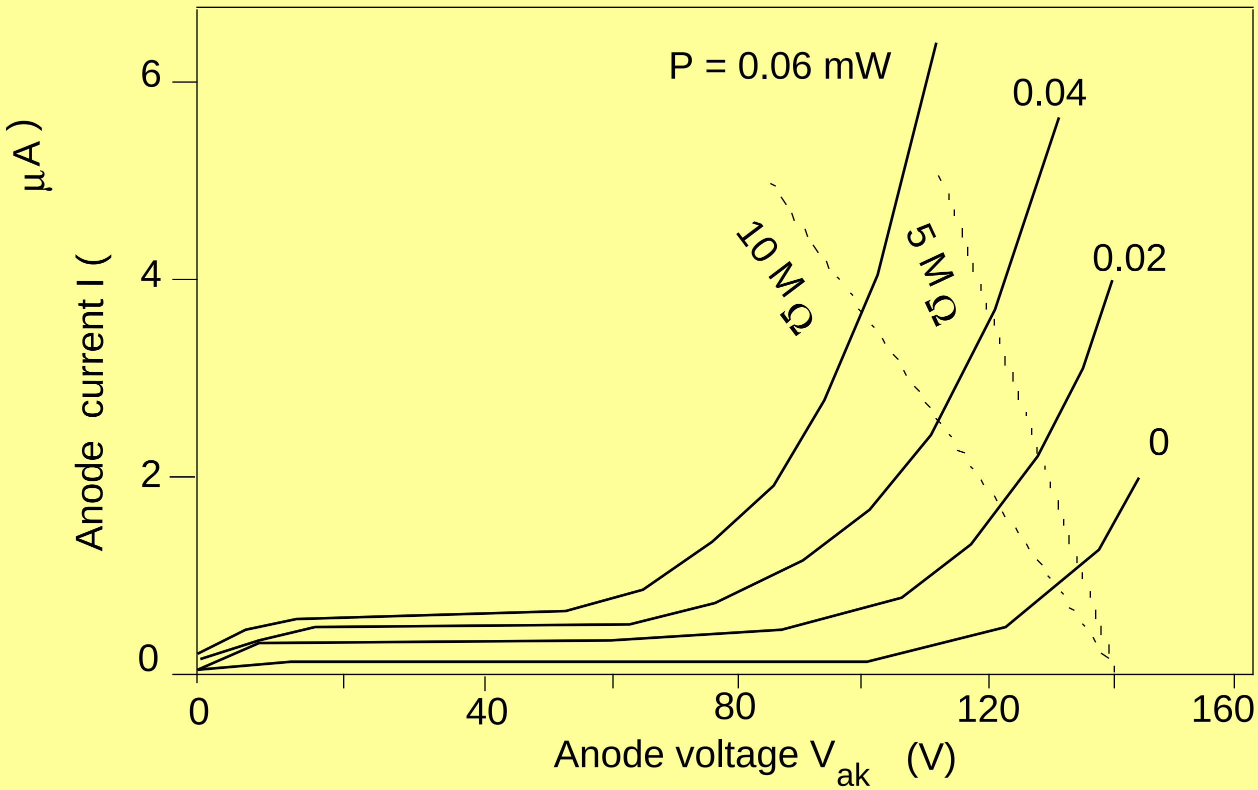
GAS PHOTOTUBE

Ionization in a low-pressure gas filling the tube is a mechanism to increase photoelectron number. Internal gain is typically G=5-20



Gas phototubes are used in industrial flame control

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