External Photoemission

Steps of photodetection in semiconductors

- absorption of photons in the material (→ α, $P=P_0 \exp -\alpha L$)
- production of charge carriers (→ $h\nu > E_g$
  $\lambda_s\,[\mu m] = hc/E = 1.24 / E[eV]$),
- drift of charge carriers under an internal electric field
  (→ junction, high μ)
- collection of charge carriers at the ohmic contacts

Materials and structures

- *single* semiconductors Si, Ge, Se, etc.
- *binary compounds* GaAs, InSb, PbS, PbSe, etc.,
- *ernary compounds* GaAlAs, InGaP, HgCdTe, PbSnTe
- *quaternary compounds* InGaAsP, etc.

energy gap E_g: from several eV to a few 10meV,

spectral range (or threshold λ_s): from the UV to the far IR.

Structures:

photodiodes (pn, pin, ms and avalanche),

bipolar and unipolar *phototransistors*,

photo-SCR,

photoresistances

Features of semiconductor detectors

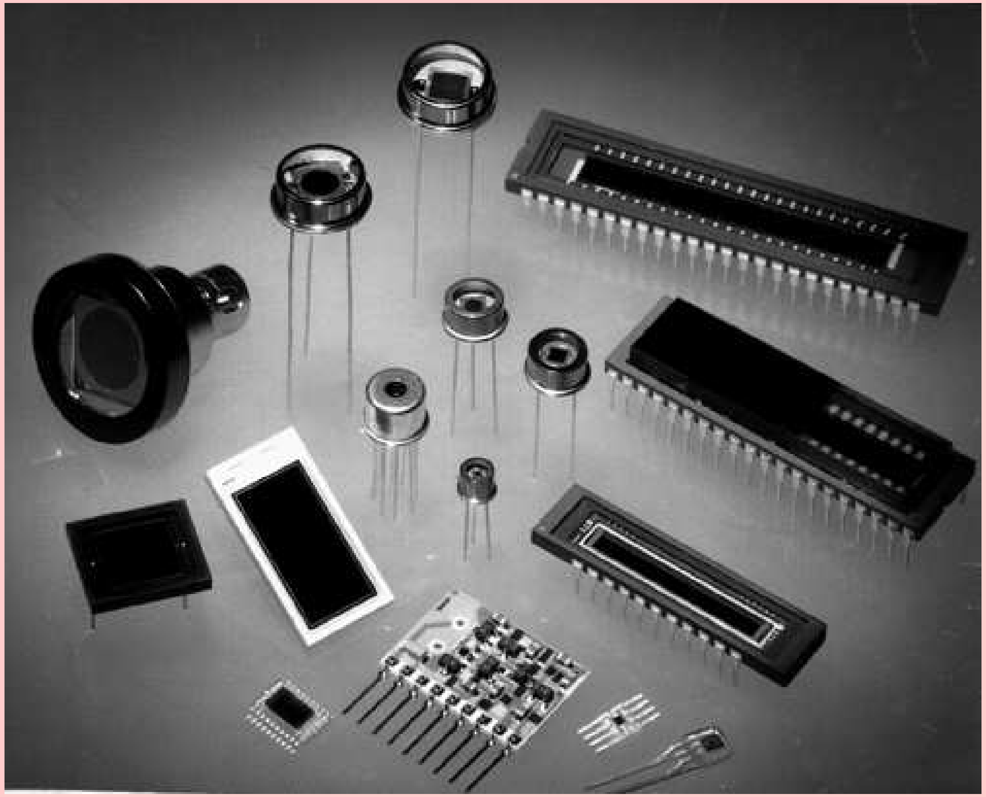
PRO's

- *compact size* and *flexibility* of geometry
- *low bias voltage*
- *spectral range* from *deep UV* to *far IR*
- high peak *quantum efficiency*
- *uniformity* of performance parameters
- excellent *ruggedness wide temperature* range
- excellent *mean time to failure* (MTTF)
- *space and hostile ambient* qualification
- generally *low cost*

CON's

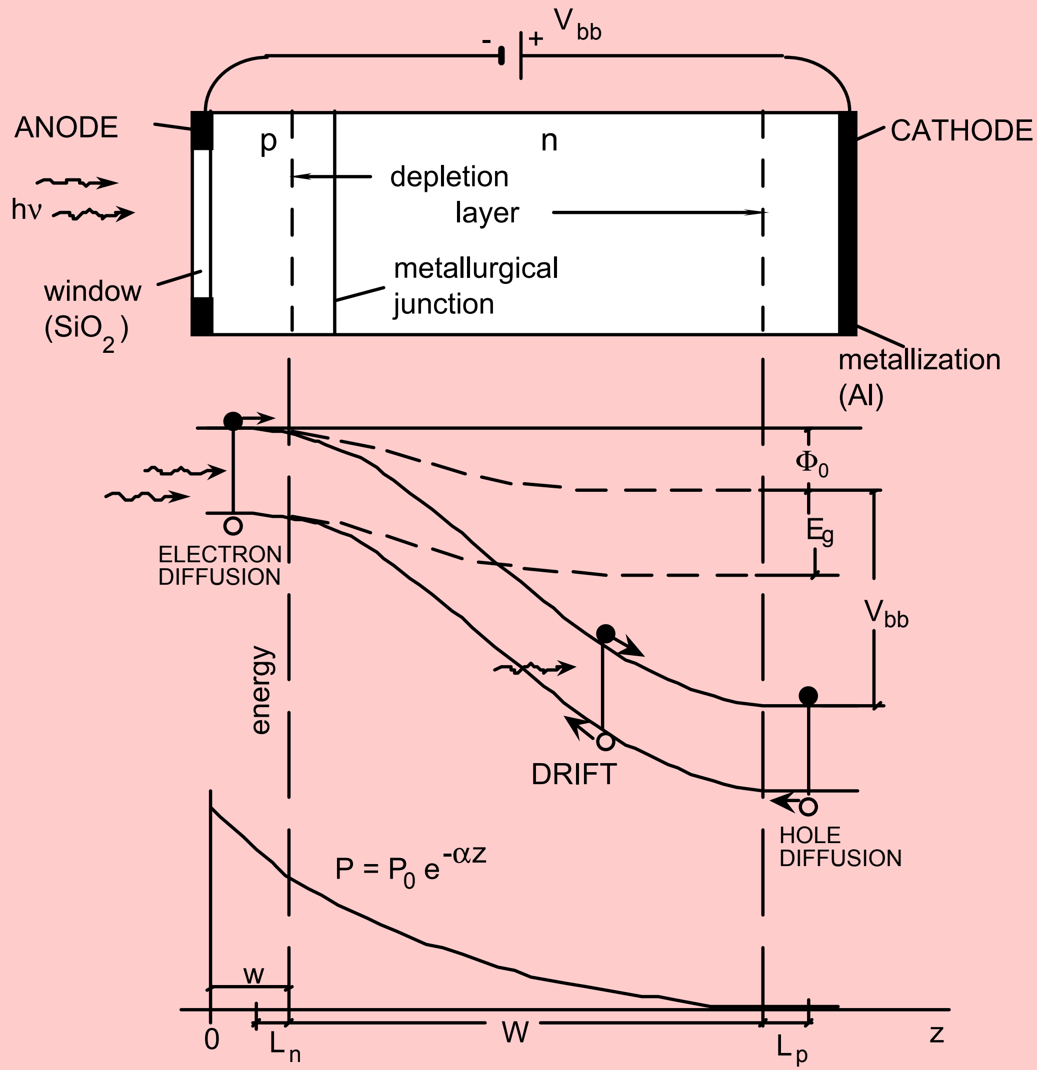
- very large *areas* difficult
- *no single-photon* capability, *GB* not the *best*
- *temperature dependence*

Photodiode's family

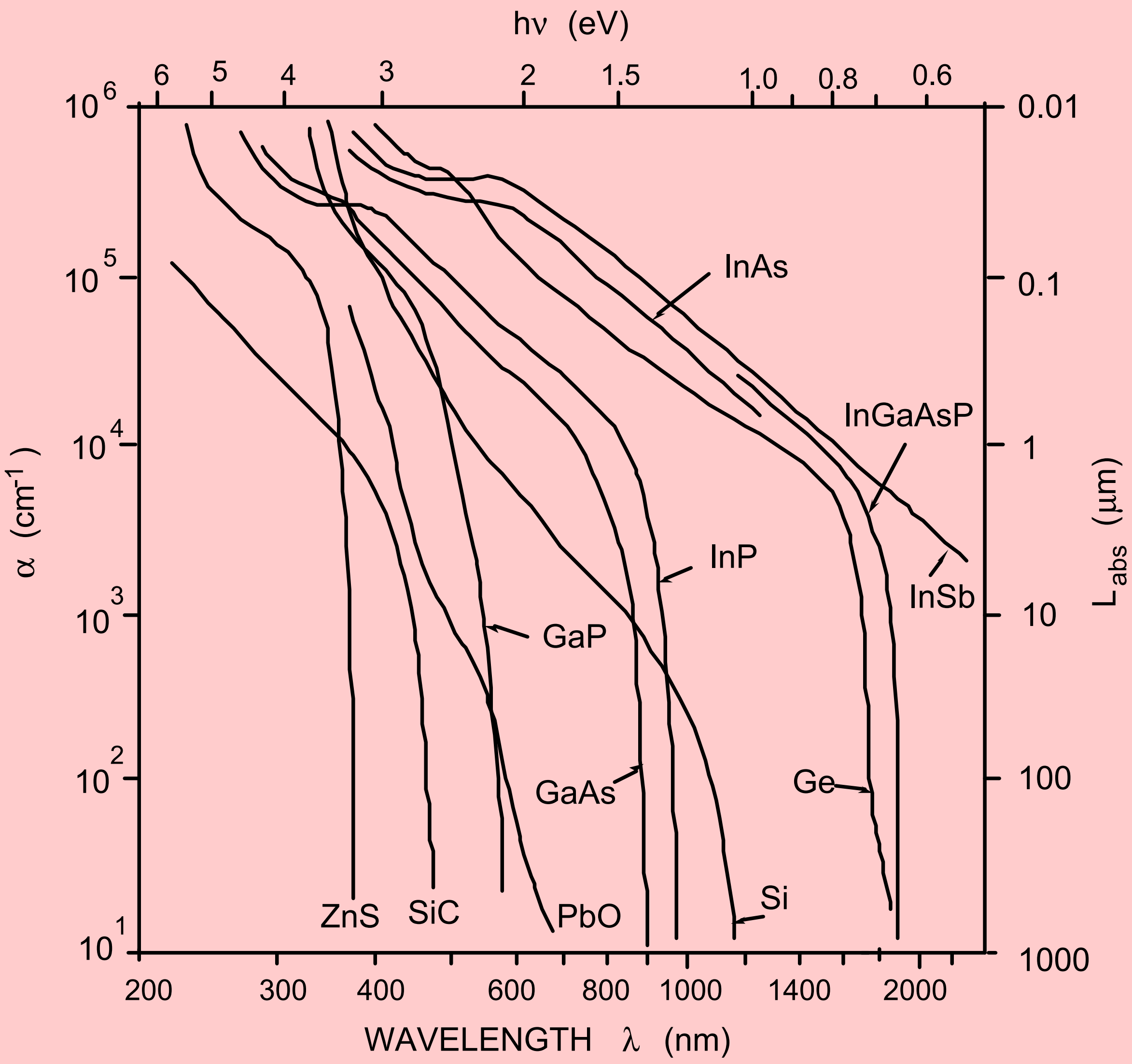


A sample of popular semiconductor photodetectors: single-element photodiodes in metal and ceramic packages, linear arrays of photodiodes and high frequency SMD photodiodes with integrated preamplifier

pn-junction Photodiode

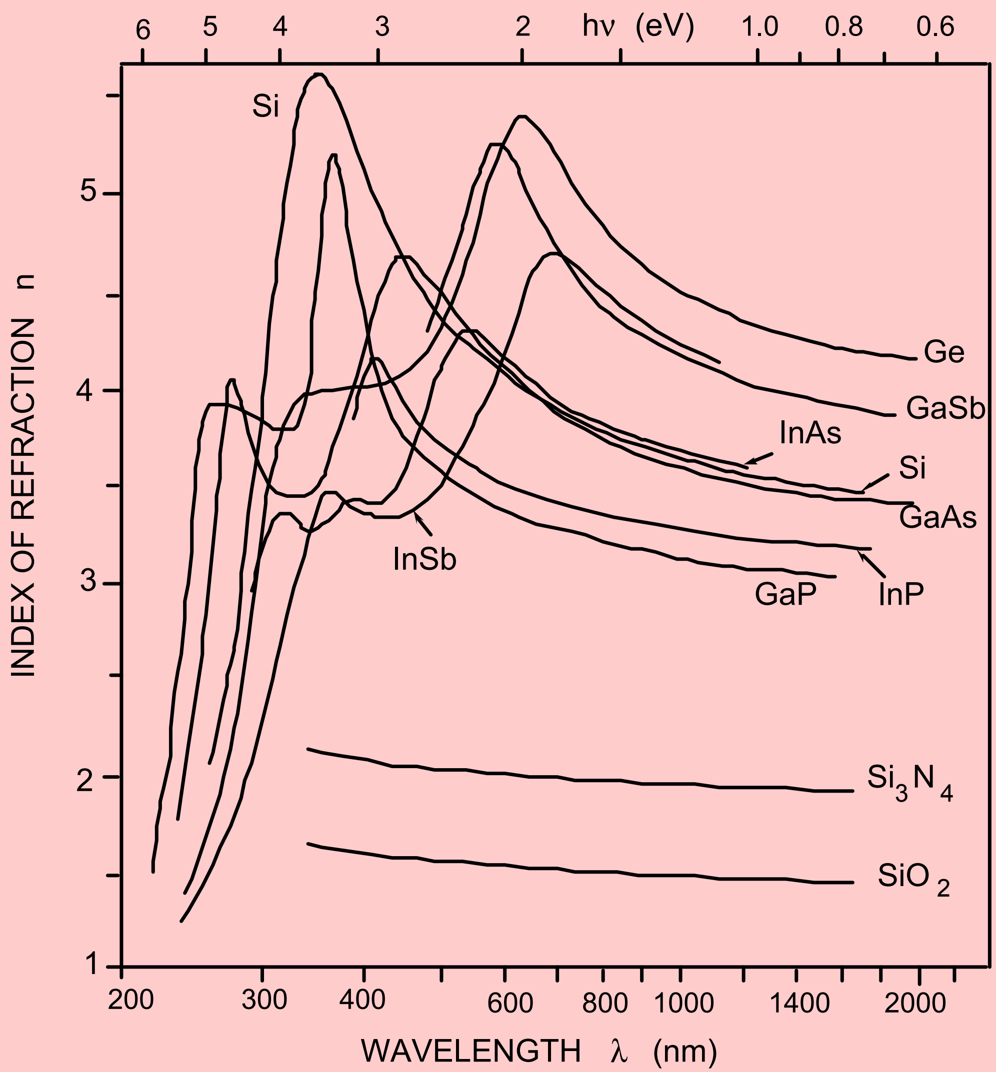


Absorption coefficient



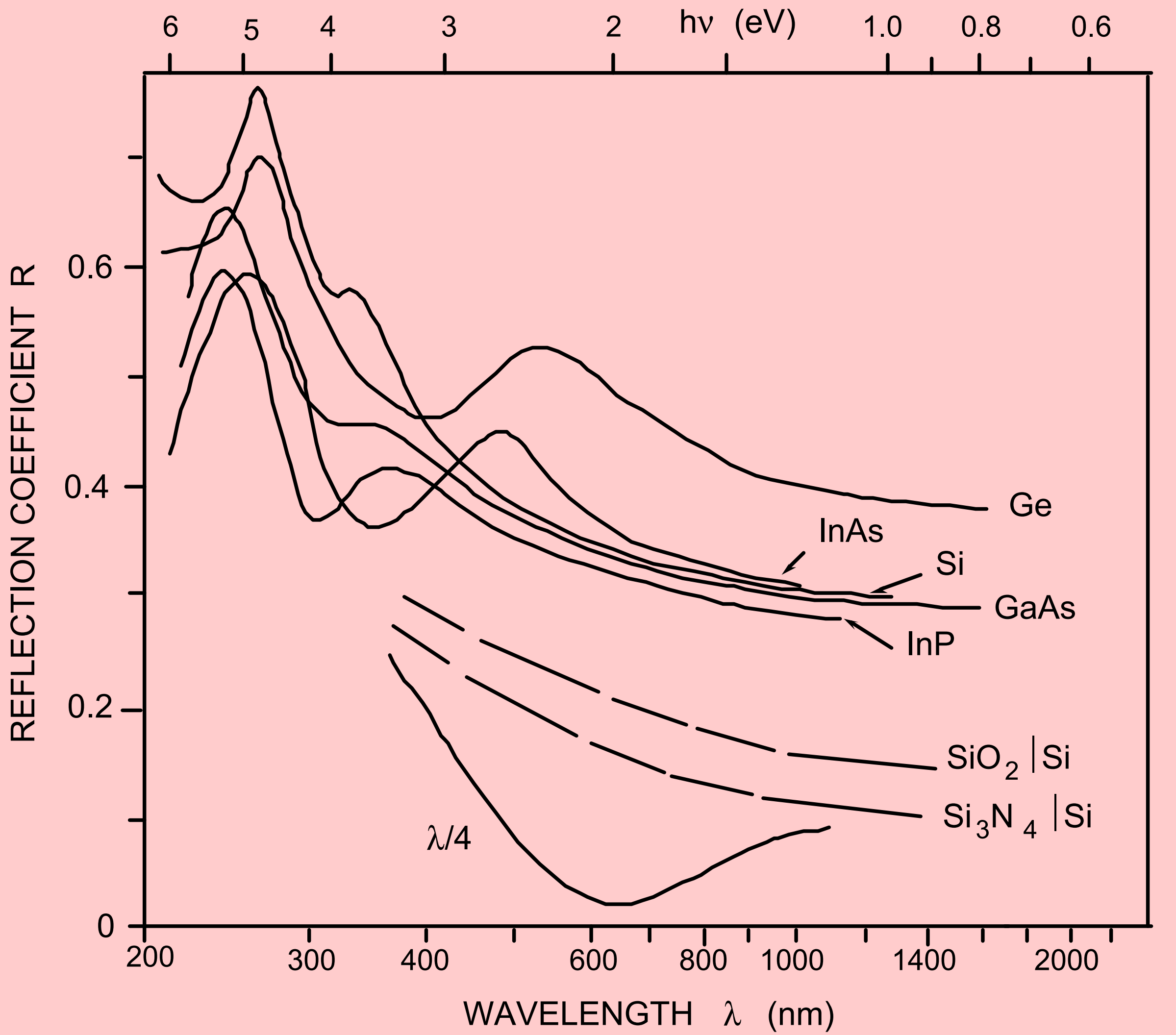
Absorption coefficient α (and $L_{abs} = 1/\alpha$) strongly varies with λ in all semiconductors (data for T=300 K)

Refraction index of semiconductors



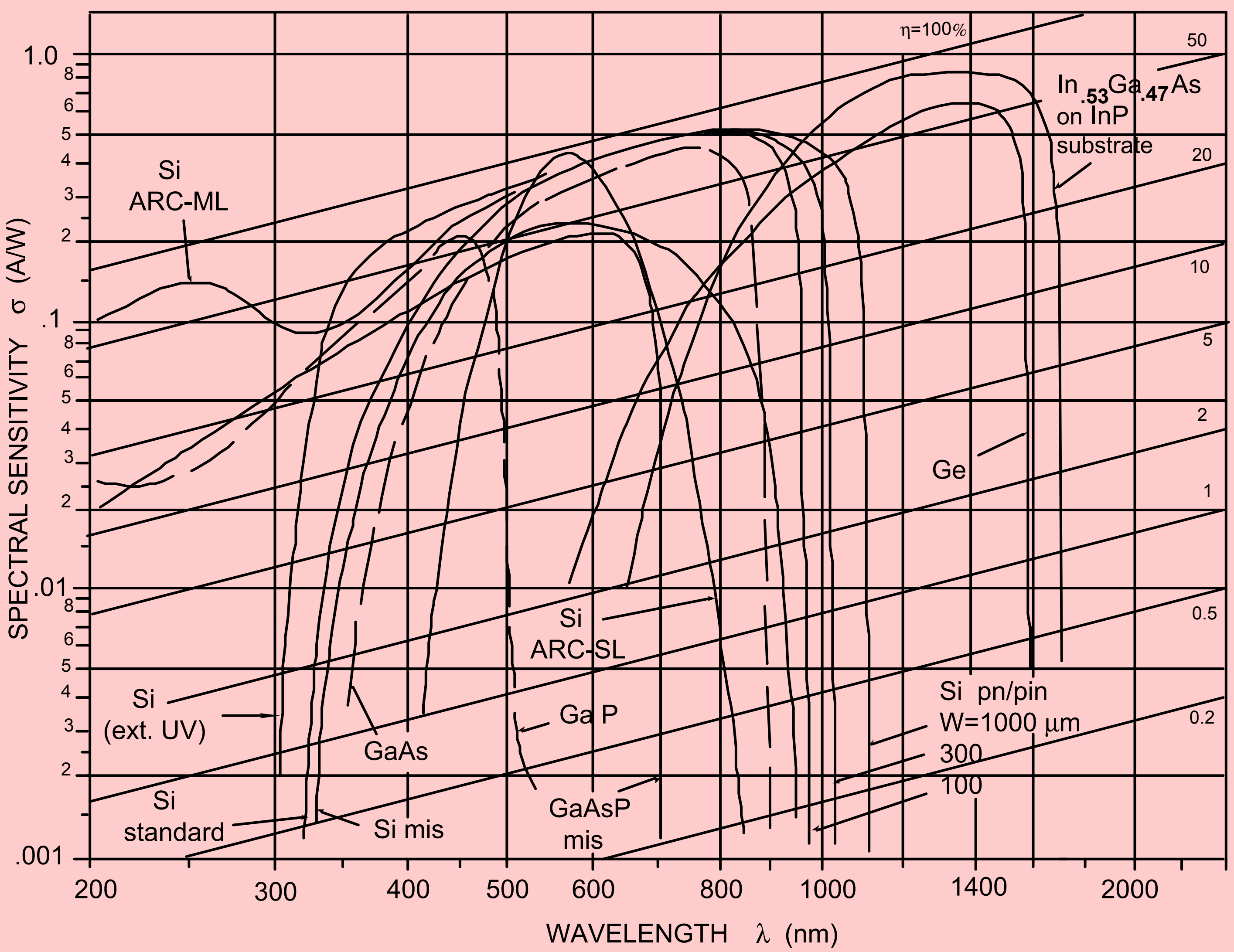
refraction index of semiconductor materials of typical photodiodes is fairly high (usually >3), giving a large reflection loss at entrance window

Reflection loss at entrance window



reflection R of vacuum-semiconductor interfaces, untreated (full lines) and single-layer anti-reflection coated

Spectral sensitivity (UV .. NIR)



spectral sensitivity

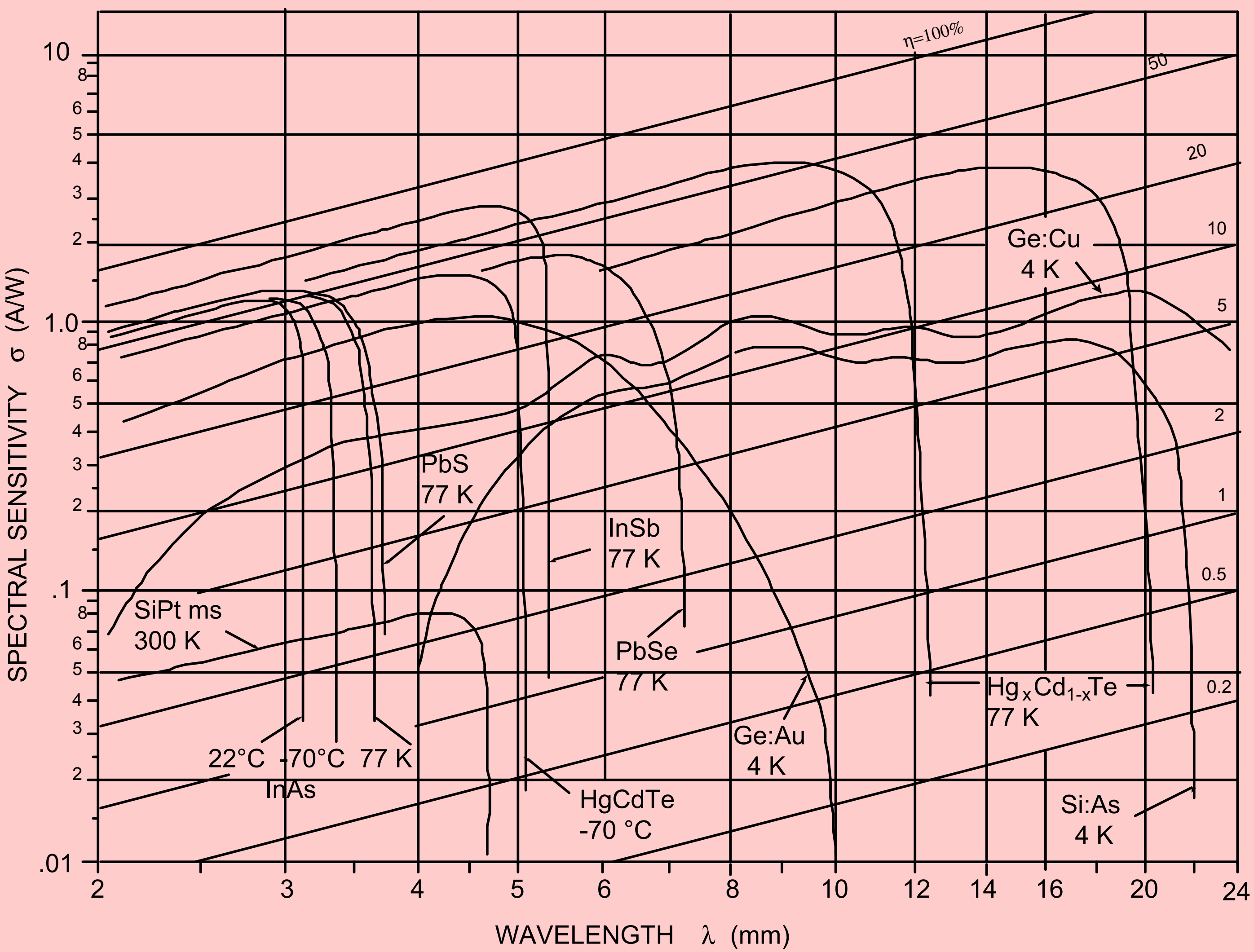
$\sigma(\lambda)$ [A/W] =

= I/P =

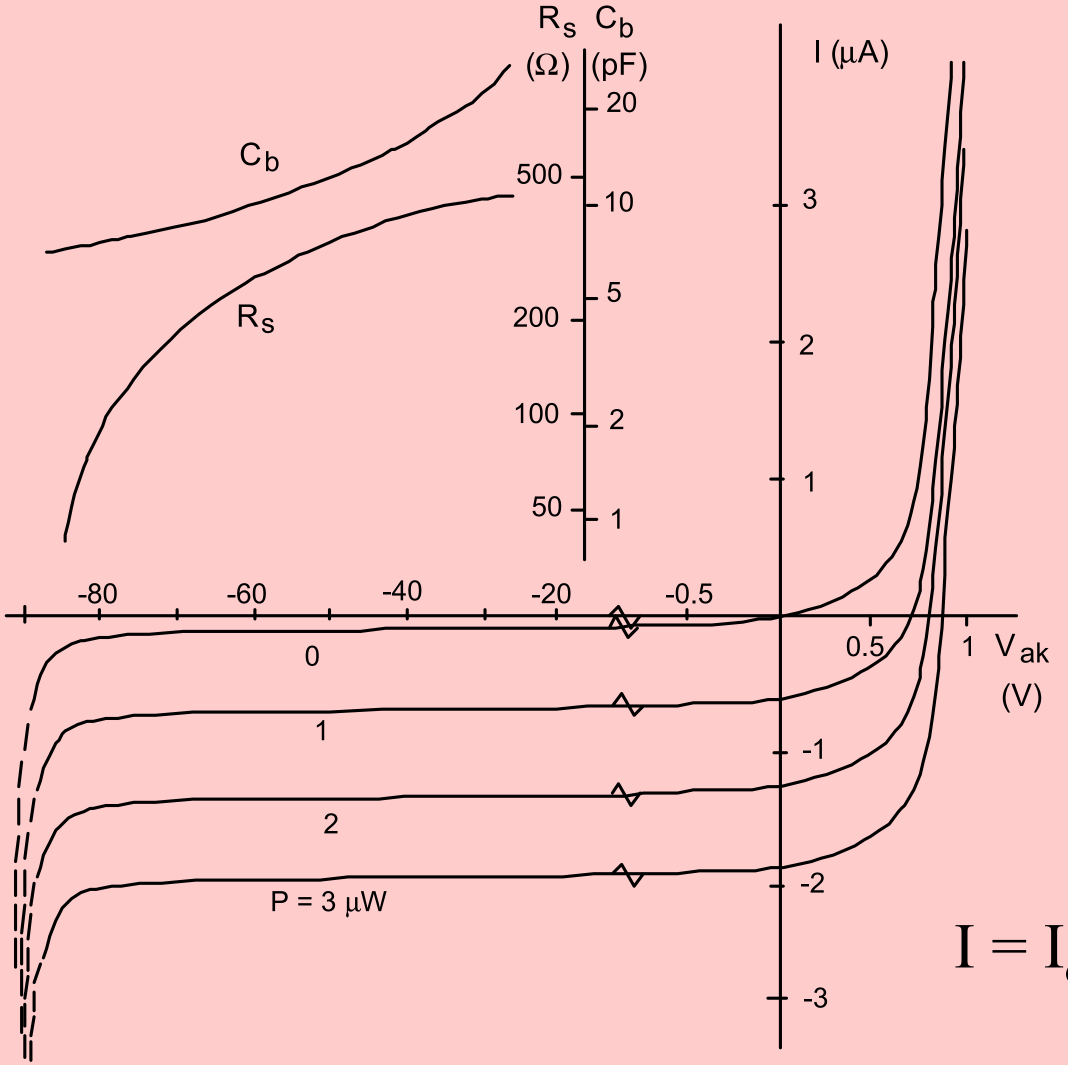
= $\eta e\lambda/hc$ =

$\eta\ \lambda[\mu m]/1.24$

Spectral sensitivity (MIR .. FIR)



pn-junction Characteristics



$$I_{ph} = \sigma P$$

$$I = I_o\ [I_{ph}\ eV/nkT)-1]\ -I_{ph}$$

Dark current and ideality factor
(advanced topic)

From Shockley standard analysis of the pn-junction, ideality factor is unity (n=1) and reverse current I_d is :

$$I_d = A\, e\, n_i^2 \,[(D_p/L_pN_D)+(D_n/L_nN_A)]$$

$$\approx A\, e\, n_i^2 \,(D_p/L_pN_D) \qquad \text{(for } N_A>>N_D\text{)}$$

where A=PD active area, $D_{n,p}$=minority diffusion constants, $L_{n,p}$=diffusion lengths, $N_{D,A}$=doping concentrations of donor/acceptor; n_i, intrinsic concentration of charge carriers is:

$$n_i^2 = N_C\, N_V \exp -E_g/kT \propto T^3 \exp -E_g/kT,$$

Taking for (D/L) a dependence T^γ from temperature, it is:

$$I_d \propto T^{3+\gamma} \exp -E_g/kT, \qquad \text{(independent from V)}$$

The, temperature coefficient of the dark current I_o=I_d is:

$$dI_o /I_o\, dT = [3+\gamma +E_g/kT] / T \approx 0.33\, [3+\gamma +E_g/kT] \quad (\%/°C,\ 300\ K)$$

These eqs. apply at weak current levels or when the intrinsic concentration of charge carrier n_i is not too low.

Dark current and ideality factor
(advanced topic, 2)

Another contribution is generation-recombination in the depleted region, through defect levels near bandgap middle, which give:

$$I = I_{g\text{-}r}\,[\exp(eV/2kT) - 1],$$

it has an ideality factor n=2; in addition, the reverse saturation current is:

$$I_{g\text{-}r} = A\, e\, n_i\, W / 2\tau$$

where W=width of the depleted region, $\tau = 1/(\sqrt{3kT/m})\sigma_t N_t$ is charge carriers lifetime, dependent on N_t and on cross-section σ_t of the g-r levels.
The term $I_{g\text{-}r}$ has (through W) a dependence V^{β} upon voltage, with β=1/2 or 1/3 for abrupt or gradual junctions; its temperature coefficient is:

$$dI_o / I_o dT = [2+E_g/2kT]/T \approx 0.33[2+E_g/2kT] \quad (\%/°C \text{ at } 300\ K)$$

The total current in the photodiode is thus the sum of I_{ph}. Basic diode equation is an approximant of such a sum. In particular, at high reverse bias the dark current is the sum of the two-saturation terms:

$$I = - I_o = - I_d - I_{g\text{-}r}$$

Trend is that of diffusion (n=1) for $n_i (D_p/L_p N_D) > W/2\tau$, and of g-r (n=2) in the opposite case.

Dark current and saturation
(advanced topic, 3)

In direct or zero bias, we obtain an ideality factor n=1 for voltage

$$V > (2kT/e) \ln [(W/2\tau)/(n_i D_p/L_p N_D)], \qquad n=2 \text{ otherwise.}$$

A final contribution to I_0 is from surface states, interfaces defects giving bangap levels. This is important only in PDs with very low I_0.

PD *saturation* :

at high I_{ph}, saturation determines the maximum signal detectable with linearity (III quadrant), the logarithmic conformity, and the voltage in the photovoltaic mode (IV quadrant).

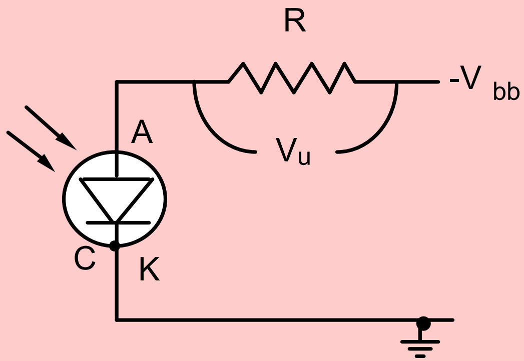
A saturation is caused by storage of charge Q collected at the boundary of undepleted regions after drift in the junction. When $Q= I_{ph}\tau$, (τ=drift time) is comparable to charge ($Q=C_b V$) supplied by ionized dopant atoms to sustain applied voltage V, junction field decreases and a reverse fields appear in undepleted regions, thus impeding increase of I_{ph} with increasing P. For a p^+n PD:

$$I_{ph(sat)} = A\, e\, N_A\, \mu^* \, V / 2W$$

where $\mu^* =(1/\mu_n+1/\mu_p)^{-1}$ is effective mobility. If generation is in the neutrality region p^+ (as, in the UV) the limit is lower [that of diffusion times ($\tau=L_n^2/D_n$)]:

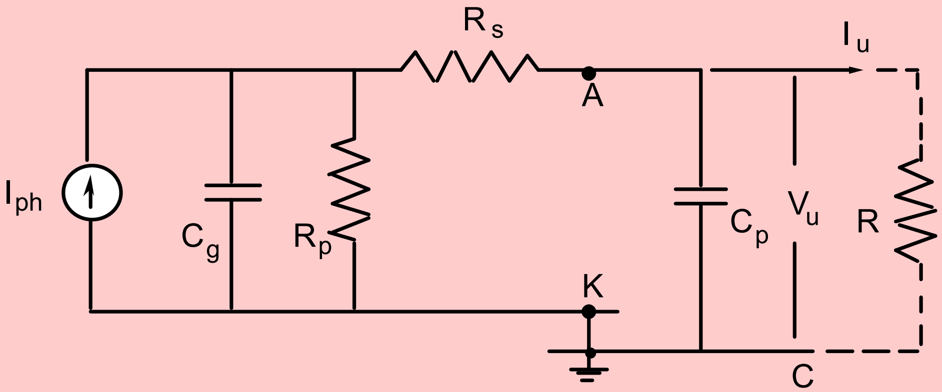
$$I_{ph(sat)} = A\, e\, N_A D_n / 2W\, L_n^2$$

Equivalent Circuits



(a)

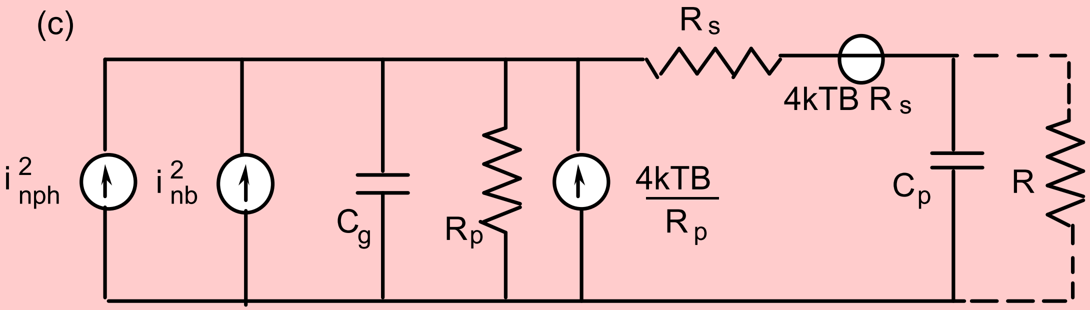
basic biasing scheme
of a pn- PD



(b)

small-signals
equivalent circuit

(c)



noise equivalent circuit

Frequency response

PD frequency response results from:

- *extrinsic cutoff* due to the $Z(\omega)$ of the parasitics external to the junction
- *intrinsic cutoff* inherent to the collection of photogenerated charges internal to junction

From the small-signal circuit:

$V_u(\omega) = I_{ph}(\omega)\, Z(\omega) =$

$I_{ph}(\omega)\, \{R_p//(1/j\omega C_g)//[R_s+(R//(1/j\omega C_p)]\}/[1+R_s/(R//(1/j\omega C_p)]$

where // is parallel operation,

$Z(\omega)$ = effective impedence seen by the PD (extrinsic cutoff)

$I_{ph}(\omega) = f(\omega)\, P(\omega)$, signal current duplicating $P(\omega)$ with a tranfer function $f(\omega)$ (intrinsic cutoff)

Frequency response (2)

Taking $R \gg R_s$ maximizes PD response (good for instrumentation applications with a modest B) and:

$$V_u(\omega) / V_u(0) = [I_{ph}(\omega)/I_{ph}(0)]/[1+j\omega(C_g+C_p)(R_p//R)]$$

and the 3-dB cutoff frequency is:

$$f_2 = 1 / 2\pi(R_p//R)(C_g+C_p)$$

For maximum speed of response, R is taken small so C_p in is short-circuited (response is sacrificed). For $R<R_s$:

$$I_u(\omega) / I_u(0) = [I_{ph}(\omega)/I_{ph}(0)]/(1+j\omega C_g R_s)$$

and cutoff frequency:

$$f_2 = 1 / 2\pi R_s C_g$$

Frequency response (3)

Mean transit time to collection by *drift* (and induced current duration):

$$\tau_d(z) = (1/2)(\tau_{dn} + \tau_{dp}) = (1/2)[(W-z)/v_n + z/v_p]$$

integrating on z (uniform generation)

$$\tau_d = (1/2)\, W(1/v_n + 1/v_p) = (W^2/2V_{bb})(1/\mu_n + 1/\mu_p)$$

$$= W^2 / 2V_{bb}\, \mu^*$$

Frequency cutoff: $f_{2d} = 0.44 / \tau_d$

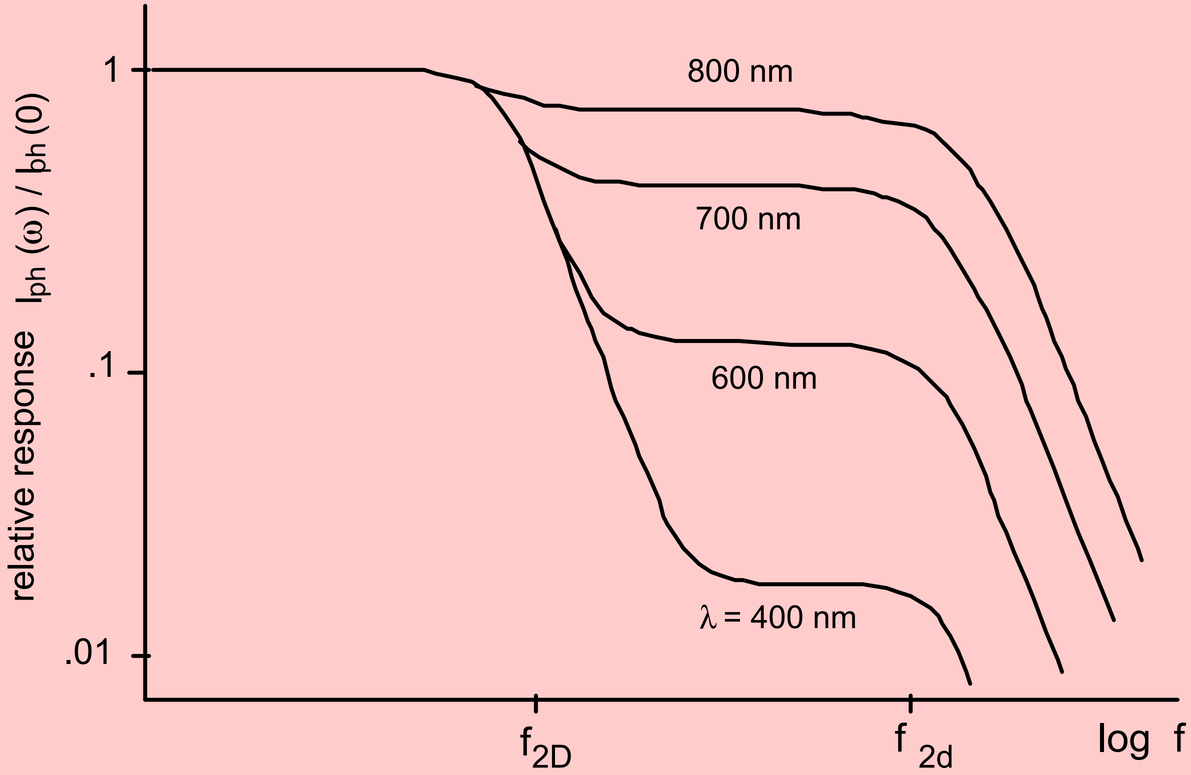
Mean *diffusion* time to collection from undepleted regions

$$\tau_{Dn,p} = L_{n,p}{}^2 / D_{n,p}$$

Frequency cutoff: $f_{2d} = 1/2\pi\, \tau_{Dn,p}$

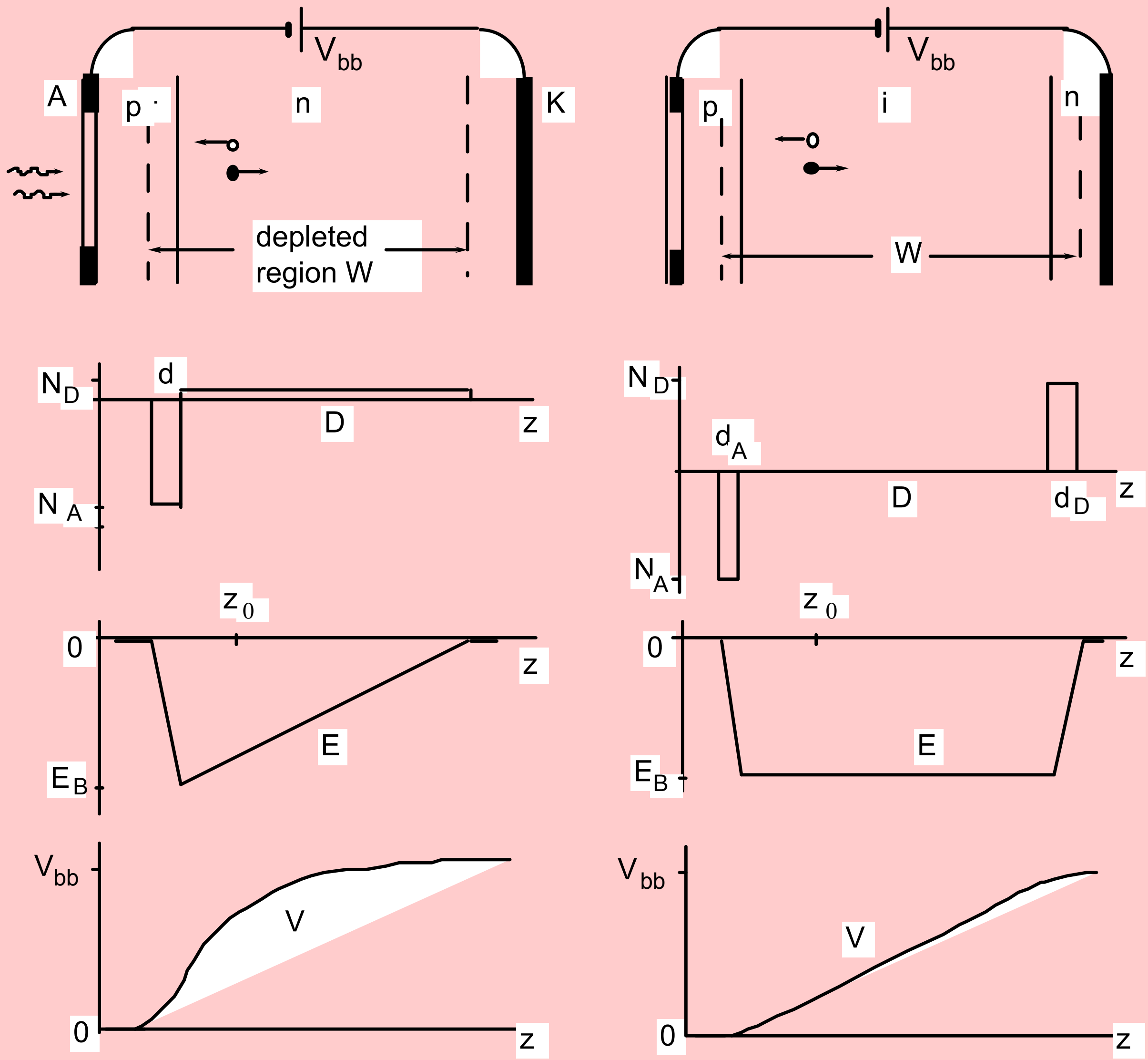
A pole-zero frequency response is found (varies with λ)

Zero-pole in pn-PDs

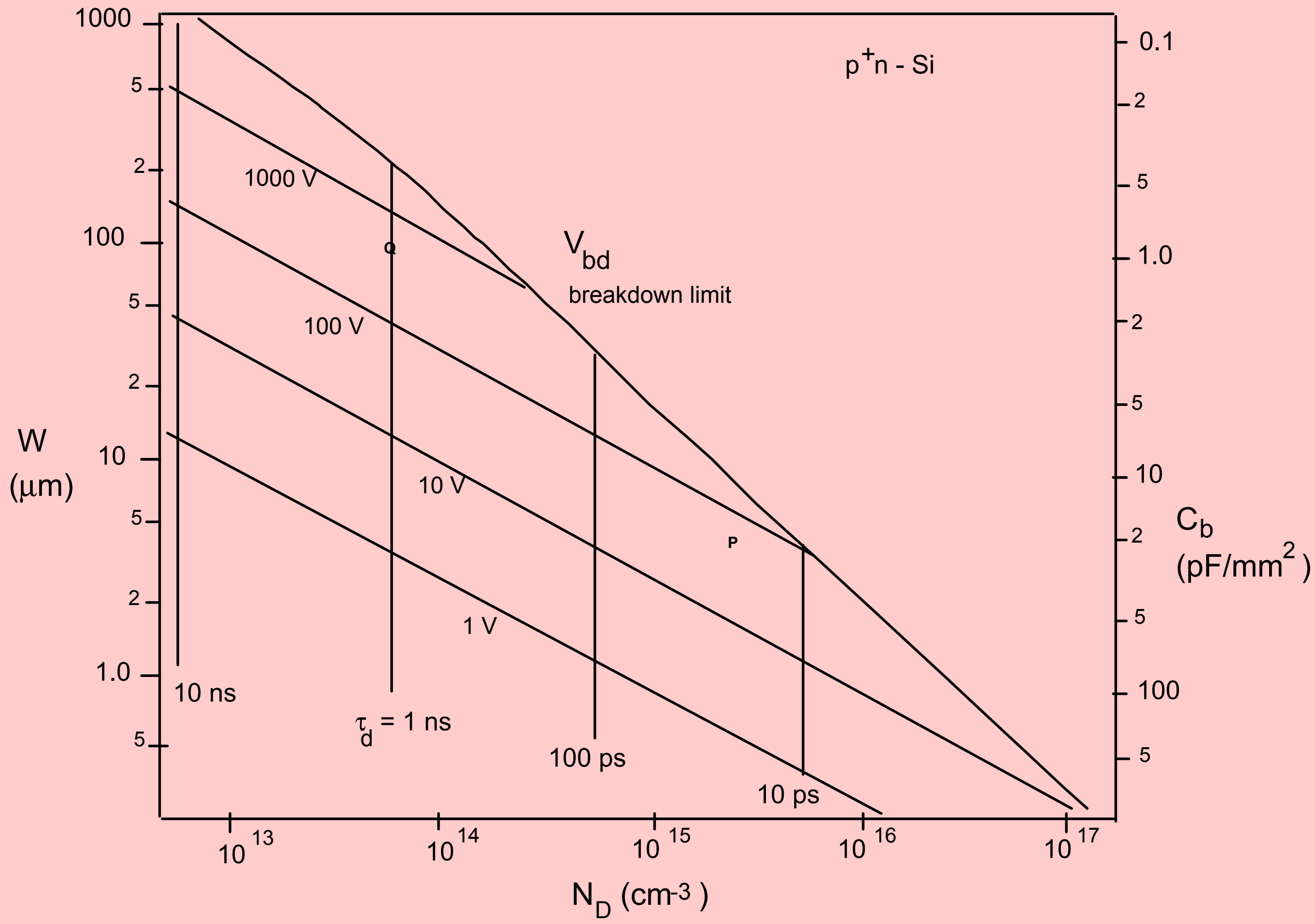


In a pn-PD, intrinsic frequency response has a zero-pole region between f_{2D} (diffusion) and f_{2d} (drift), more markd at smaller λ. Typical values are f_{2D}=1 MHz, f_{2d}=200 MHz.

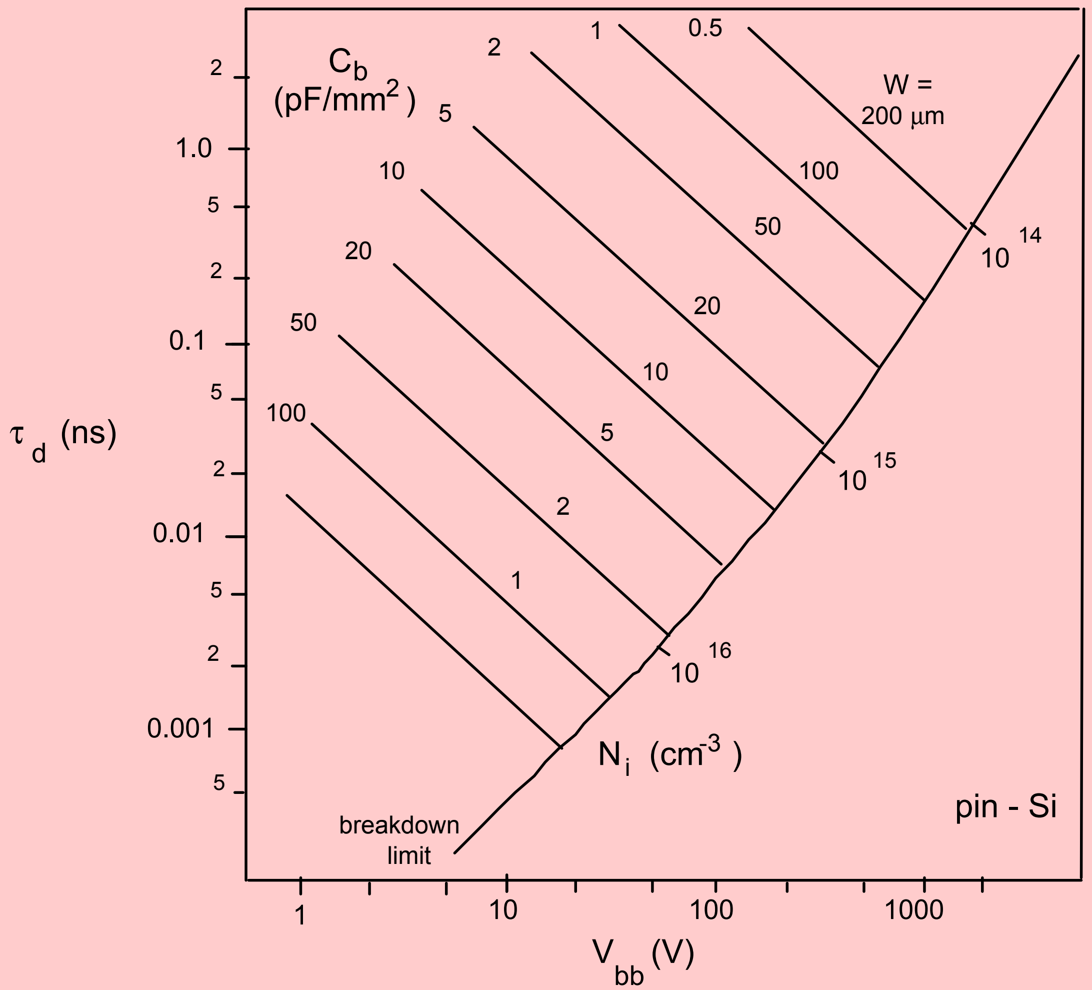
pn and pin junction PDs



design nomogram for SI pn-junction PDs



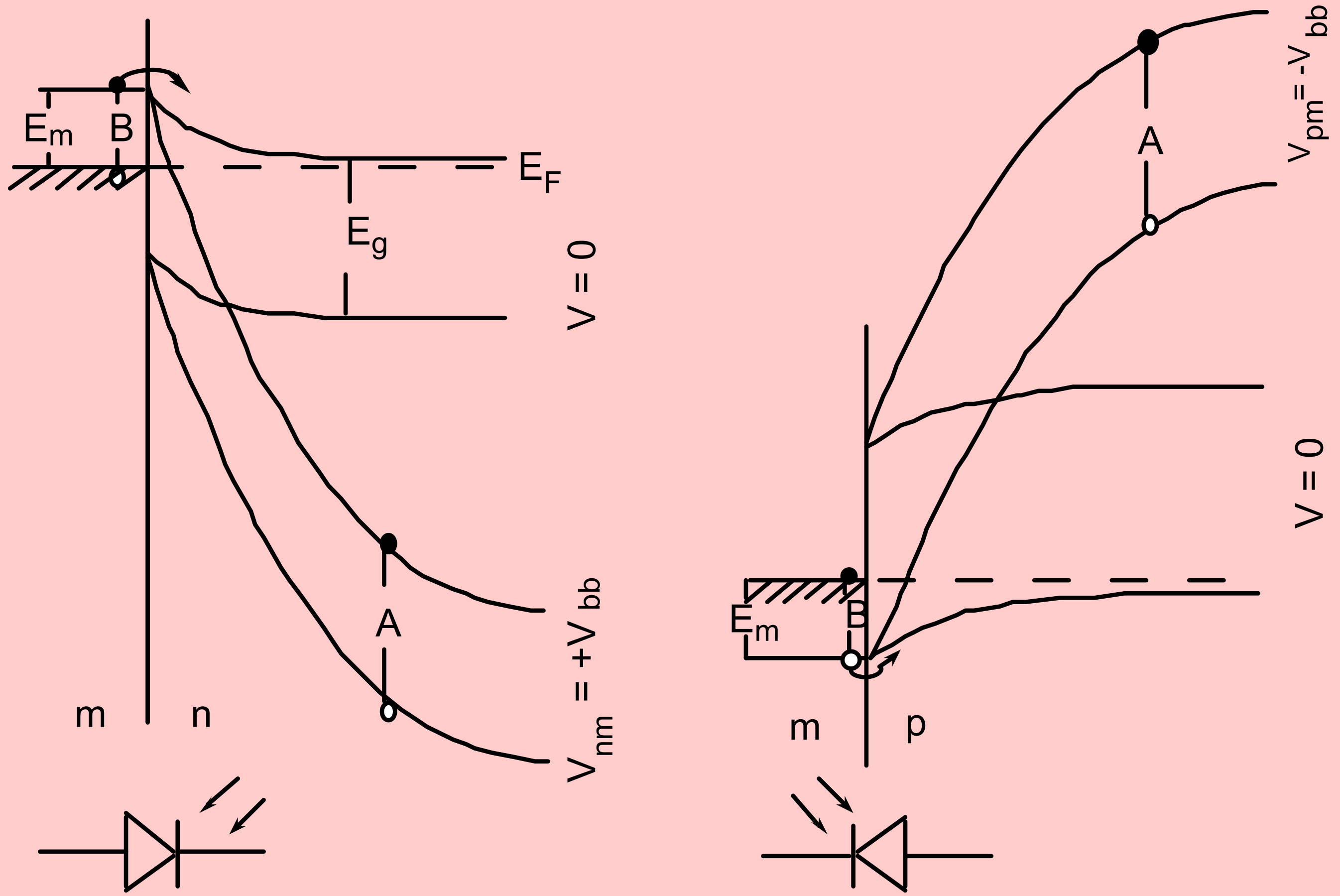
design nomogram for Si pin-junction PDs



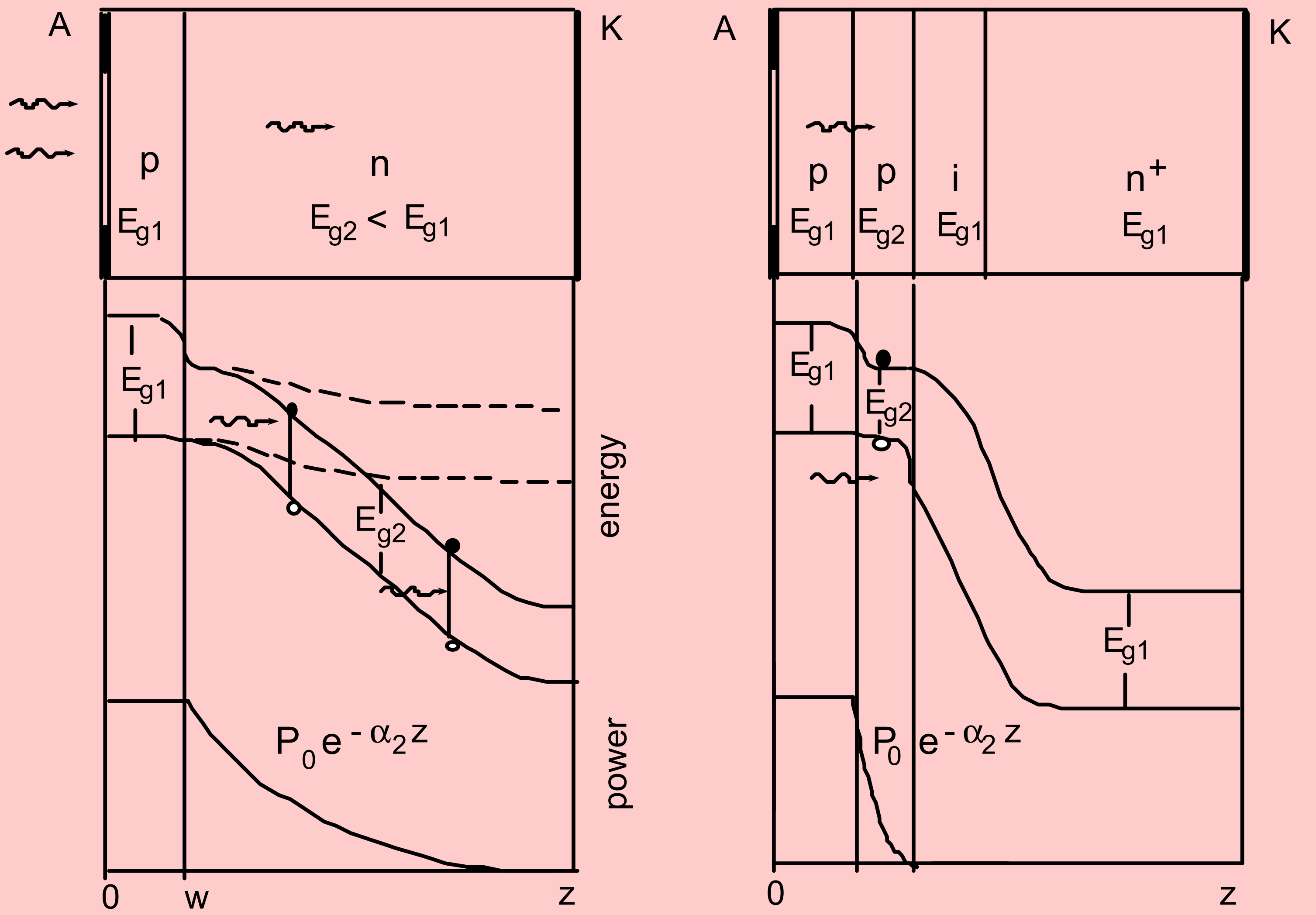
Advantages of pin over pn PDs

- thickness W of the absorption region is independent from V_{bb}, (which has no influence on the spectral response; a good η is got even at low bias V_{bb} near threshold $\lambda \approx \lambda_s$)
- with W>> d_A,d_D, diffusion contribution is small - (frequency response is independent of λ)
- since E≈const in the active layer, intrinsic speed of response is optimized (time τ_d);
- reverse current (and g-r contribution) is nearly independent of V_{bb}, whence a very high value of R_p.

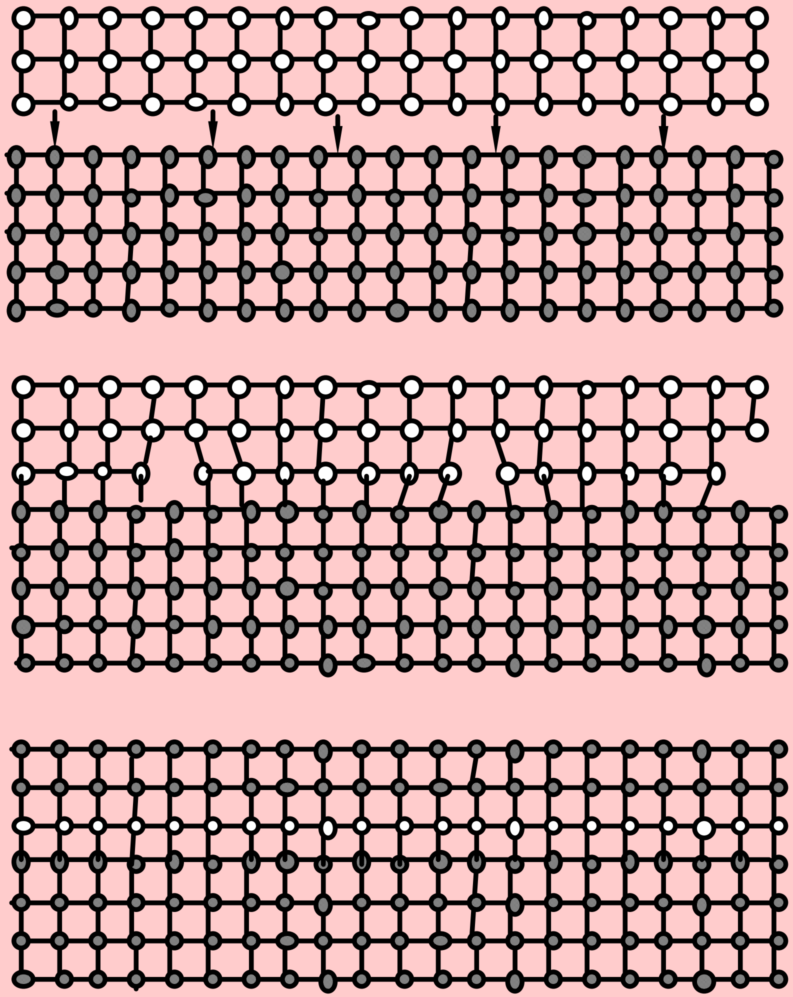
Schottky (or metal-semiconductor) PDs



Heterojunction PDs



Lattice matching in heterostructures



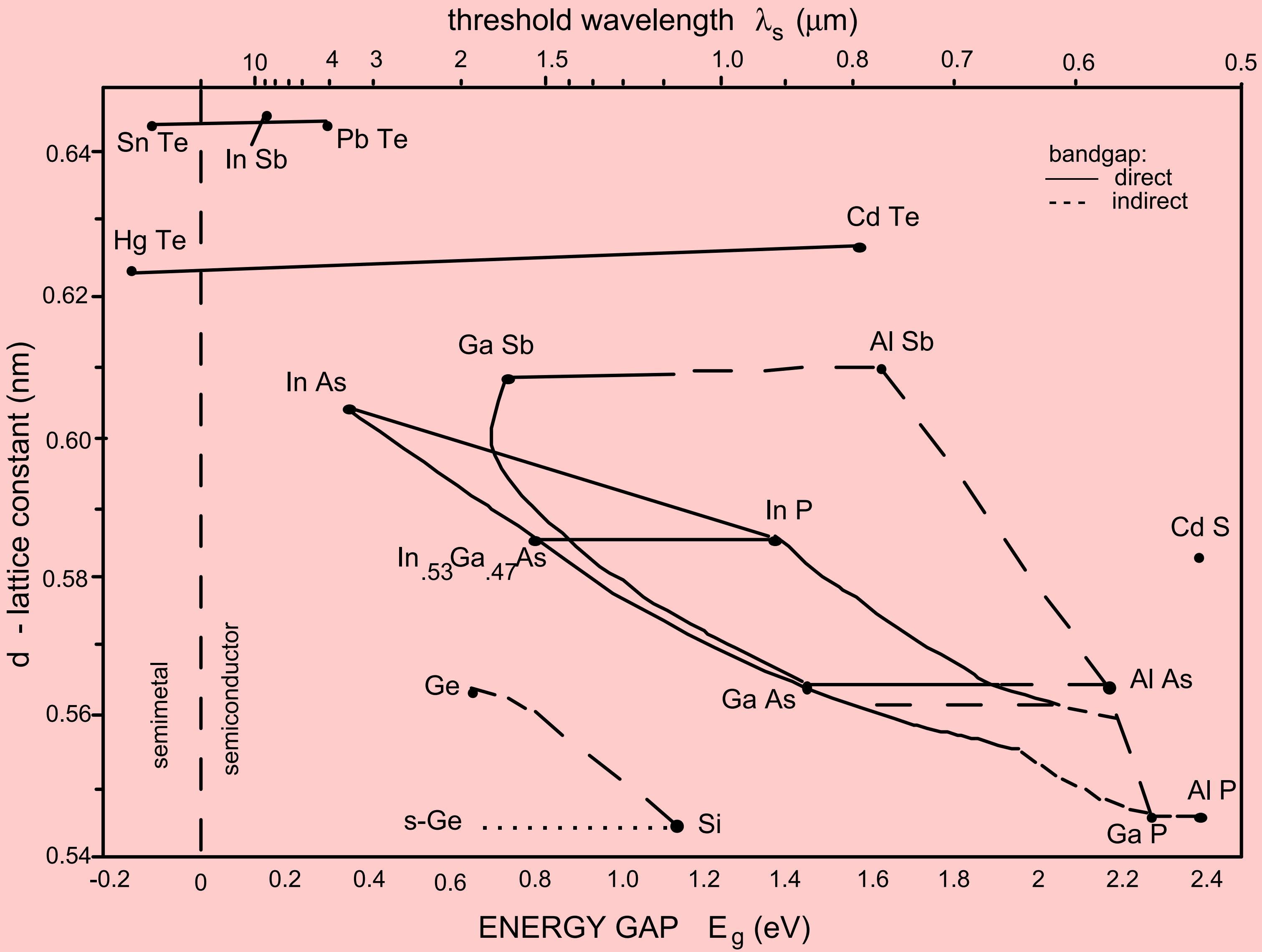
a)

b)

c)

A material with a lattice size different from substrate (a) will produce a layer with dislocation defects (b), but, if layer is very thin (c) , it is strained and layer has no defects

Lattice, composition and energy gap



Common PD structures