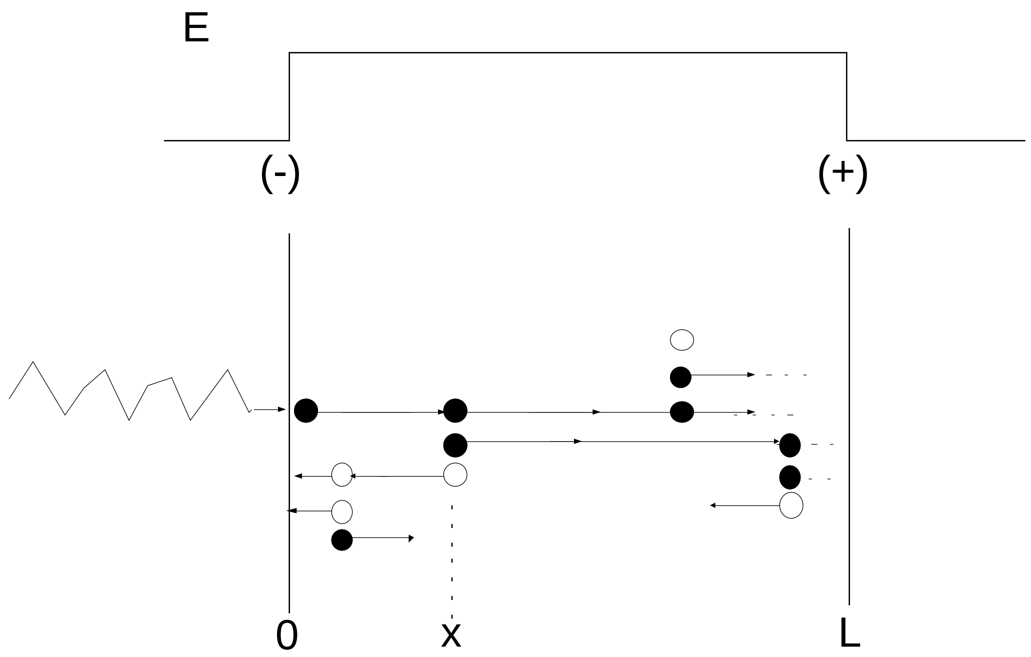
Avalanche multiplication



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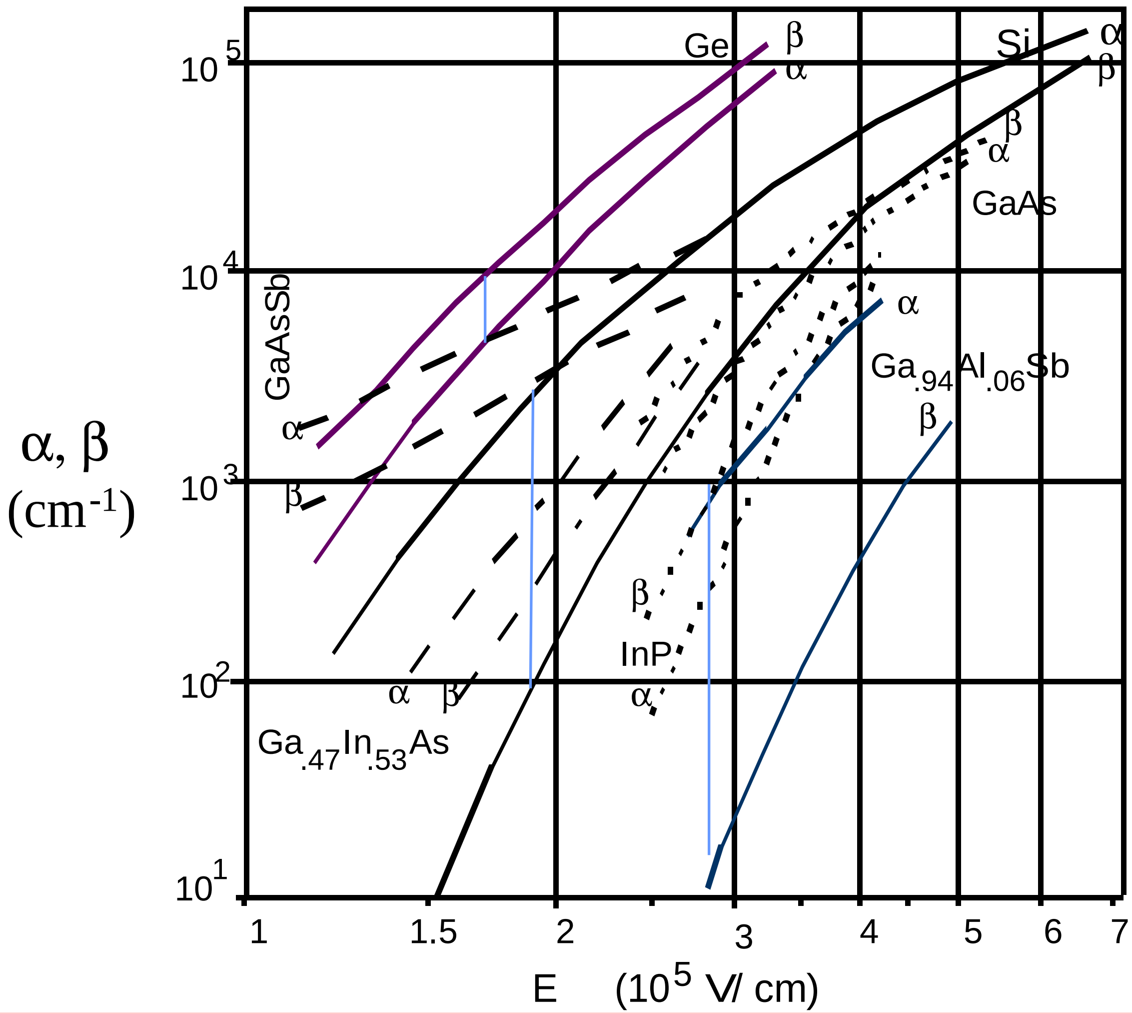
Ionization coefficients α, β



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APD Gain

$$di_n/dx = \alpha i_n + \beta i_p, \qquad di_p/dx = -(\alpha i_n + \beta i_p)$$

with: $i_n(0) = I_{ph}$, $i_n(L) = I$, $i_p(L) = 0$

then, $d^2 i_n/dx^2 = (\alpha - \beta) di_n/dx$,

$i_n = [C_1/(\alpha - \beta)]\exp(\alpha - \beta)x + C_2$, $\beta i_p = -[\beta C_1/(\alpha - \beta)]\exp(\alpha - \beta)x - \alpha C_2$.

$$M = \frac{(\alpha - \beta)\ \exp(\alpha - \beta)L}{\alpha - \beta \exp(\alpha - \beta)L}$$

special cases: for $\beta << \alpha$: $M = \exp \alpha L$,

for $\beta = \alpha$: $M = 1/(1 - \alpha L)$

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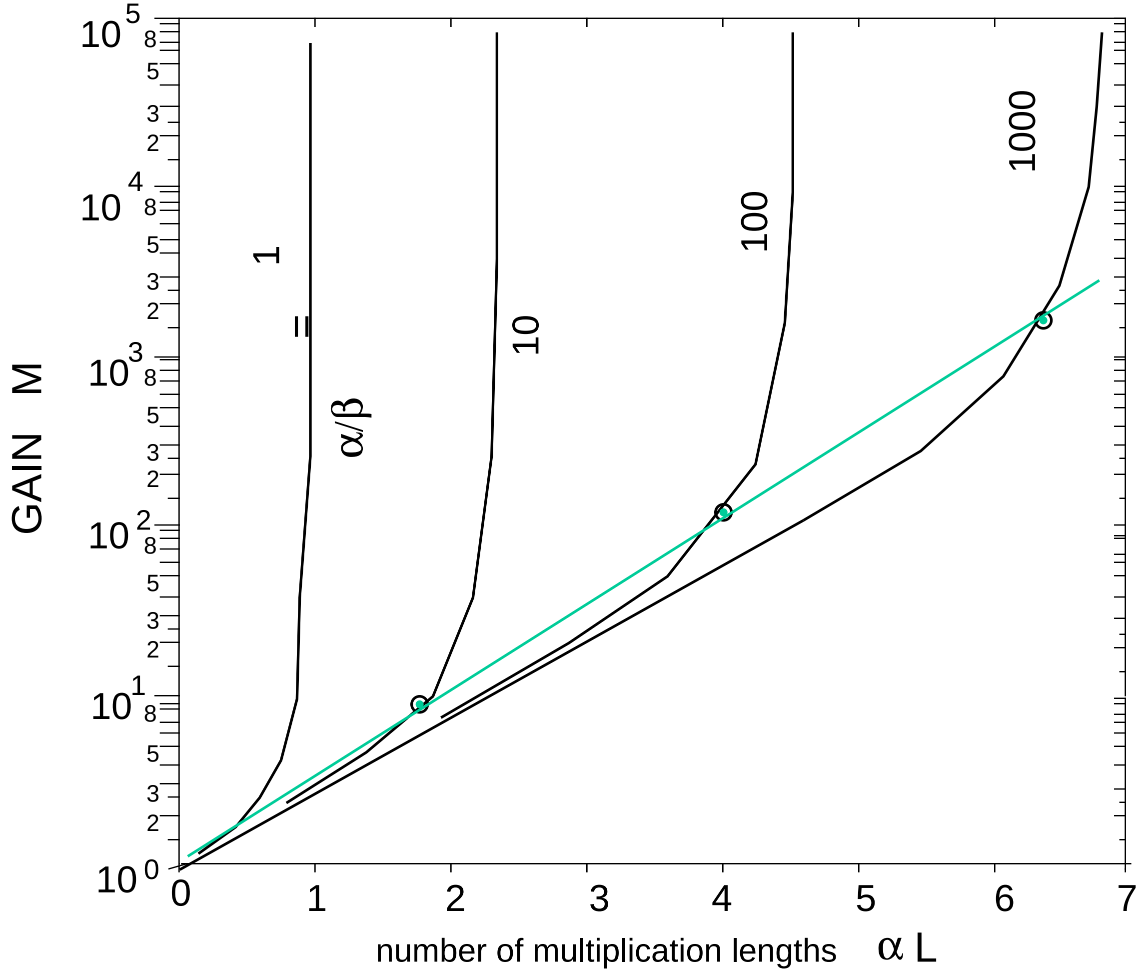
APD gain vs αL



$M_o=\alpha/\beta$ is the optimal gain

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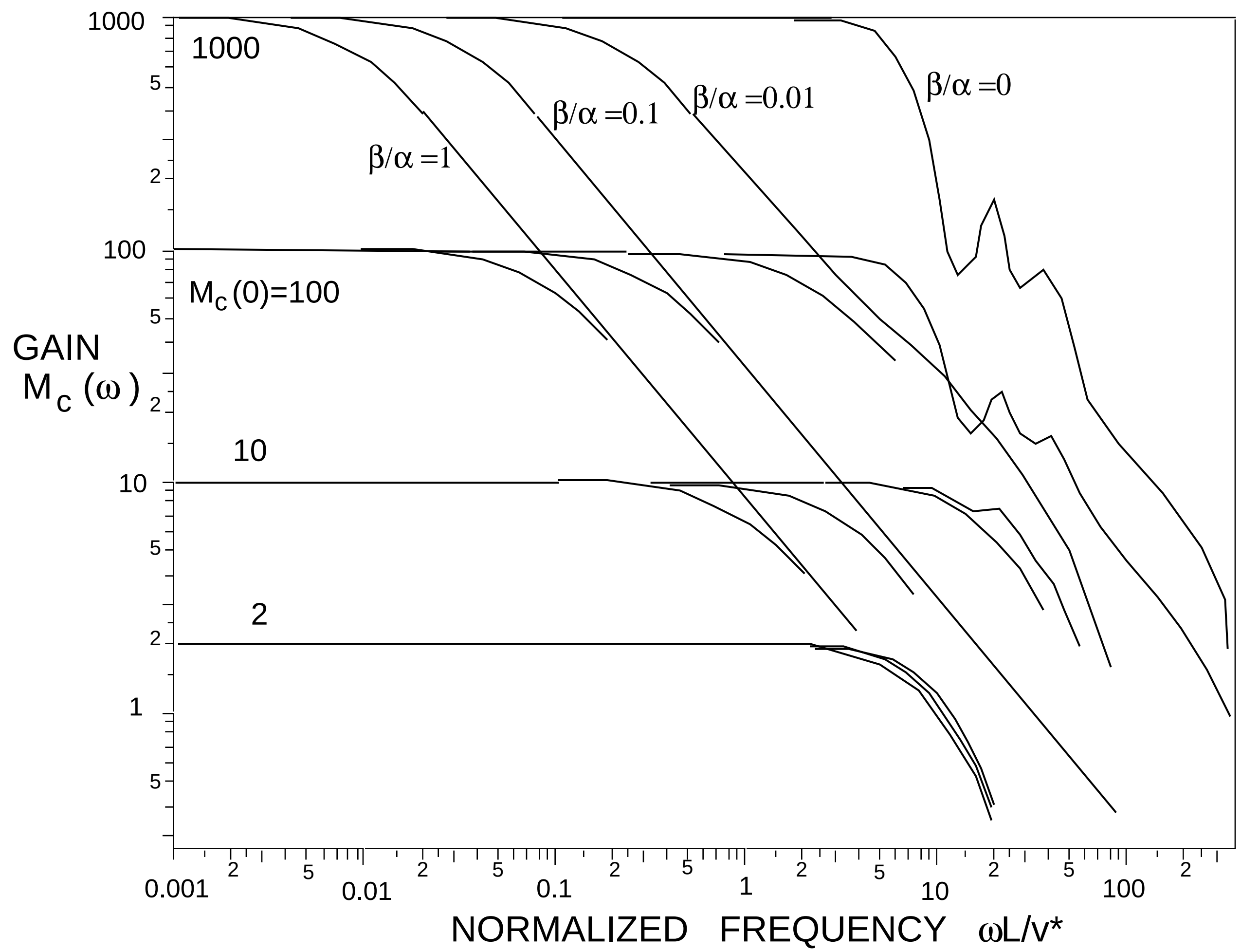
Frequency response



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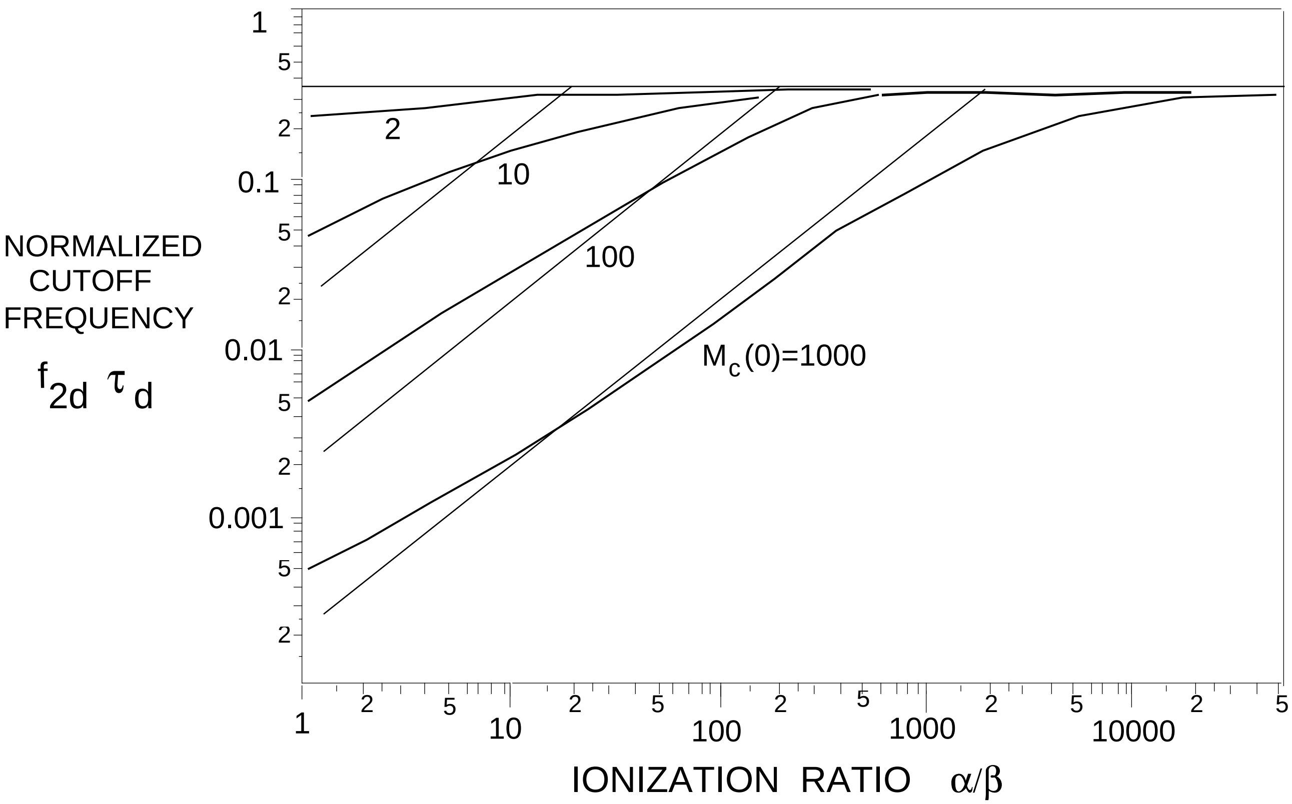
3-dB cutoff frequency



$M_o = \alpha/\beta$ is the optimal gain

$$f_{2d} \cong 0.36\,/\tau_d \quad (M<<M_o), \qquad f_{2d}\,M \cong 0.36(\alpha/\beta)/\tau_d \quad (M>M_o)$$

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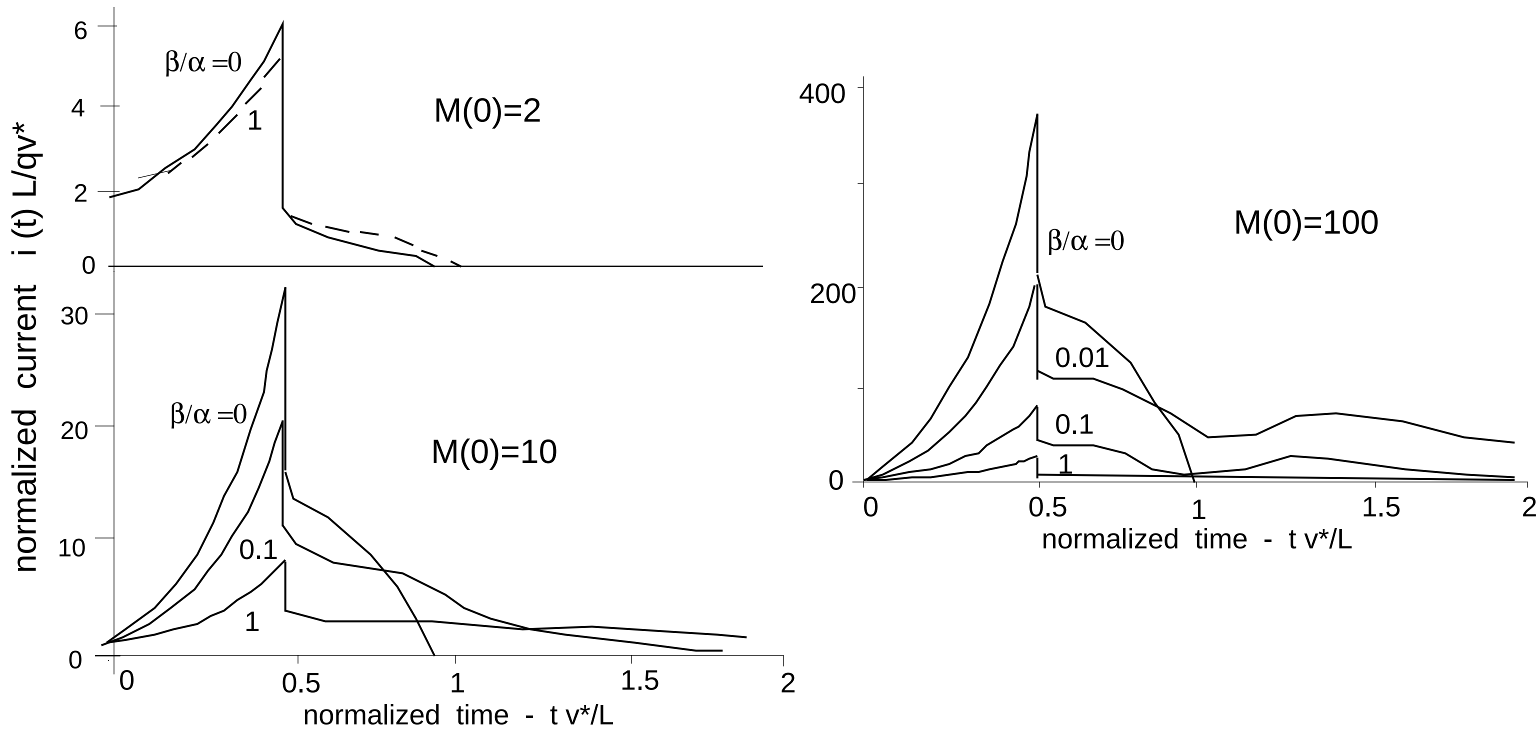
Delta response



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noise

relative variance of output charge for 1 pair at x=0:

$$\sigma_M^2(0)/M_c^2(0) = 1+\beta\, M_c(0)/(\alpha-\beta)-\alpha M_c^2(L)/M_c(0)(\alpha-\beta)$$

$$= 1+M_c(0)\{\beta/(\alpha-\beta)-[\alpha/(\alpha-\beta)]\,\exp{-2(\alpha-\beta)L}\}$$

for moderate gains M_c:

$$\sigma_M^2(0)/M_c^2(0) \approx 1 \qquad \text{for } M_c(0)<\alpha/\beta$$

$$\approx M_c(0)\beta/\alpha \qquad \text{for } M_c(0)>\alpha/\beta$$

once again, $M_o=\alpha/\beta$ is the optimal gain. Noise current:

$$\sigma_I^2 = 2eB\, I_{ph}\,(M^2+\sigma_M^2) = 2eB\, I_{ph}\, M^2\, F$$

$$F = 1+\sigma_M^2/M^2$$

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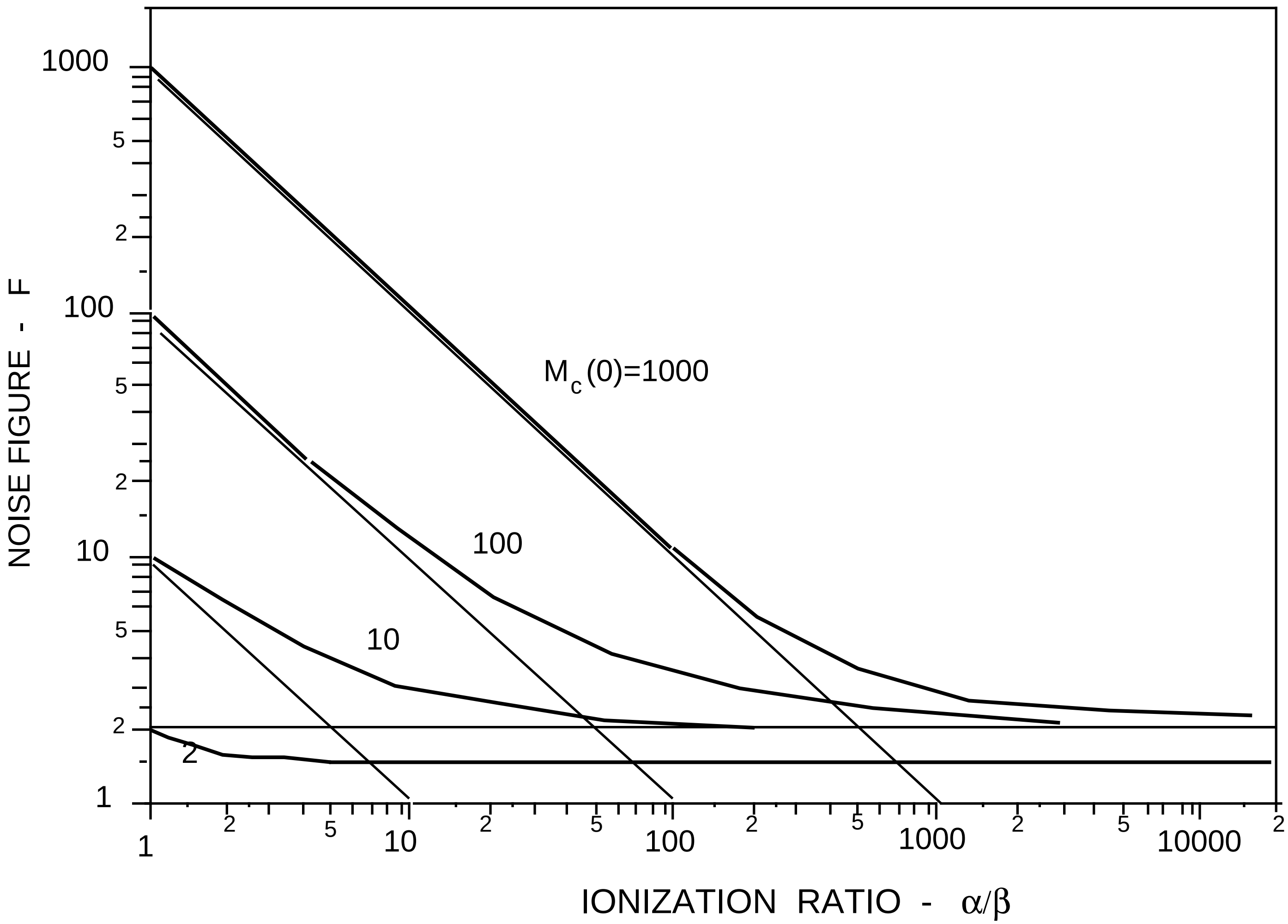
Noise figure



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Optimum gain and beyond

$$\sigma_I^2 = 2eB\,(I_{ph}+I_o)\,M^2\,F + 4kTB/R$$

$$\sigma_{in}^2 = 2eB\,(I_{ph}+I_o)\,F + 4kTB/RM^2$$

but, $S=I_{ph}$, $N^2 = \sigma_{in}^2$, and $F= M\beta/\alpha$

$$(S/N)^2 = I_{ph}^2 / [2eB(I_{ph}+I_o)\,M\beta/\alpha + 4kTB/RM^2]$$

S/N is maximum at a M_{max} found as:

$$M_{max}= [(\alpha/\beta)(4kT/e)\,/R(I_{ph}+I_o)]^{1/3}$$

for instance, for $R=50\Omega$, $I_{ph}+I_o=1nA$ and $\alpha/\beta=1$: $M_{max}=125$

practical limit for M: bandwidth decreasing by $M\beta/\alpha$ at $M>\alpha/\beta$

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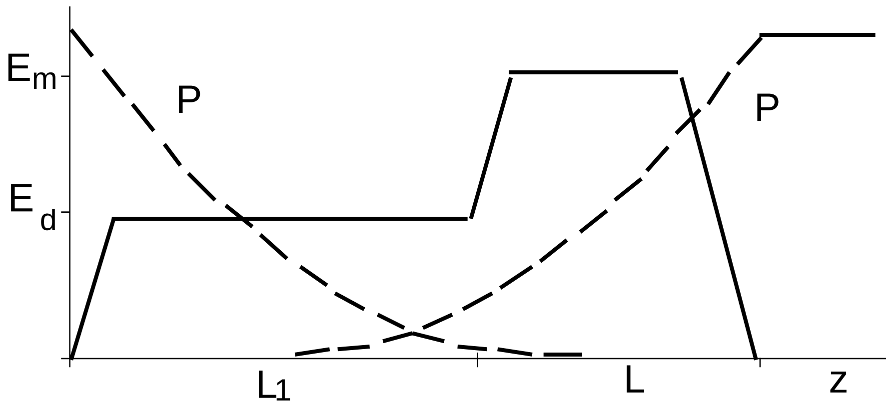
APD desirable structure

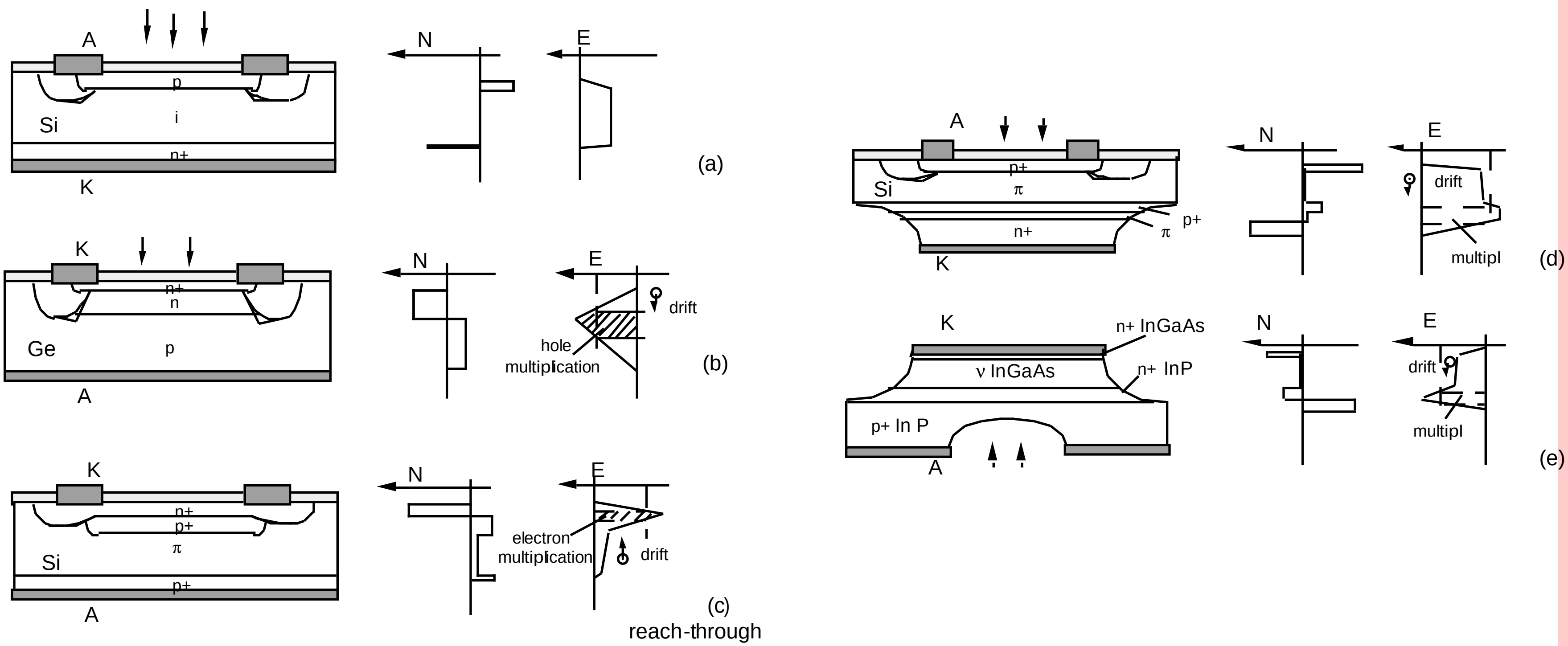


two regions desirable, to separate :

•photon dissipation in $L_1(\approx 1/\alpha)$ and the carrier drift (medium E_d)

• multiplication in L of most efficient ionizing carrier (high E_m)

APD structures



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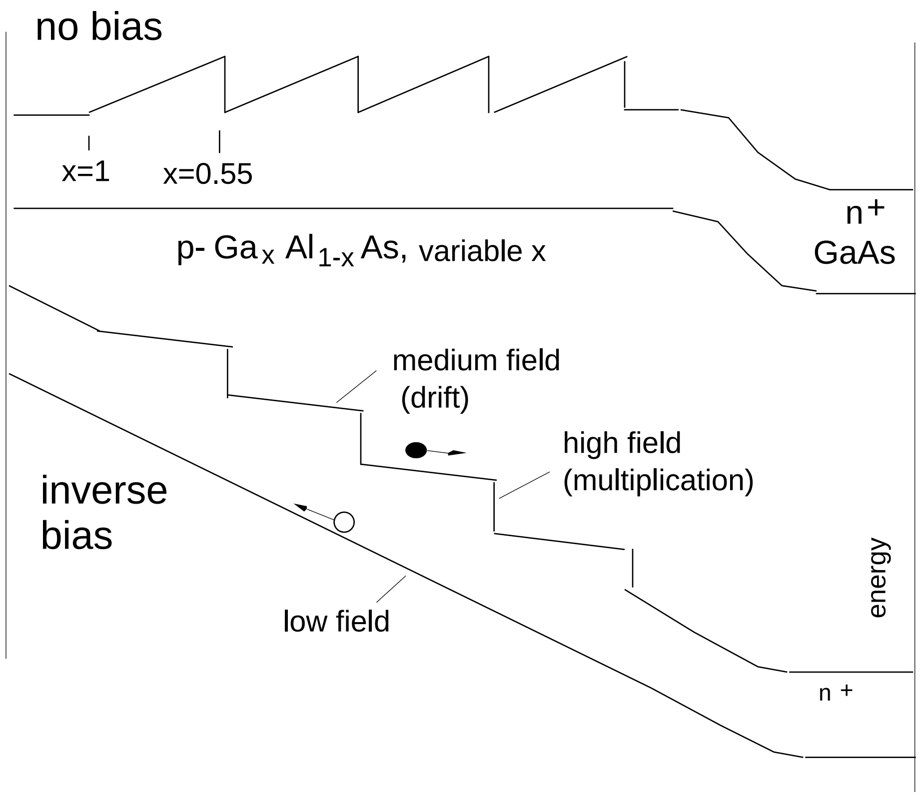
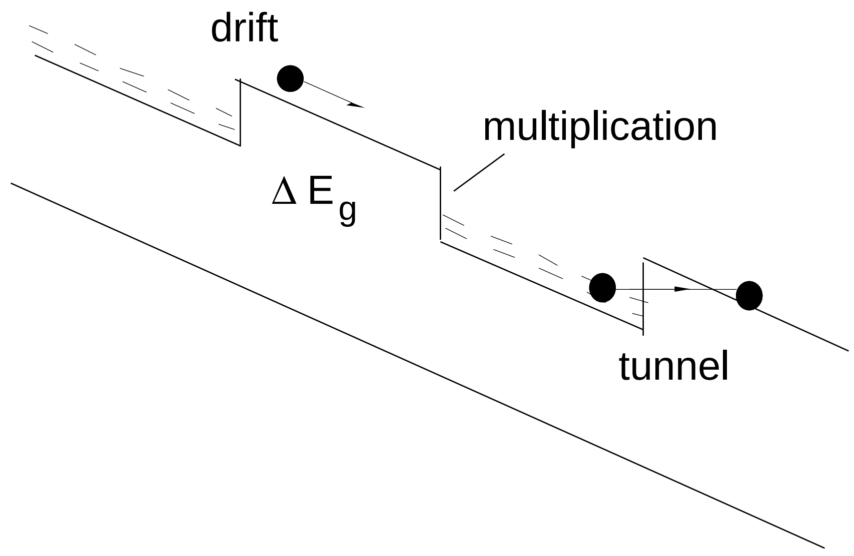
Staircase APD



MQW APD



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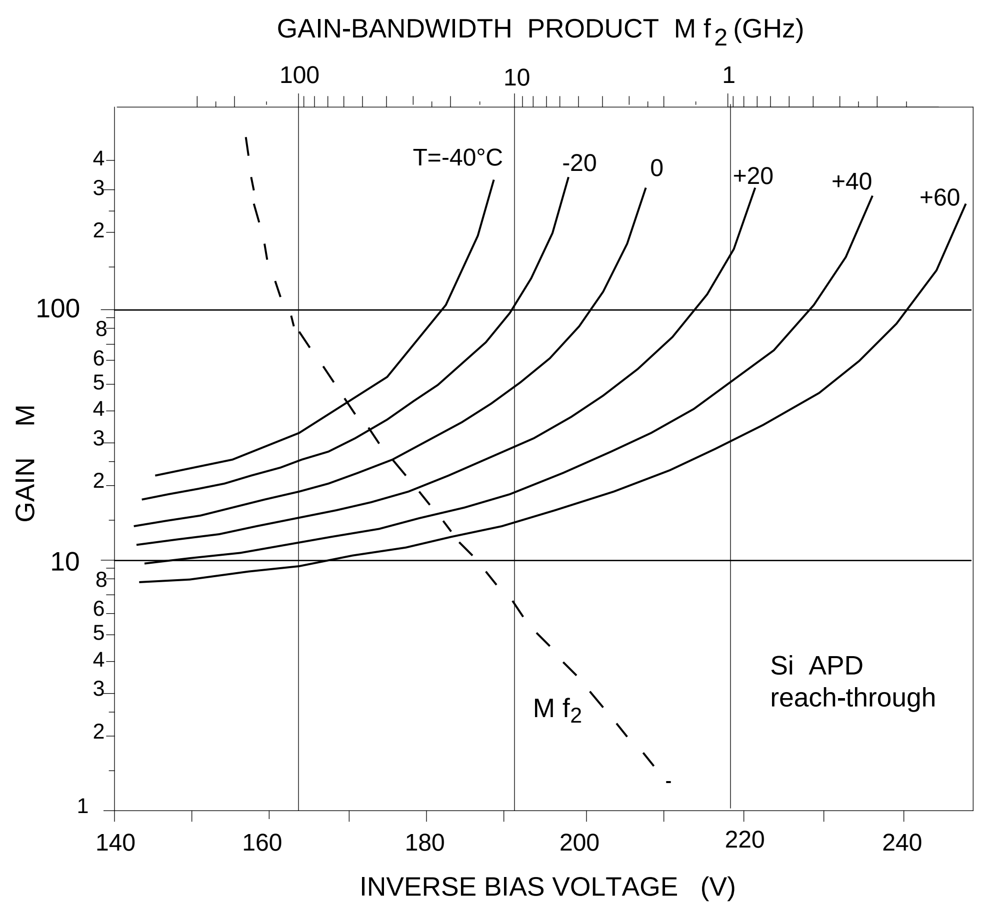
APD Biasing and Use Requisites



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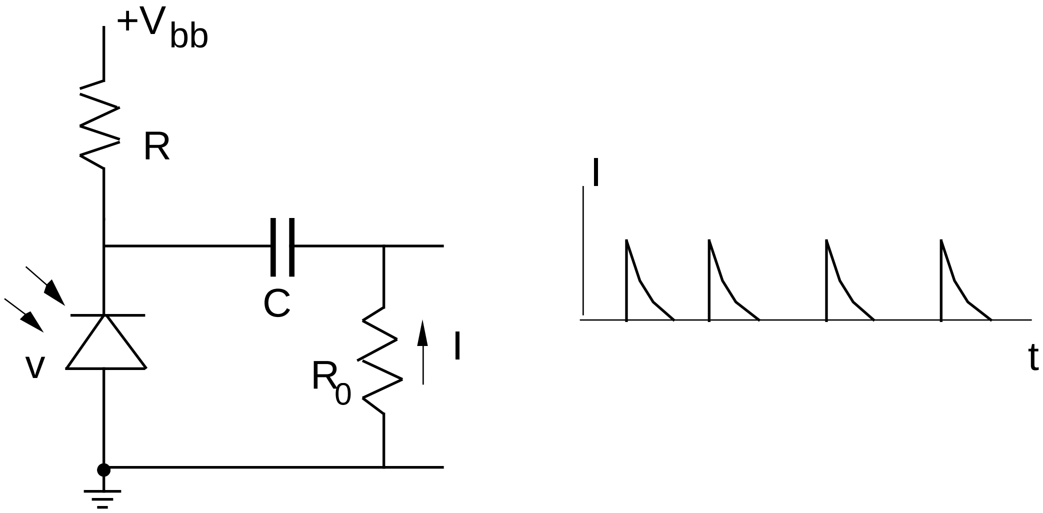
SPAD



in quiescent conditions, $V_{bb}>V_{\infty}$, $M=\infty$

a single charge-pair makes I increase fast up to $V_{ak}=V_{bb}-RI < V_{\infty}$;
then M returns to a finite value

Max. photon rate: $F_M<\tau_{rec}= R_oC$; dark rate: $F_b=J_0A/q$

Dynamic range: $F_M/F_b=10^3$ typ.

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