# Categorization of Image Devices

- *Image Pickup* detectors: individual pixel are organized serially in a single electrical signal, suitable for transmission (TV, etc.) or processing
- *Direct-Vision* detectors: an intensified or spectrally converted replica of the input image is supplied at an output screen

Requisites for Image Pickup devices:

◊ a photosensitive surface to accommodate NxM pixels

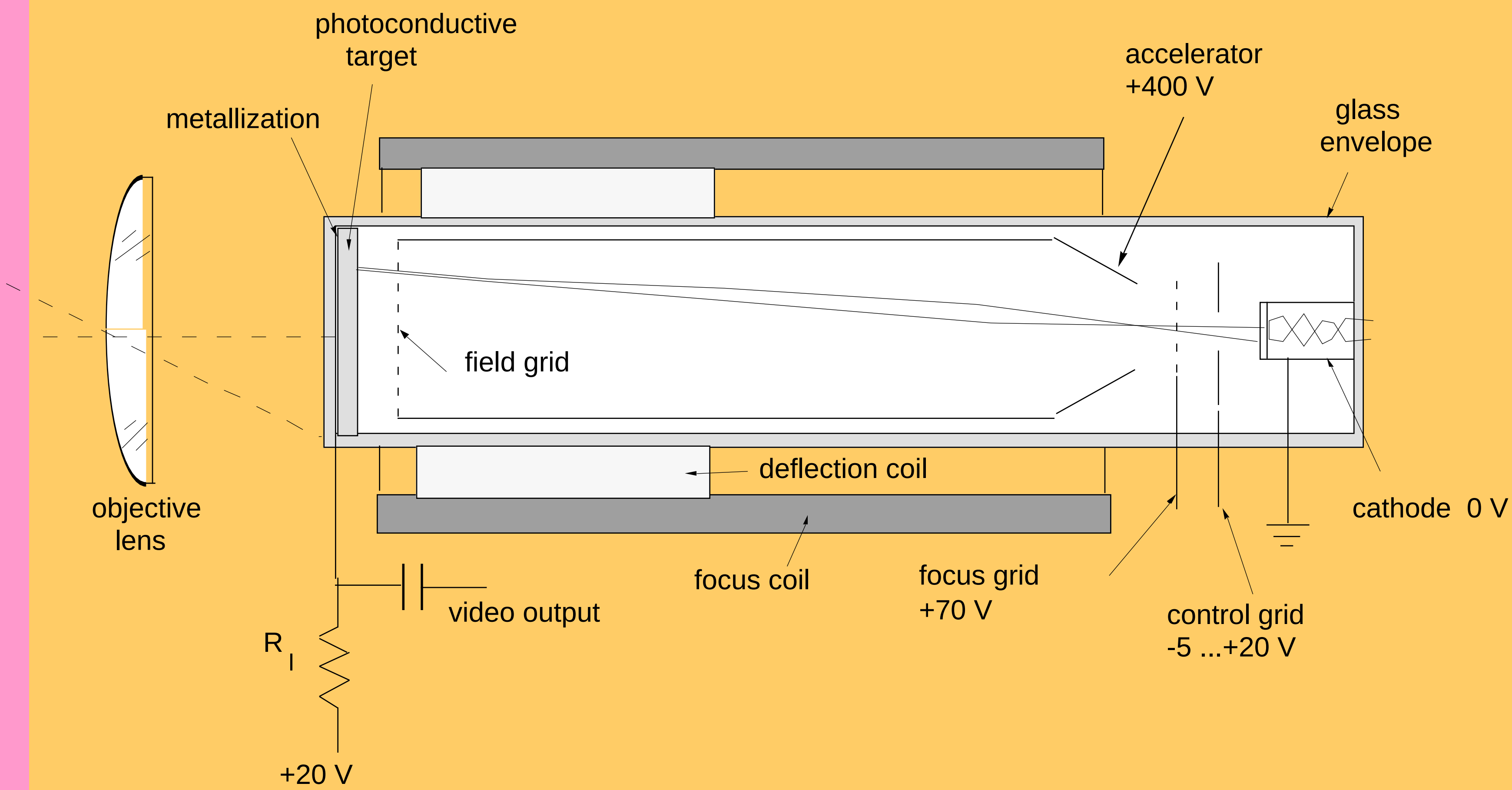
◊ a provision to single out the individual image pixels

◊ an arrangement for sequential readout of photogenerated charge

◊ an integration of the photogenerated charge between successive readouts, i.e., the frame period $T_f$.

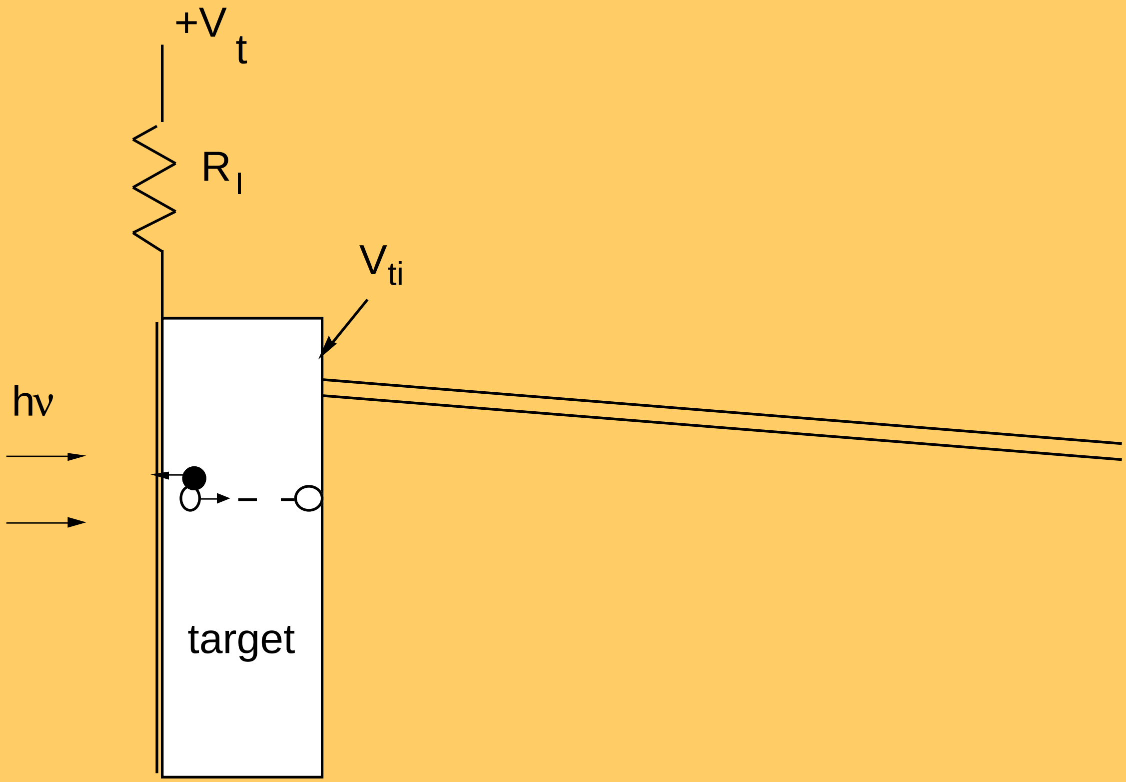
from:"Photodetectors", by S.Donati, Prentice Hall 2000

# The vidicon



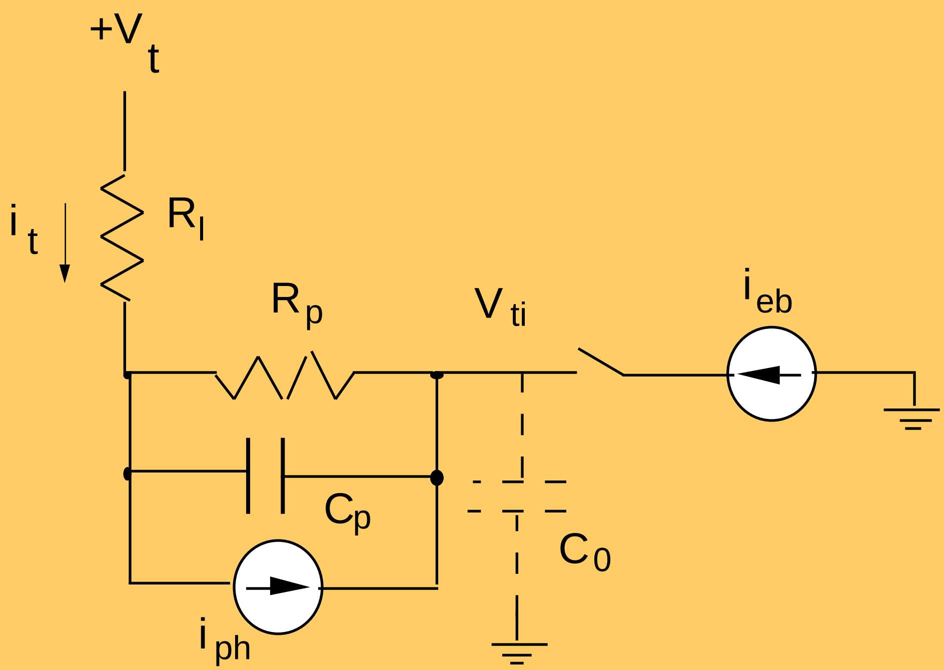

from:"Photodetectors", by S.Donati, Prentice Hall 2000

# Target storage




$$V_{ti} = Q/C_t = \sigma p\, T_f /C_t$$

# Target readout




$$i_t = Q/t_p = \sigma p T_f / t_p$$

$$f_2 = 1/2\pi(R_l // R_p)(C_p + C_0)$$

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

## Internal gain and beam effects

• Actually, the target is a PC and yields a photoconductive *gain* M. Thus, spectral sensitivity is $M\sigma$.

• Trapping time $\tau_n$ (determining gain $M=\tau_n/T$) is kept less than or comparable to frame period $T_f$ (16 or 20 ms), to avoid *image lag*.

• Gain is proportional to *target voltage* $V_t$ - an easy way to adjust the video current.

• Electron beam current $i_{pe}$ shall be > $i_t$ (of brightest pixel), or charge deposited by beam $Q_{pe}=i_{pe}t_p$ will not compensate $Q=\sigma pT_f$ ($=i_t t_p$), leaving a residual $Q-Q_p$ after a frame. Next frame residual charge doubles, and so on until charge spreads transversally on adjacent pixels, the *blooming* effect.

• Best with $i_{pe}$ as small as possible, to: (i) make crossover small; (ii) keep the beam-readout noise low.

## Signal and noise

The average level of the video current $i_t$ is calculated as:

$$i_t = \sigma P_q = \sigma A E_t = \sigma A \delta E_{sc} /4(F/)^2$$

where $E_t$ is the target illuminance, given by $\delta E_{sc} /4(F/)^2$ using scene illumination, $\delta$=scene diffusivity and F/= objective lens F-number.

Noise current variance as:

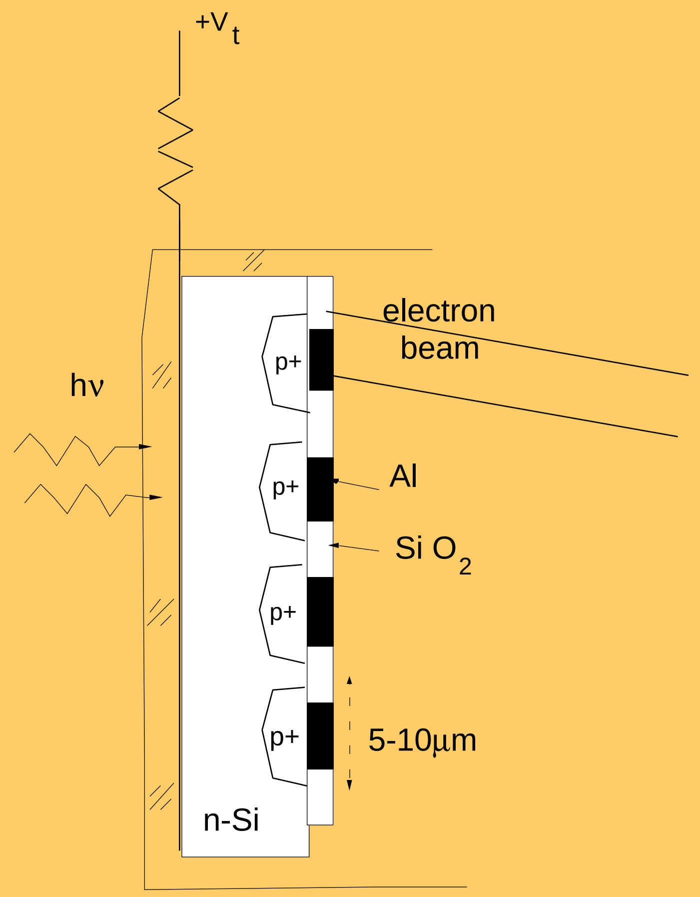
$$\sigma^2_{it} = 2e [1+2(M-1)^2](i_t+I_0)B + 2e\kappa i_{pe}B+4kTB/R_l$$

where $i_t$ and $I_0$ are the signal and target dark-current, second term is the electron beam readout noise (with $\kappa$ a factor about unity), and the last term is the load Johnson noise.

# A sample of vidicons

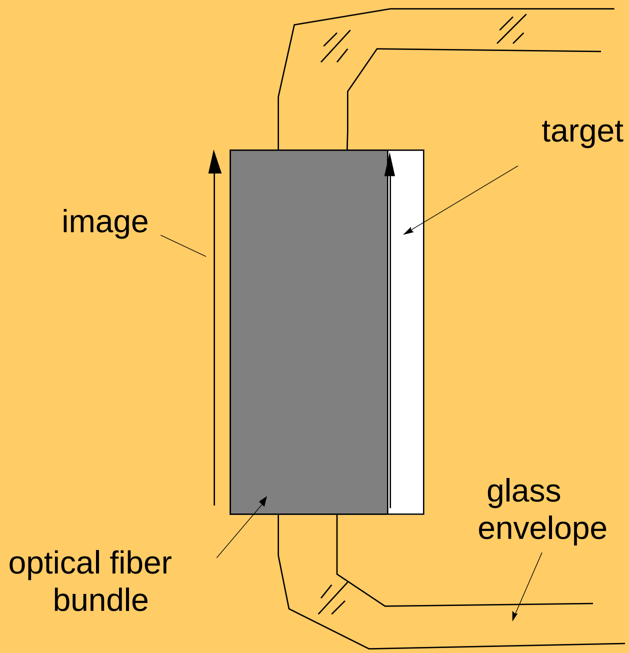
from:"Photodetectors", by S.Donati, Prentice Hall 2000

# Si-target vidicon




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

# Fiberoptics faceplate vidicon




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

# Fiberoptics and Intensified Vidicon

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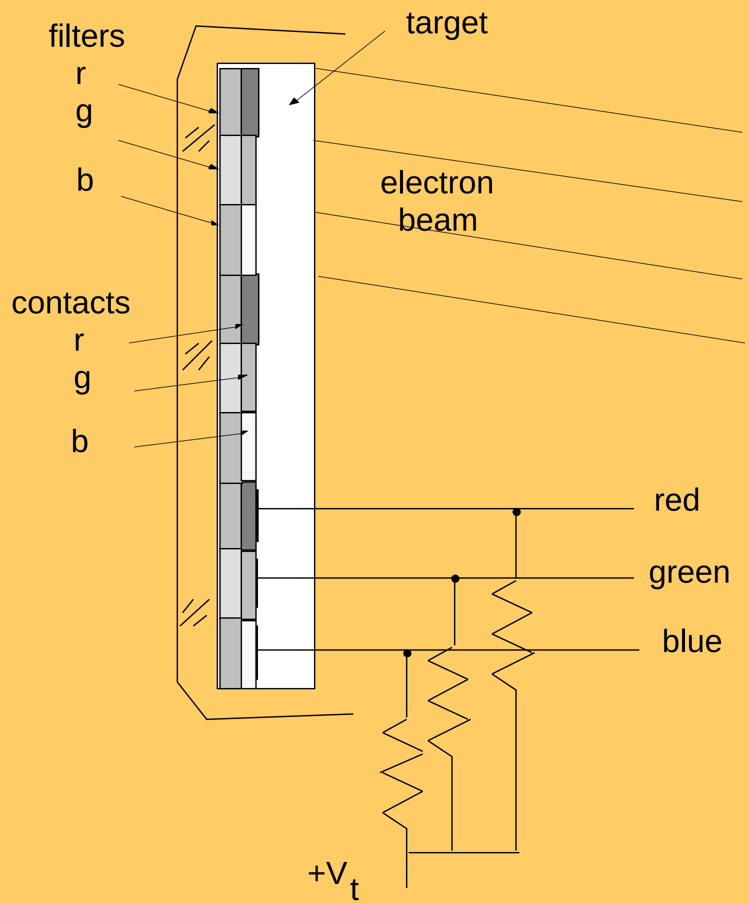
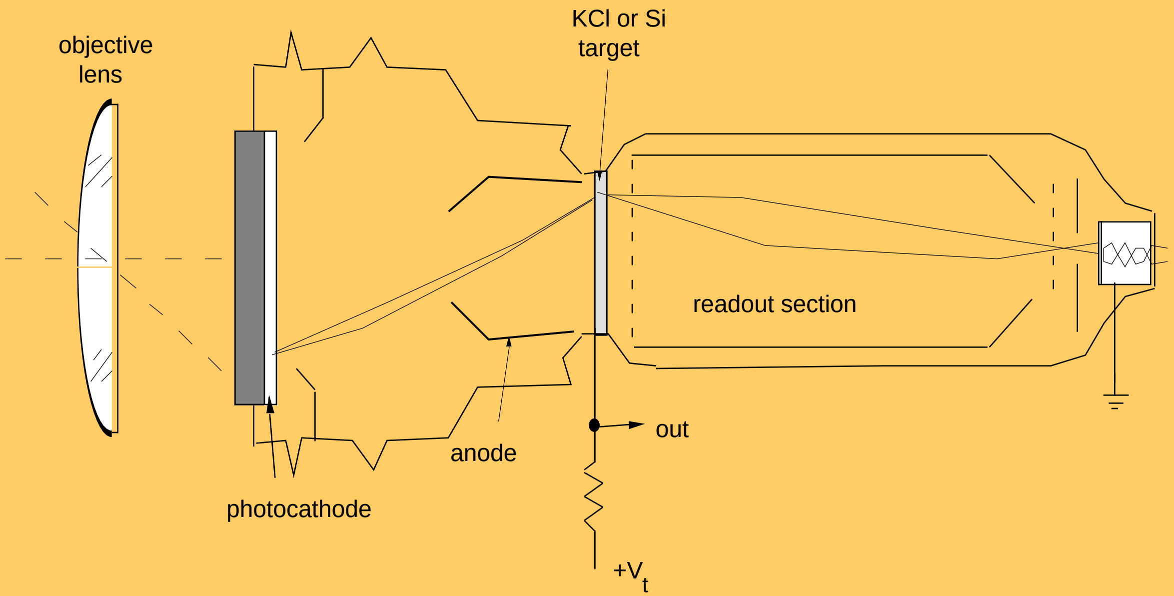
from:"Photodetectors", by S.Donati, Prentice Hall 2000

# Color vidicon




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

# Intensified vidicon



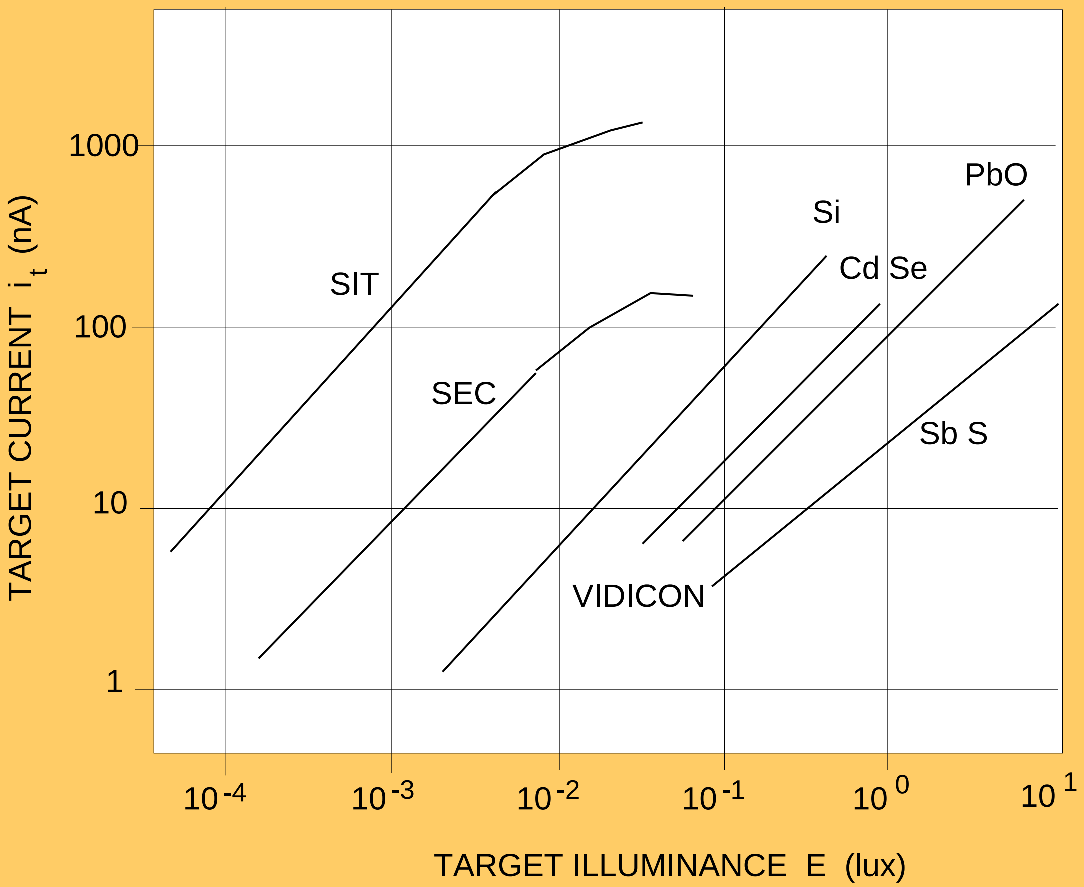

from:"Photodetectors", by S.Donati, Prentice Hall 2000

# Vidicon parameters

- *luminous* or *spectral sensitivity*, given μA/lm or μA/W
- *dark current* $I_0$, in the range 1-10 nA typ. for a vidicon;
- video *dynamic range*, ratio of the max. to min. useful signal, limited by saturation and noise, usually 2-3 decades;
- *linearity* of response, or γ (gamma) of the log $i_t$ vs log$E_t$ curve, given by the slope of the curves;
- *image format*, or the *diagonal* (expressed in inches) of the image scan area, which influences the total number of pixels;
- *spatial resolution*, expressed in lp/mm or lp/fr (line-pairs per mm or per frame) that can be resolved;
- residue or *lag*, usually specified as the percentage of signal persisting after three frames;
- *uniformity* υ of the target response from point to point.
- image *defectiveness*, in the form of white/black fixed points appearing on the image, called *blemishes*.

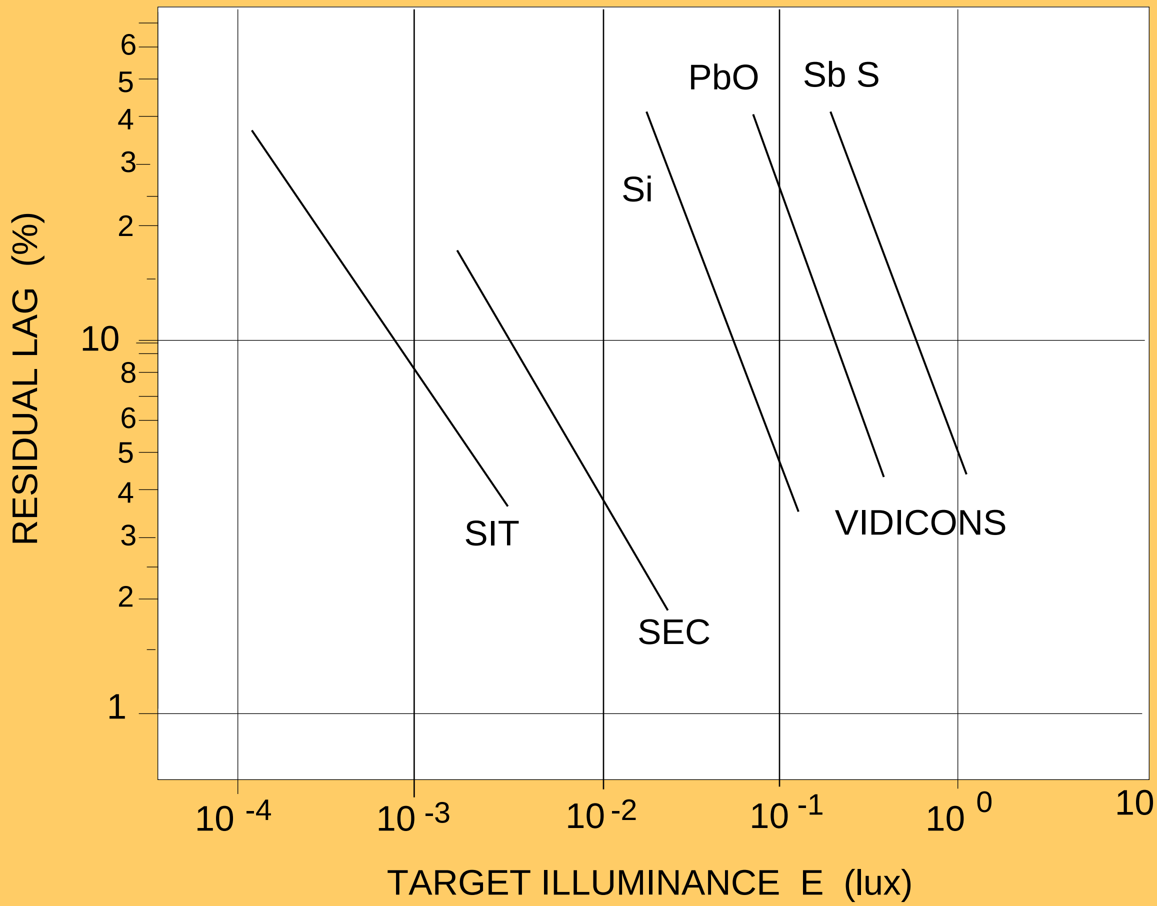
from:"Photodetectors", by S.Donati, Prentice Hall 2000

# ‘Gamma’ curve of image pickup tubes




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

# Lag in image pickup tubes

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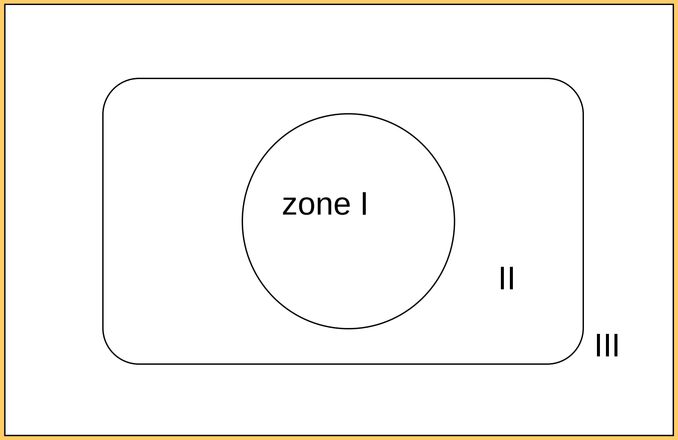
# Blemish classification

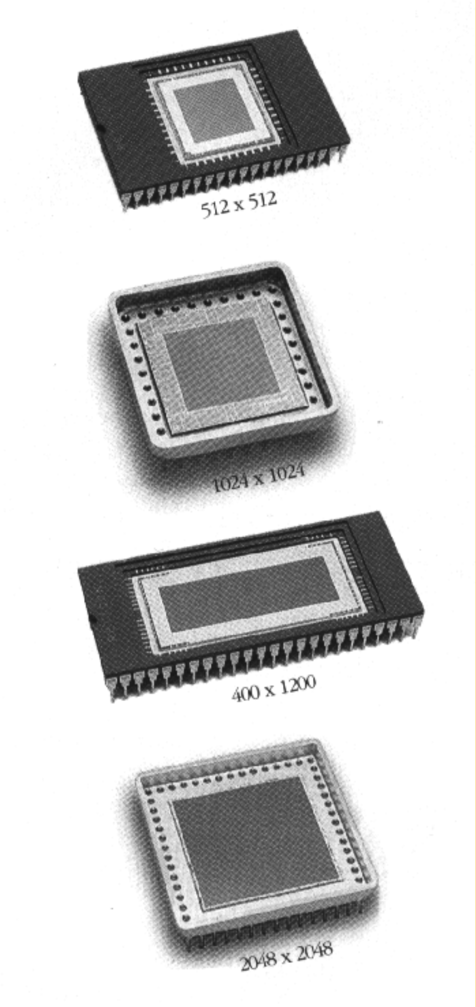



In zones I, II, II, a top quality (A-class) tube may have 0, 1, 3 defects not larger than 1 pixel, a class B 1, 3, 10 and a industrial-class (X-class) 5, 20, >20.

Tube price is dependent on this specification, with a typical ratio 10: 5 :1 (at equal size).

# CCDs

Popular silicon CCDs in several formats




512x512 pixels

1024x1024

400x1200

2048x2048

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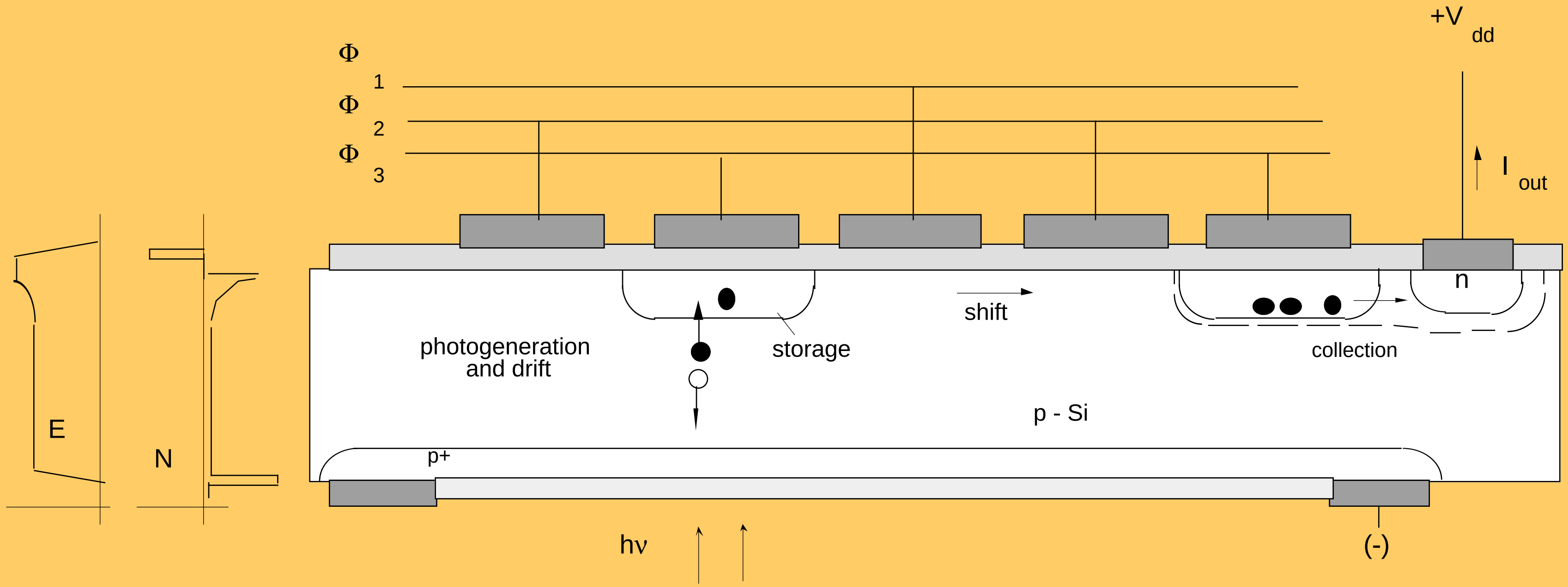
# CCD basic structure

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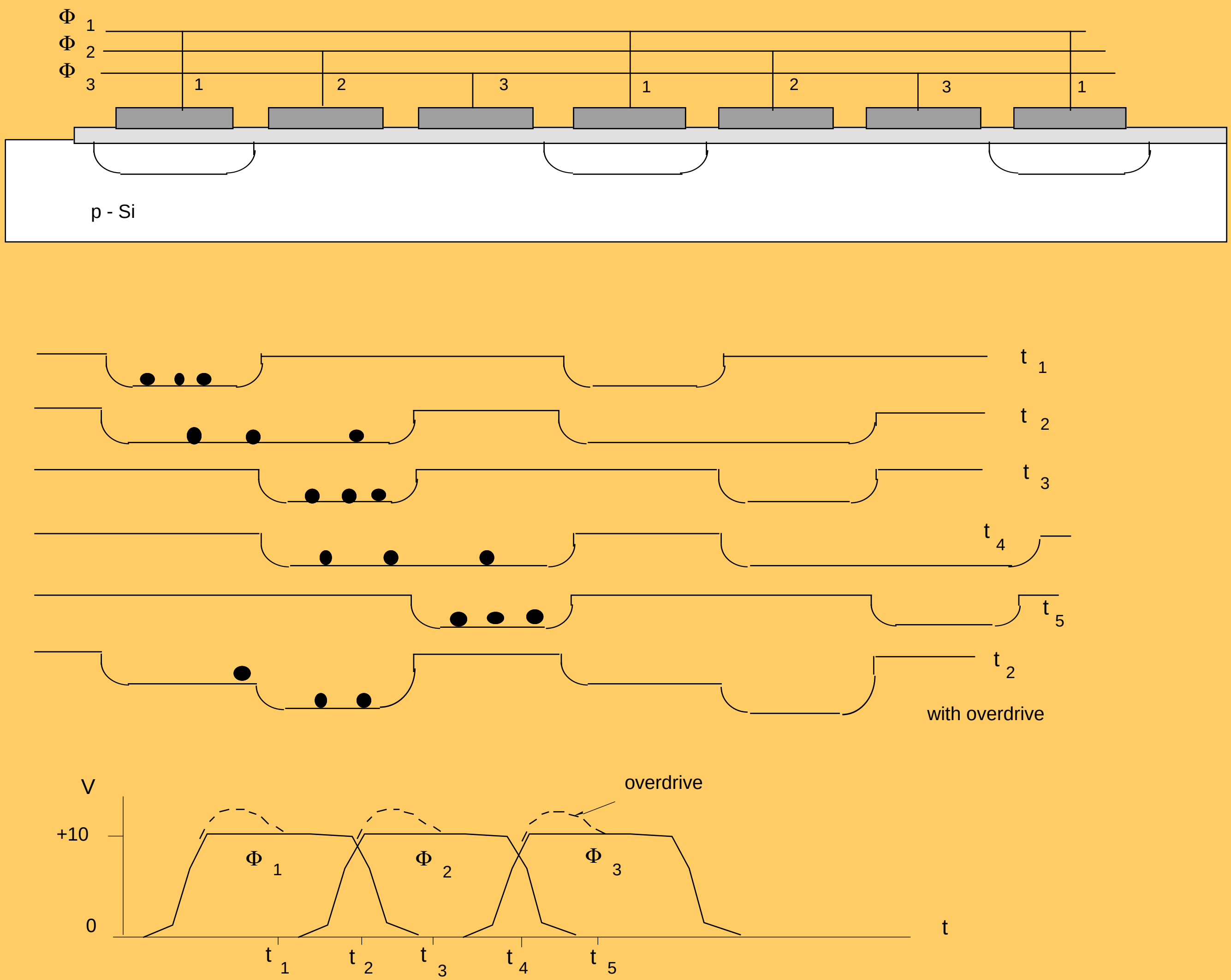
# Charge transfer mechanism

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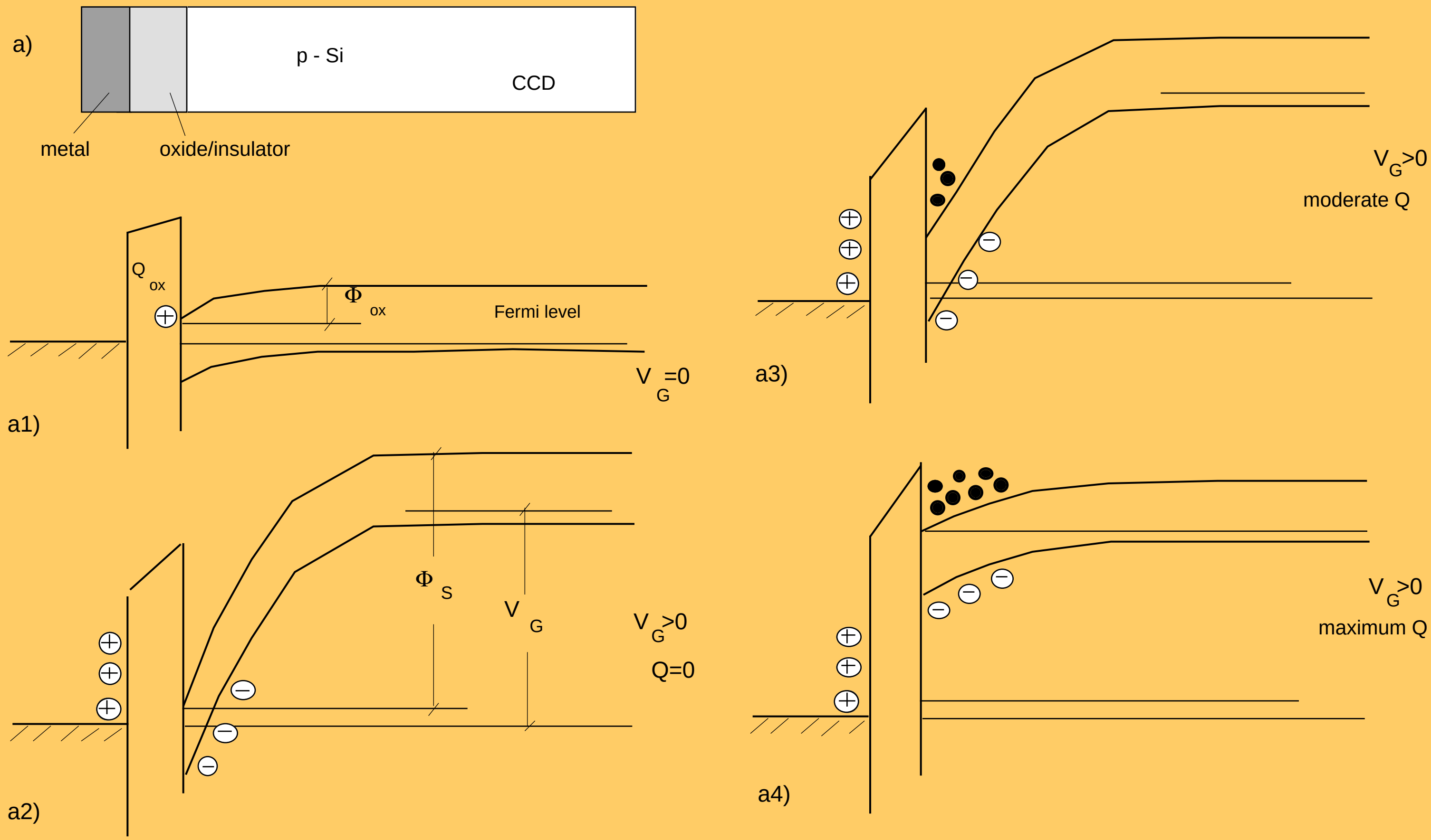
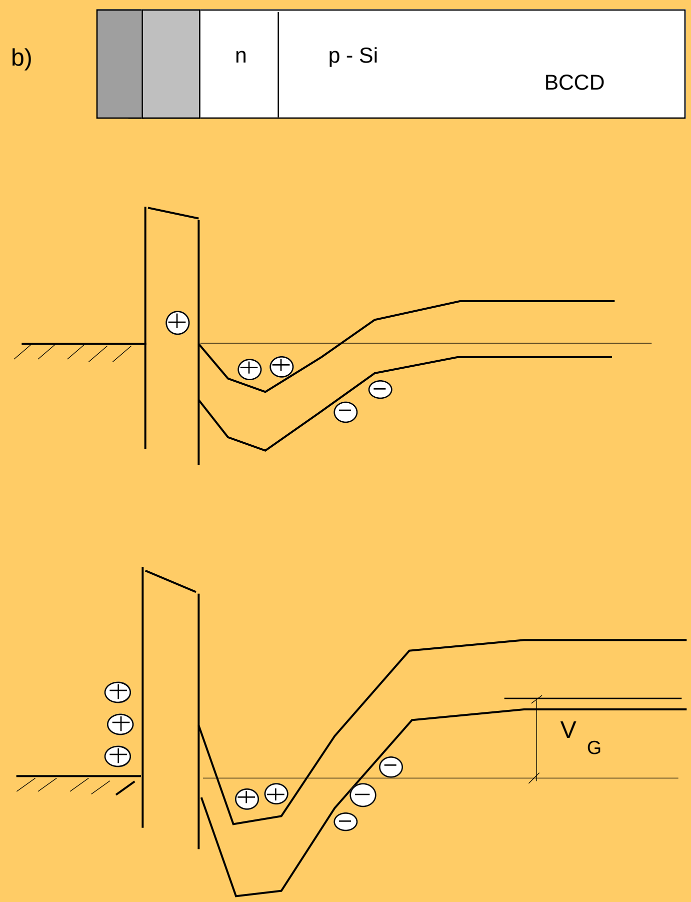
# Potential well



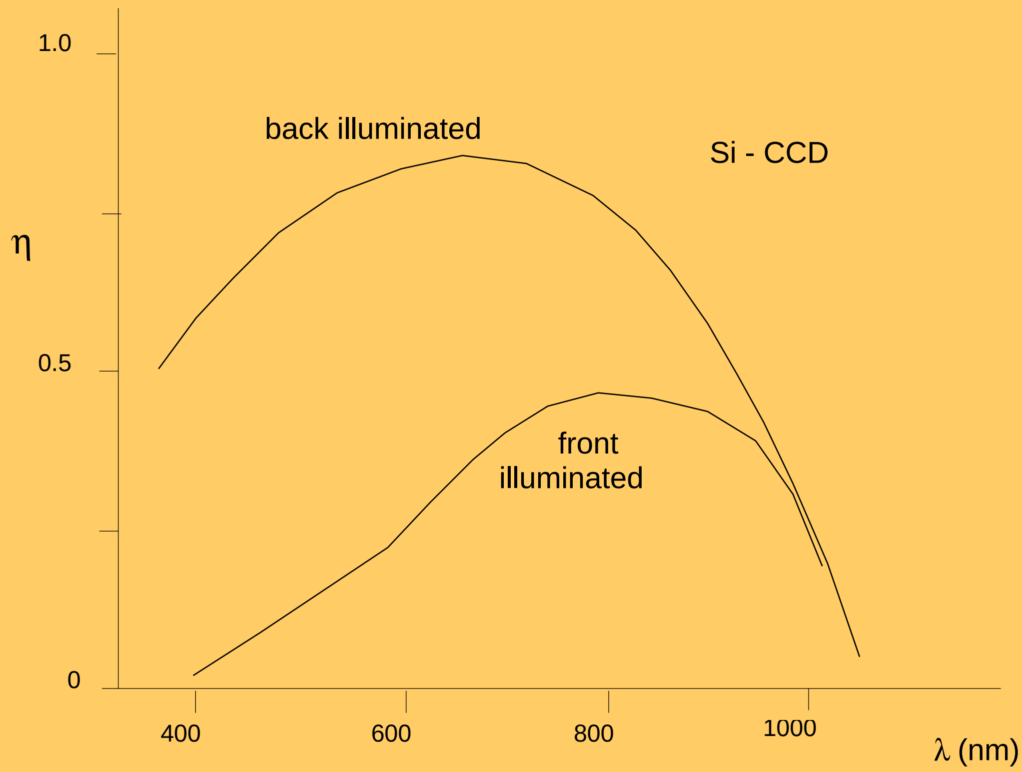

from:"Photodetectors", by S.Donati, Prentice Hall 2000

# Buried channel




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

# Optical entrance

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# A few results about electrical parameters

- Potential well: $\Phi_s = V_G - (\Phi_{ms} - \Phi_{ox}) - e(WN_A + N)/C_{ox}$

  well depth: $W = [2\varepsilon_s \Phi_s / eN_A]^{1/2}$

  depletion capacitance: $C_s = \varepsilon_s / W = [e\varepsilon_s N_A / 2\Phi_s]^{1/2}$ $(\ll C_{ox})$

- Saturation charge:

  strong inversion condition: $\Phi_s = 2\Phi_F = (2kT/e)\ln(N_A/n_i)$

  saturation charge density: $Q_{max} = C_{ox} V_G = \varepsilon_{ox} V_G / w_{ox}$

- Dark current:

$$I_d = I_{g\text{-}r} + I_d + I_{ss} = Ae\, n_i W/2\tau + Ae\, n_i^2 D_n / L_n N_A + Ae\, n_{ss}/2\tau$$

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# CCD frequency response

sources of *intrinsic* response frequency-cutoff:

- photodetection (drift/diffusion time),
- image sampling in pixels (i,ntegration and dump),
- scanning and readout of the charge packets (transfer).

sources of *extrinsic* response frequency-cutoff:

- preamplifier or output front-end (readout section).

For each of the above, a transfer function F(ω) will be computed, and the product of cascaded F(ω) will give the overall cutoff - to be not smaller than the video signal frequency $f_v$.

Important to note, F(ω) is connected to the spatial resolution function F(k) of the device: scanning in time $t_p$ pixels spaced by W, the scanning speed is $v=W/t_p$ and angular (time) frequency ω (rad/s) is related to angular (spatial) frequency k (rad/mm) of the image: $v=\omega/k$.

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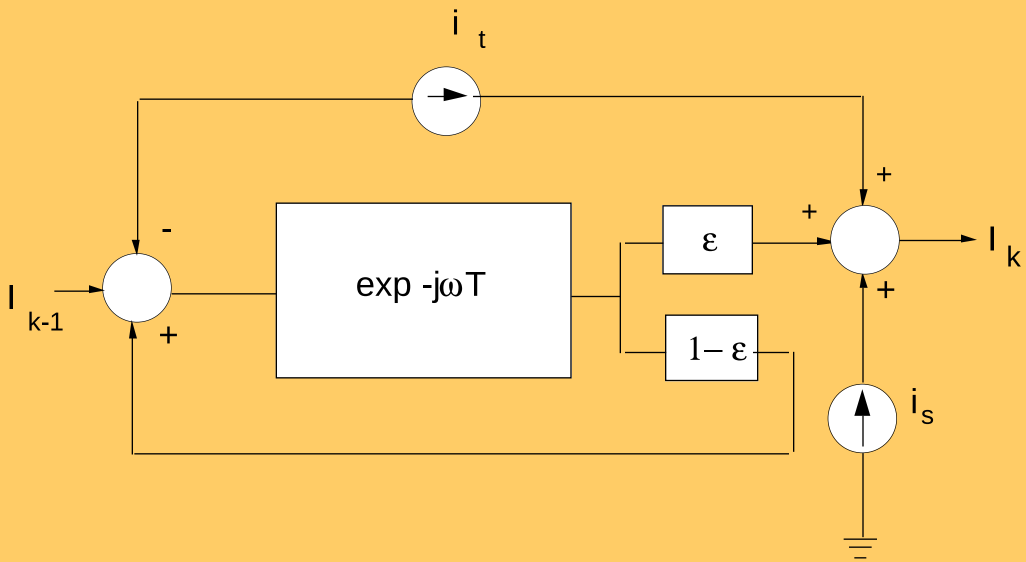
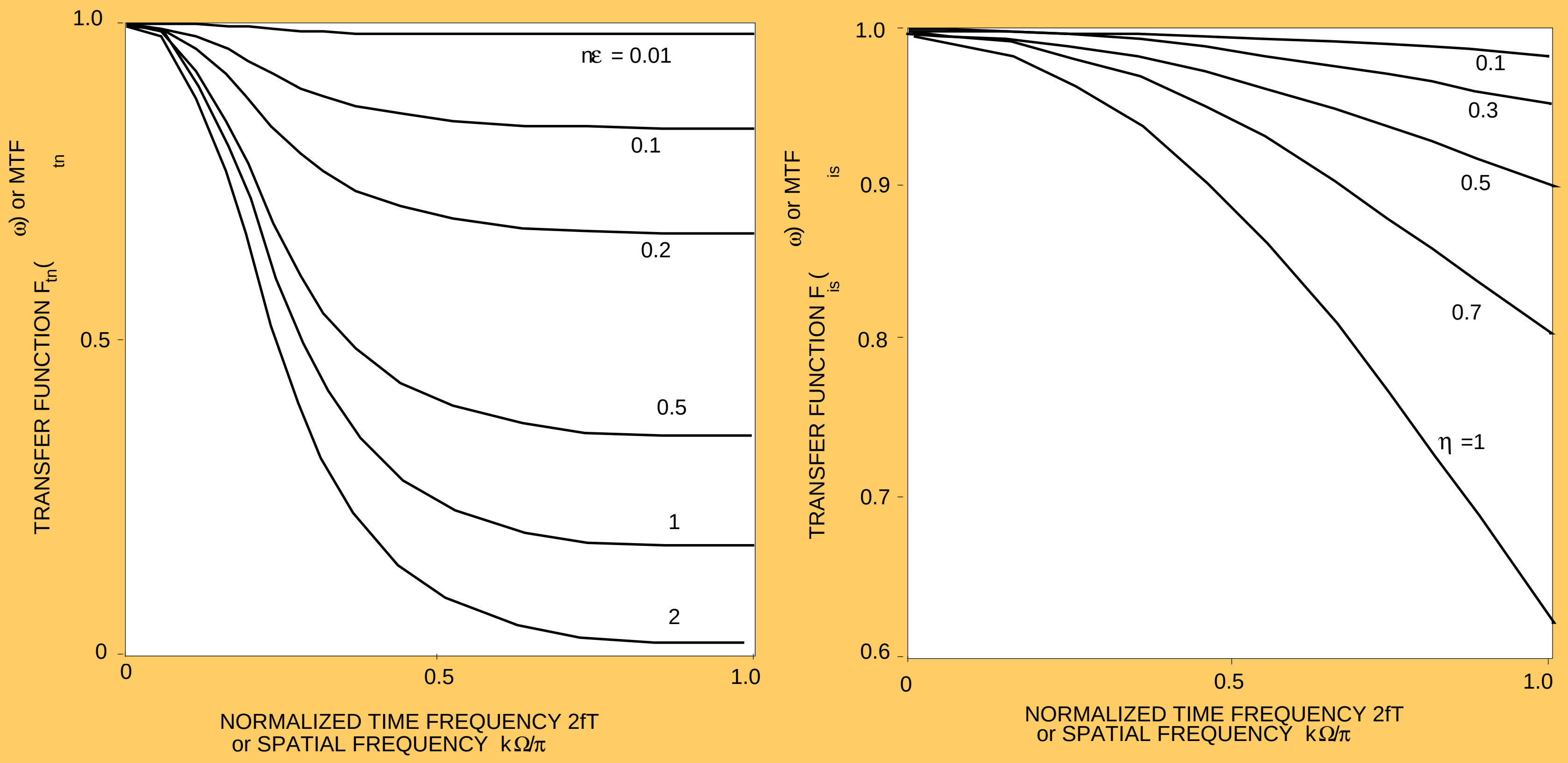
# Cell equivalent circuit




k-th cell is schematized by a delay T (clock phase) , a transfer inefficiency ε and shot-noise generators $i_t$ (transfer) and $i_s$ (storage)

# CCD transfer frequency-response

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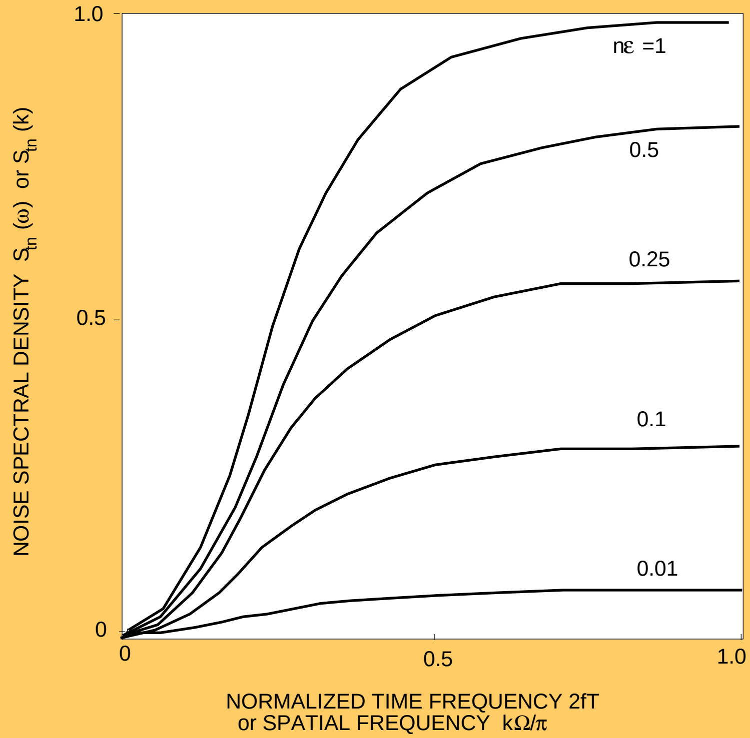
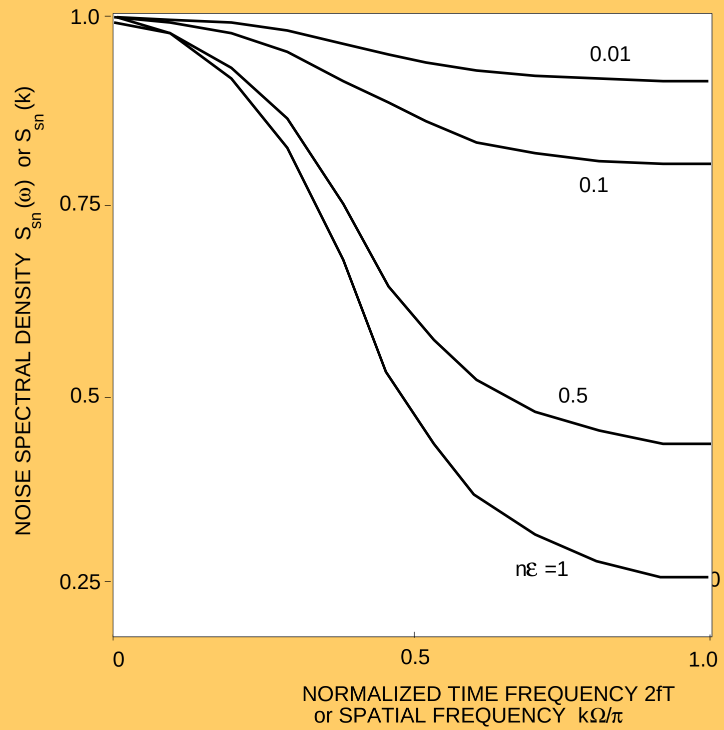
# Spectral density of transfer and storage noise

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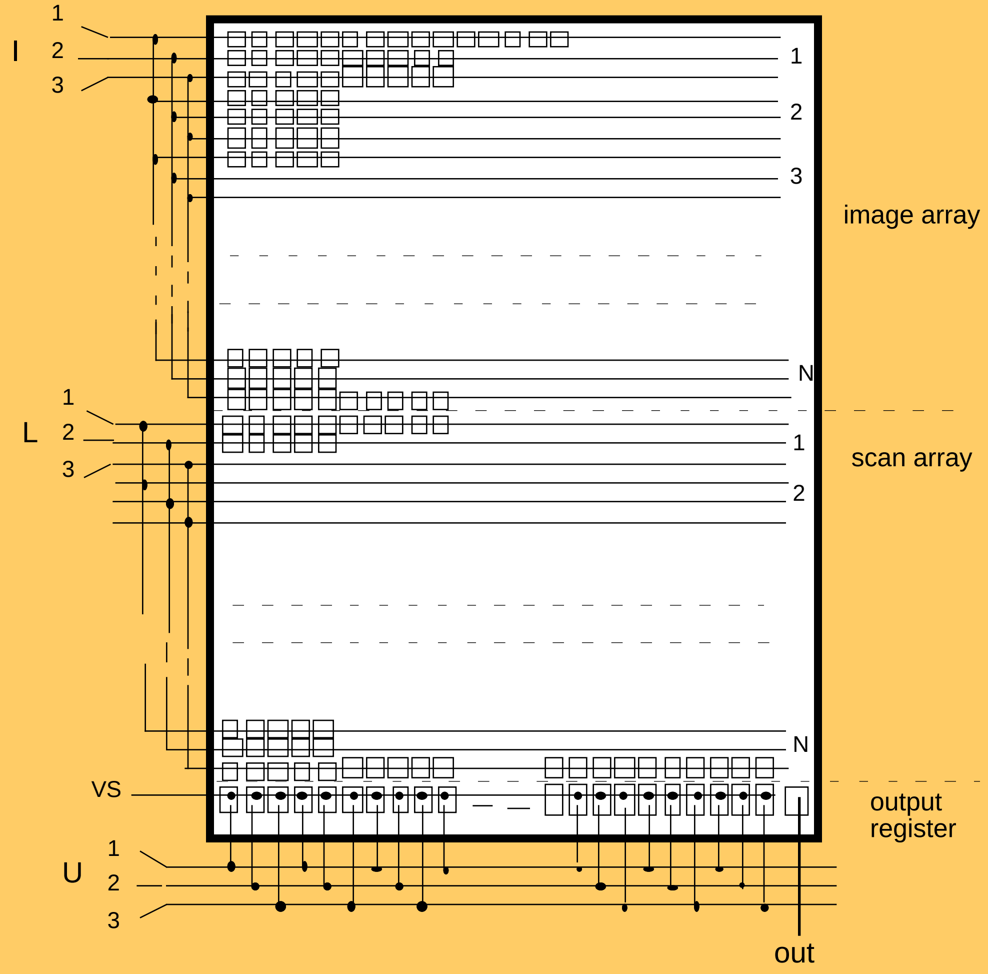
# Resumé on intrinsic cutoff and noise

Summarizing the above rusult:

- frequency cutoff: *transfer* has a severe effect, requiring $n\varepsilon < 0.2$ to avoid loss respect to Nyquist frequency 1/2T
  *sampling* gives a minor loss near 1/2T even with complete cell filling ($\eta$=1)
- noise: *transfer* has a minor effect (zero in dc), about $2nq_{ph}/T$ at $n\varepsilon=0.2$
  *storage* is max in dc, then damps off; at $n\varepsilon=0.2$ gives (0.7-1) $2nq_s/T$

In practice, storage noise dominates in surface-channel CCDs, while in buried-channel CCDs it is strongly reduced and one can achieve a performance limited by the dark current noise.

# Image organization: frame-transfer CCD

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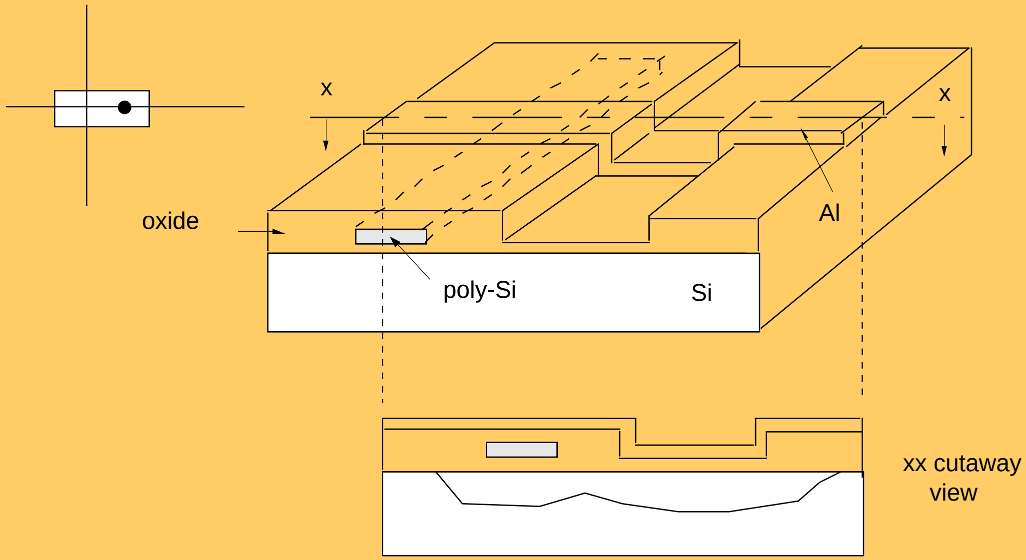
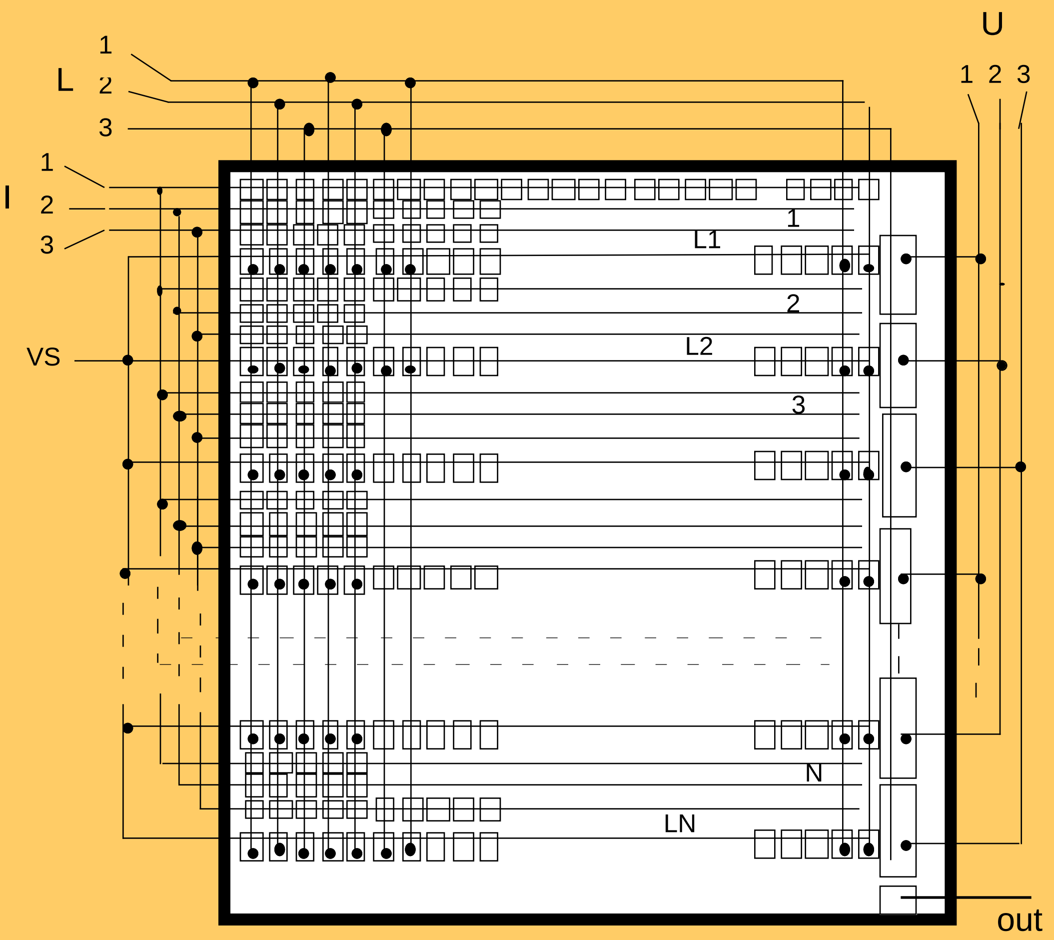
# Detail of double-level contacts



# Image organization: interline-transfer CCD

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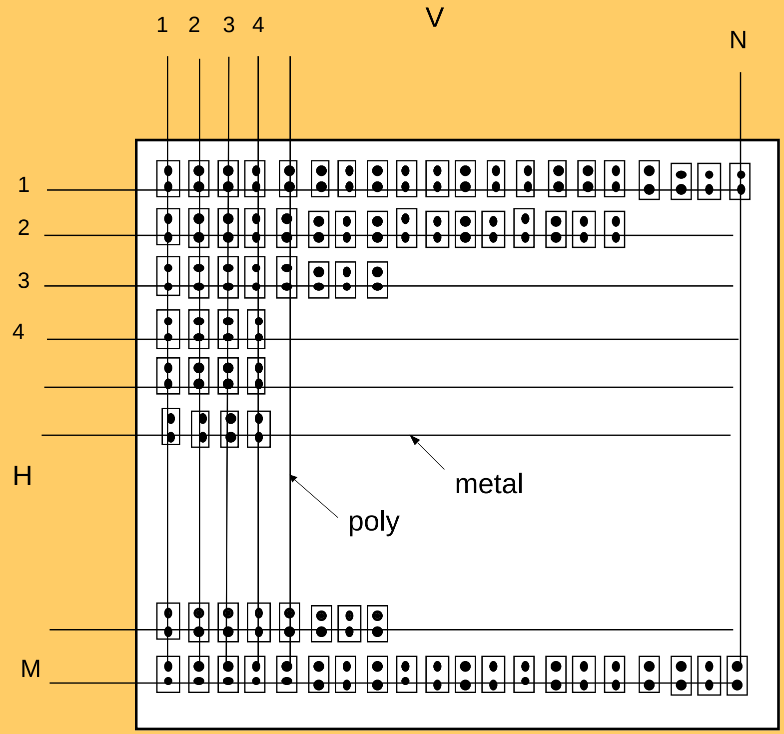
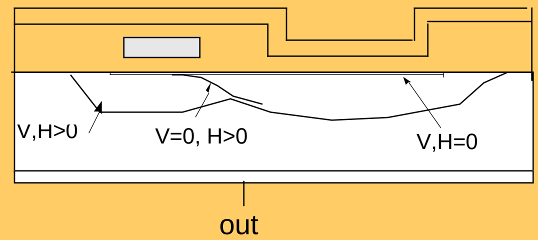
# Image organization: CID (charge-injection CCD)

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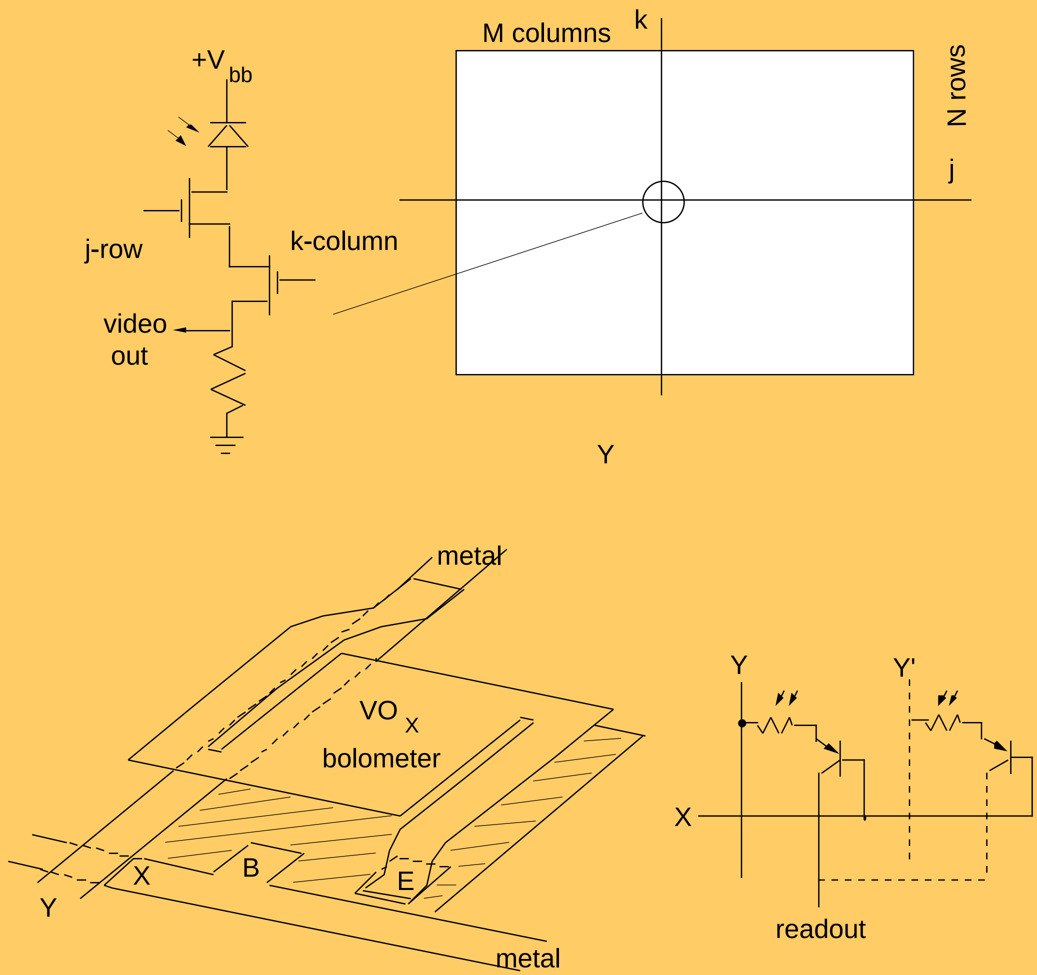
# Infrared MSA

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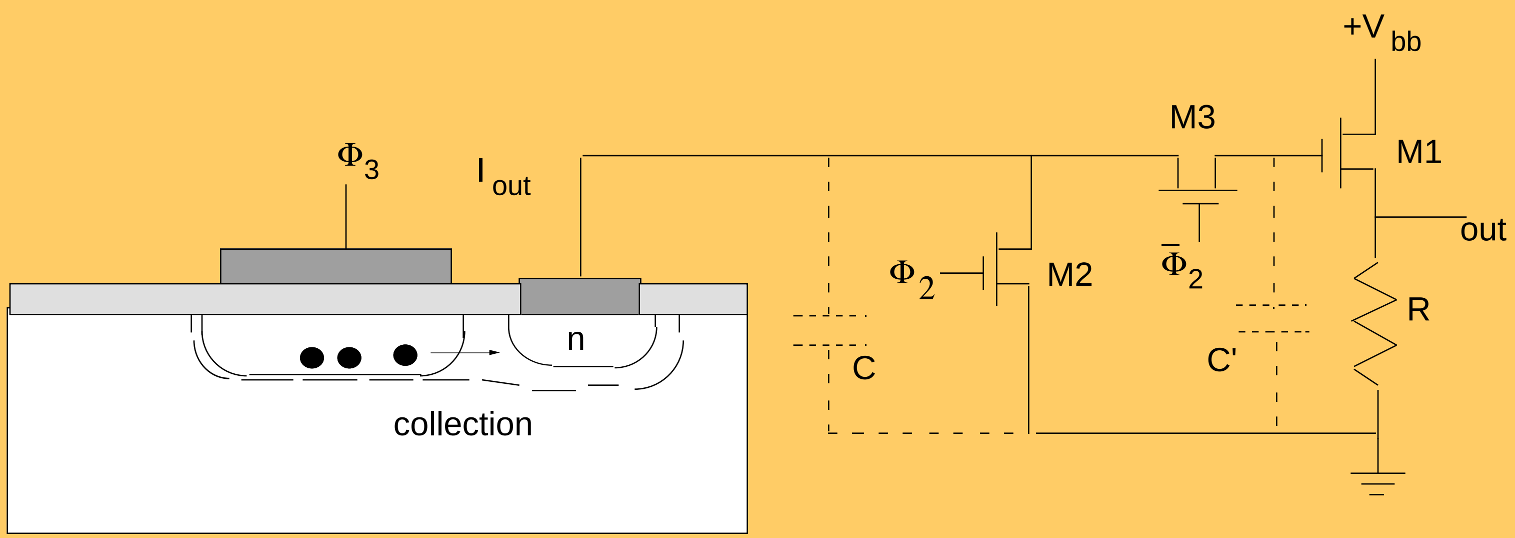
# Output stage




noise: $v^2_n = 2e[FI_{ph}+2nI_d]B\,R^2 + (8/3)\,kT\,B/g_m + kT/C + 4kTBR$

$\approx 2e[FI_{ph}+2nI_d]B\,R^2 + (8/3)\,kT\,B/g_m + kT/C$ (for $g_m R >> 1$)

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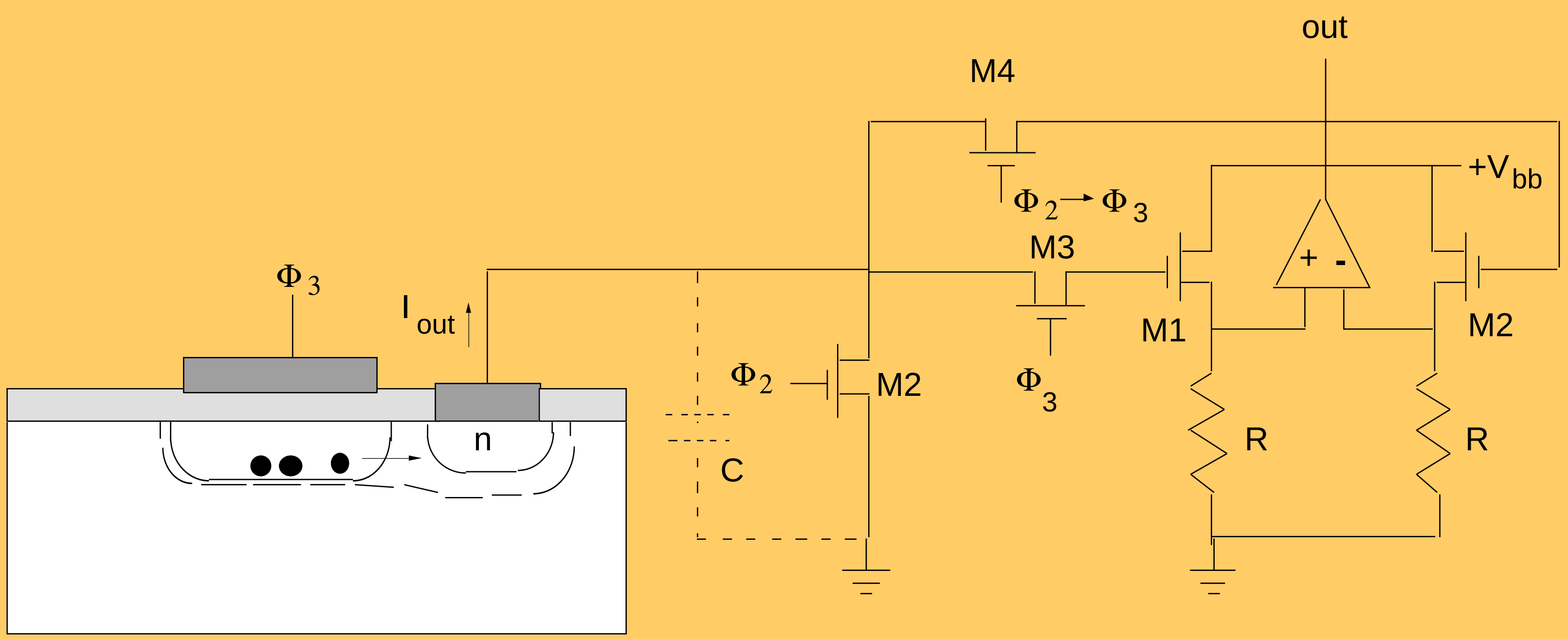
# Correlated double-sampling output stage




noise: $v^2_n = 2e[FI_{ph}+2nI_d]B\,R^2+(8/3)\,kT\,B/g_m$

$$i^2_n = 2e[FI_{ph}+2nI_d]B+(8/3)\,kT\,B/g_m\,R^2$$

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