Detection of Light

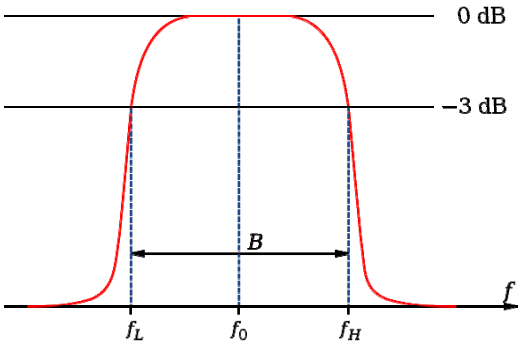
See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Sidenote: Bandwidth

The bandwidth is the range of frequencies [Hz] that can be processed or detected by a given system.

$\Delta f = f_{upper} - f_{lower}$

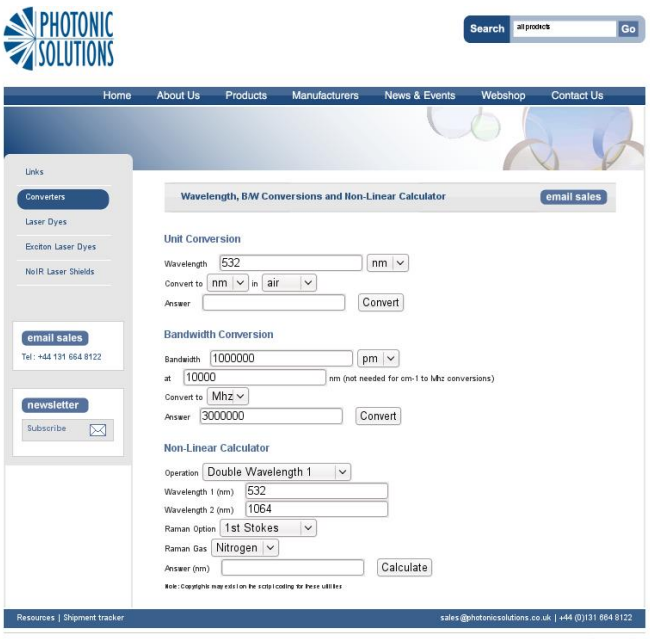
$f_{u/l}$ refers to the -3dB point ($1/\sqrt{2}$)



Note that: $\nu = \frac{c}{\lambda} \rightarrow df = \frac{c}{\lambda^2} d\lambda$

Or check out, e.g.:

http://www.photonicsolutions.co.uk/wavelengths.asp



Noise

Goal: Estimate the total noise in the system

The G-R Noise

Photoconductor absorbs N photons: $N = \eta\varphi\Delta t$

→ create N conduction electrons and N holes (but consider only e^- since $\mu_{e-} \gg \mu_p$)

Randomly **g**enerated e- *and* randomly **r**ecombined e- → two random processes

Assumption: noise sources are Poisson distributed

Hence: RMS noise ~ $(2N)^{1/2}$.

Now calculate the associated noise current: $\left\langle I_{G-R}^2 \right\rangle^{1/2} = \dfrac{q\sqrt{2N}G}{\Delta t}$

With the mean detector current $I_{ph} = \eta q \varphi G$

one gets:

$$\left\langle I_{G-R}^2 \right\rangle = \frac{q^2(2N)G^2}{(\Delta t)^2} = \left(\frac{2q}{\Delta t}\right)\left(\frac{qNG}{\Delta t}\right)G = \left(\frac{2q}{\Delta t}\right)\left\langle I_{ph}\right\rangle G$$

G-R Noise Bandwidth

The G-R noise has a wide frequency range, which we associate with an equivalent noise bandwidth $\Delta f = f_2 - f_1$.

electrical system: power ~ (amplitude)^2

similarly: bandwidth ~ (response function)^2

or: $$\Delta f = \int_0^\infty |U(\xi)|^2 d\xi$$

where U(ξ) is the normalized electrical response (current or voltage)

For a system with exponential response $U \sim e^{-t/\tau}$: $$\Delta f = df = \frac{1}{4\tau}$$

Or if the signal is integrated over time Δt_{int}: $$\Delta f = \frac{1}{2\Delta t_{int}}$$

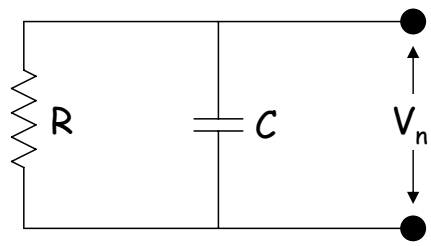
The noise current $\langle I^2_{G\text{-}R} \rangle$ can now be rewritten as:

$$\langle I^2_{G-R} \rangle = \left(\frac{2q}{\Delta t}\right)\langle I_{ph} \rangle G = (2q2\Delta f)\langle \varphi q \eta G \rangle G = 4q^2 \varphi \eta G^2 \Delta f$$

Johnson noise

The Johnson or Nyquist noise is a fundamental thermodynamic noise due to the thermal motion of the charge carriers.

Consider a photoconductor as a RC circuit:



This system has *one* degree of freedom: V_n

which is associated with an average energy of $\frac{1}{2}$ kT

The energy E_{st} stored in a capacitor is $E_{st} = \frac{1}{2}CV^2$, hence: $$\frac{1}{2}C\langle V_n^2 \rangle = \frac{1}{2}kT$$

The fluctuations in E_{st} are associated with the Johnson noise current I_J.

kTC Noise (another way to look at it)

Of course, the power in I_J can also be expressed thermodynamically:

$$\langle P \rangle t = \frac{1}{2} kT \quad \text{where} \quad t = RC \quad \text{and} \quad \langle P \rangle = \frac{1}{2} \langle I^2 \rangle R$$

Hence, $\langle I_J^2 \rangle = \frac{2\langle P \rangle}{R} = \frac{2\frac{1}{2}kT}{Rt} \overset{\Delta f = 1/4\tau}{=} \frac{4kT}{R} \Delta f$

The charge on the capacitor is $Q = CV$. Above we derived $C\langle V^2 \rangle = kT$.

Hence: $\langle Q^2 \rangle = C^2 V^2 = kTC$

This charge noise is also called kTC noise or reset noise.

Johnson noise and kTC noise are equivalent, and due to the Brownian motion of the charge carriers.

Other Noise Sources: 1/*f* noise

Most electronic devices have increased noise at low frequencies, often dominating the system performance.

However, there is no general understanding of it.

Empirically, $\langle I_{1/f}^2 \rangle \propto \frac{I^a}{f^b} \Delta f \quad \text{where} \quad a \approx 2, b \approx 1.$

Bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, and junction field effect transistors (JFETs) may contribute to this noise.

Due to the lack of solid physical understanding of this type of noise it is simply termed 1/f noise.

Combining Noise Sources

So far we discussed:

the G-R noise $\left\langle I_{G-R}^2 \right\rangle = 4q^2 \varphi \eta G^2 \Delta f$

the Johnson noise $\left\langle I_J^2 \right\rangle = \frac{4kT}{R} \Delta f$

the 1/f noise $\left\langle I_{1/f}^2 \right\rangle \propto \frac{I^a}{f^b} \Delta f$

Note that all processes depend on the bandwidth $\Delta f = 1/(2\Delta t_{int})$

If the signal is Poisson distributed in time the relative error of the measurement is proportional to $1/\sqrt{t}$ or $(\Delta f)^{\frac{1}{2}}$.

(longer t_{int} means smaller bandwidth means smaller relative errors)

The total noise in the system is $\left\langle I_N^2 \right\rangle = \left\langle I_{G-R}^2 \right\rangle + \left\langle I_J^2 \right\rangle + \left\langle I_{1/f}^2 \right\rangle$

Noise currents vary randomly in phase → noises are added quadratically

Signal currents are correlated in phase → signals are added linearly

Performance Specifications

The Noise Equivalent Power (NEP)

Important parameters:

- signal power on the detector P_s
- electronic frequency at which detector is read

NEP ≡ signal power that yields an RMS signal-to-noise of unity in a system that has an electronic bandpass of 1 Hz.

Units are [W/√Hz]

Better detectors have smaller NEP!

$$\frac{S}{N} = \frac{P_S}{NEP(df)^{1/2}} \overset{df=\frac{1}{2\Delta t_{\text{int}}}}{=} \frac{P_S(2\Delta t_{\text{int}})^{1/2}}{NEP}$$

or:

$$NEP = \frac{P_S\sqrt{2\Delta t_{\text{int}}}}{S/N}$$

An equivalent, more practical definition is:

$$NEP = \frac{I_N}{S}$$

where I_N [A Hz$^{-1/2}$] is the total noise current in the system, and S [A W^{-1}] is the responsivity.

Case 1: Background Limited Performance (BLIP)

Detector performance is limited by the statistics of the incoming photon stream: $\langle I_{G-R}^2 \rangle >> \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle$

With $S = G\frac{q\eta\lambda}{hc}$ and $\langle I_{G-R}^2 \rangle = 4q^2\varphi\eta G^2\Delta f$ one gets:

$$NEP_{G-R} = \frac{I_{G-R}}{S} = \frac{(4q^2\varphi\eta G^2)^{1/2}hc}{Gq\eta\lambda} = \frac{2hc}{\lambda}\left(\frac{\varphi}{\eta}\right)^{1/2}$$

(the factor Δf disappears from $\langle I^2_{g-r}\rangle$ as we use the "normalized" noise current in units of [A/√Hz]).

- Here, the NEP can only be improved by increasing the quantum efficiency η.
- In the infrared the photon noise is often dominated by the "sky" background, not by the signal.
- Reaching BLIP is the best observing case (the limit given by nature).

Case 2: Johnson Noise Limited Performance

Detector performance is limited by its internal thermodynamic noise: $\left\langle I_J^2 \right\rangle >> \left\langle I_{G-R}^2 \right\rangle + \left\langle I_{1/f}^2 \right\rangle$

With $S = G\dfrac{q\eta\lambda}{hc}$ and $\left\langle I_J^2 \right\rangle = \dfrac{4kT\Delta f}{R}$ one gets:

$$NEP_J = \frac{I_J}{S} = \frac{(4kT)^{1/2} hc}{R^{1/2} Gq\eta\lambda} = \frac{2hc}{Gq\eta\lambda}\left(\frac{kT}{R}\right)^{1/2}$$

(the factor Δf disappears from $\langle I^2_{g-r} \rangle$ as we use the "normalized" noise current in units of [A/√Hz]).

• Here, the NEP can be improved by increasing the quantum efficiency η, the photoconductive gain G, the detector resistance R or by reducing the operating temperature.

The Noise Equivalent Flux Density (NEFD)

NEFD ≡ the incident flux density that yields unity signal-to-noise in unity bandwidth.

$$NEFD = \frac{E_S \sqrt{2\Delta t_{\text{int}}}}{S/N}$$

...where E_S [W m^{-2} Hz^{-1}] is the measured flux density.

The NEFD usually includes the full system incl. the camera optics.

S/N and Observing Time

Measuring an astronomical signal is usually more complex

1. One spends half of the time observing the background flux ("sky") → $t_{int} = t/2$ → $(S/N) \sim 1/\sqrt{2}$
2. One calculates (source – sky) → noise increases by $\sqrt{2}$

Net effect: (S/N) is a factor 2 below the ideal measurement…

…unless: on-chip nodding/dithering/jittering/…

Extrinsic Photoconductors

Sensitivity to Longer Wavelengths

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24\mu m}{E_g[eV]}$$

Requires smaller E_g to get response to longer wavelengths

		Ge		Si	
Impurity	Type	Cutoff wavelength λ_c (μm)	Photoionization cross section σ_i (cm^2)	Cutoff wavelength λ_c (μm)	Photoionization cross section σ_i (cm^2)
Al	p			18.5	8×10^{-16}
B	p	119	1.0×10^{-14}	28[a]	1.4×10^{-15}
Be	p	52		8.3	5×10^{-18}
Ga	p	115	1.0×10^{-14}	17.2	5×10^{-16}
In	p	111		7.9	3.3×10^{-17}
As	n	98	1.1×10^{-14}	23[a]	2.2×10^{-15}
Cu	p	31	1.0×10^{-15}	5.2	5×10^{-18}
P	n	103	1.5×10^{-14}	27[a]	1.7×10^{-15}
Sb	n	129	1.6×10^{-14}	29[a]	6.2×10^{-15}

Operating Conditions

The lower excitation temperatures also allow for large thermally excited dark currents → operation <u>only</u> at low temperatures.

Notation

Notation: *semiconductor:dopant*

Examples: Si:As, Si:Sb, Ge:Ga, …

Thickness of the Sensitive Detector Layer

The absorption coefficient for extrinsic photoconductors is $a(\lambda) = \sigma_i(\lambda) N_I$

where σ_i is the photoionization cross section (see table above) and N_I is the impurity concentration.

With typical impurity concentrations of 10^{15} – 10^{16} cm^{-3} and typical photo-ionization cross sections of 10^{-15} – 10^{-17} cm^2 the absorption coefficients of extrinsic photoconductors are 2 – 3 orders of magnitude less than those for direct absorption in intrinsic photoconductors.

➔ Active volumes of extrinsic detectors must be larger to get good quantum efficiencies (a few millimeters → "bulk photoconductors").

Artefacs, Problems and Undesired Properties

Limitations to the Doping Process

- Unwanted conductivity modes, such as hopping: when impurity atoms are close together their wave functions overlap and conduction can occur directly without raising an electron into the conduction band.

- Solubility of the impurity atoms in the semiconductor crystal. Typical upper limits are 10^{16} – 10^{21} cm^{-3}.

➔ Typical wanted impurity concentrations are 10^{15} – 10^{16} cm^{-3} for silicon.

Unwanted Impurities

Generally, unwanted impurities (contamination) are a severe problem. Typical levels of boron in silicon are 10^{13} cm^{-3}.

Often, compensation (doping to counter-balance unwanted impurities) is necessary for low-level extrinsic photonductors.

→ Majority carrier: type created by dominant dopant (e.g., holes for p-type)

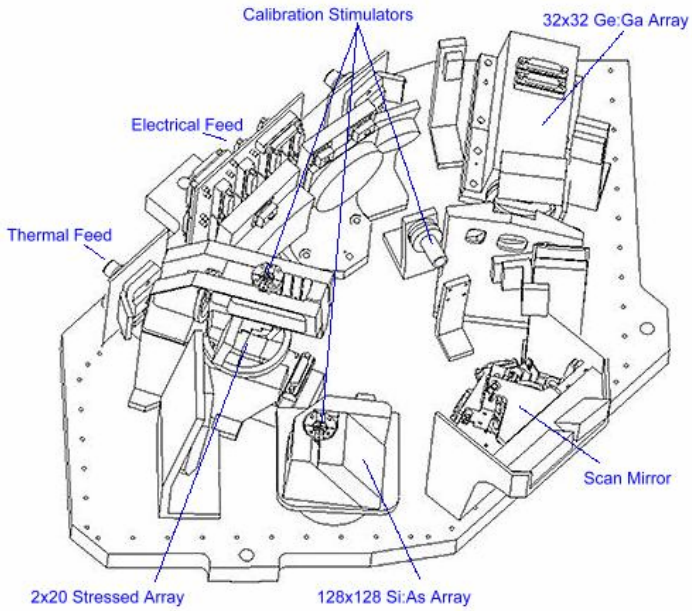
→ Minority carrier: opposite type, usually smaller concentration

Intrinsic Absorption in Extrinsic Semiconductors

The dopants do not interfere with the intrinsic absorption process ➔
Intrinsic absorption always prevails over extrinsic absorption since the number of semiconductor atoms is >> the number of impurities.

→ Use of strong optical blocking filters.

Example: "light leak" in the Spitzer-MIPS 160μm channel



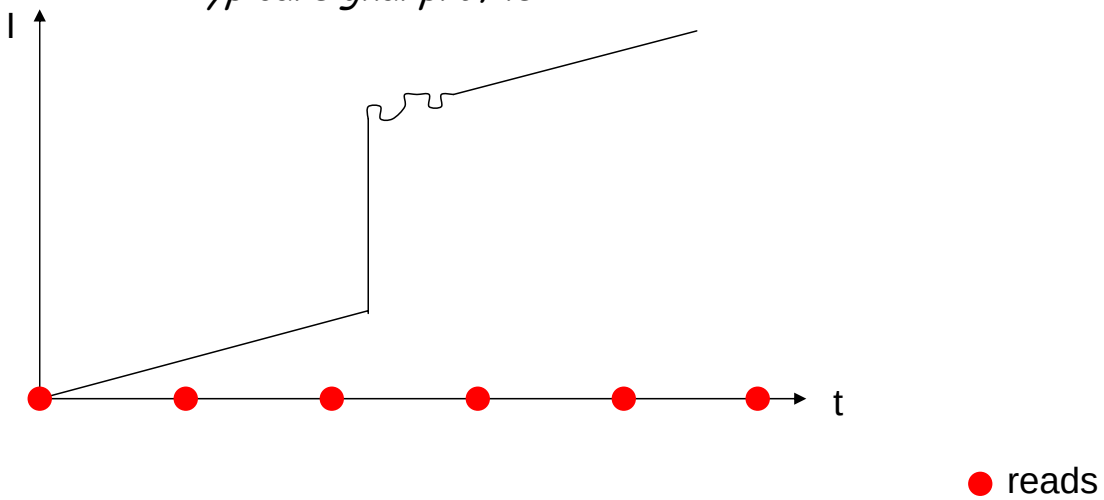
Ionizing Radiation Effects

(Mainly for detectors in space)

High energy particles create large numbers of free charge carriers (electron/hole pairs) in any solid state detector.

However, extrinsic photoconductors are larger (higher probability to get hit) are used in space for longer wavelengths, and operate at low backgrounds.

Typical signal profile:



Ionizing Radiation Effects (2)

Specific effects in extrinsic photoconductors:

- p-type impurity: free electrons are captured by the minority donors
- n-type impurity: free electrons are captured by the minority acceptors

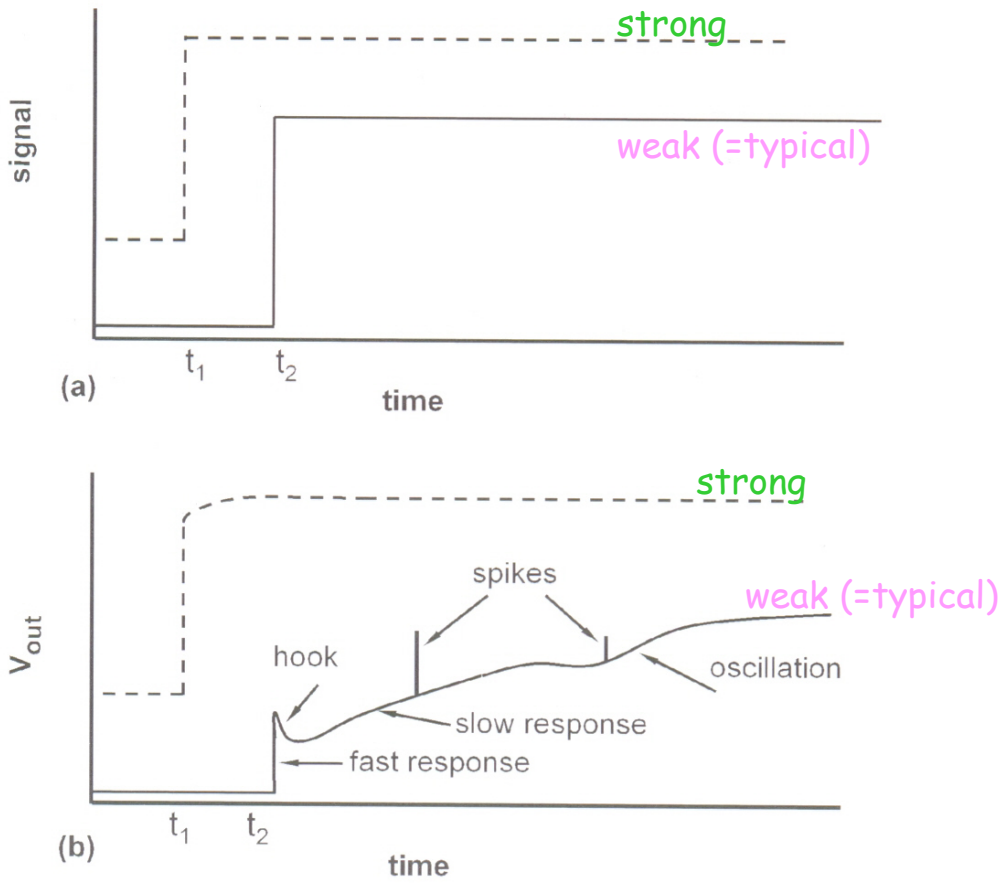
In both cases the compensation gets reduced and the responsivity and the noise are increased.

➔ Renders temporarily useless data. (Example: t_{int} of 1000s → 30% chance to get hit at L2 per small pixel).

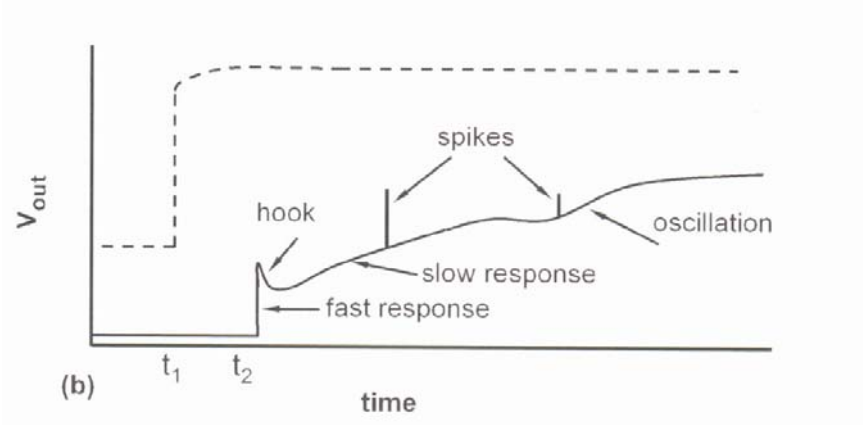
Mitigation strategies:

- "Annealing": heat up to 20K (Si) or 6K (Ge) and cool again to 6K (Si) and 2K (Ge)
- "Bias boost" – increase bias voltage to above the breakdown level
- Flooding the detector with light (→ electrons)

"Non-ideal" Behaviours



"Non-ideal" Behaviour: Background Levels



We said that the dielectric relaxation time constant is important ("faster is better").

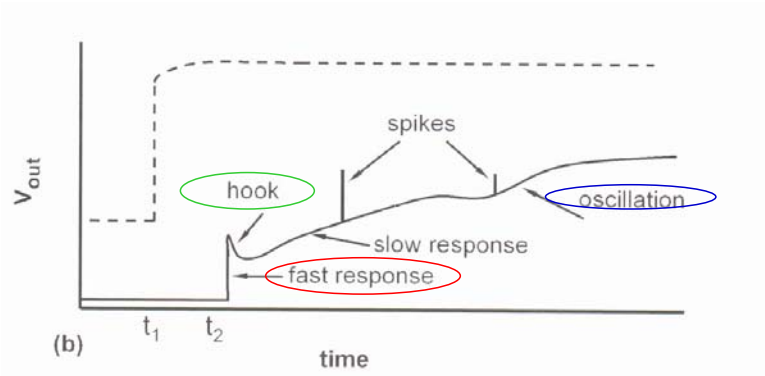
$$\tau_d = \frac{\kappa_0 \varepsilon_0}{\mu_n n_0 q} = \frac{\kappa_0 \varepsilon_0}{\sigma} \propto \frac{1}{\varphi}$$

(where κ_0 = dielectric constant and ε_0 = permittivity of free space, or electric constant)

High background fluxes produce lots of free charge carriers → smaller relaxation times → well behaved in high background conditions.

But: under low-background conditions, the signal will be extracted while the detector is still in a non-equilibrium state.

"Non-ideal" Behaviour: Transient Response

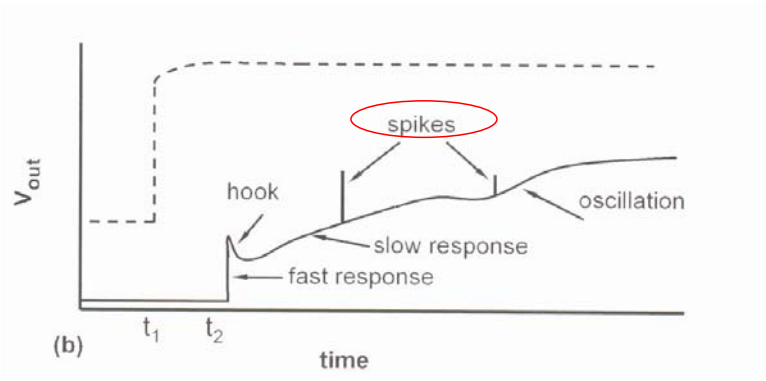


Generation and recombination of charges → fast response

Charge carrier absorption at electrical contacts ~ dielectric relaxation time constant τ_d → "slow" adjustment of $\bar{E}$-field → oscillations

Hook: non-uniform illumination due to shading by the contacts → illuminated areas have lower resistance than shaded area under the contacts → equilibrium only within dielectric relaxation time τ_d → G is reduced → overall response drops.

“Non-ideal” Behaviour: Spikes



Conduct junction (conductor ⇔ semiconductor) : charges migrate → large Ē-fields.

One uses “graded contacts” to increase conductivity by adding dopants in a thin layer just below the contact.

If φ changes → Ē-field must adjust but can also accelerate charge carriers (“mini avalanche”) → spike

Mitigation: constant bias, low gain reduces spiking

Solution

Calibration, calibration.