Detection of Light

INTRINSIC

PHOTOCONDUCTORS

AND NOISE

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

Intrinsic Photoconductors

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Most basic kind of electronic detector (CCDs, high-speed photoconductors):

Principle: $E_\gamma > E_g$

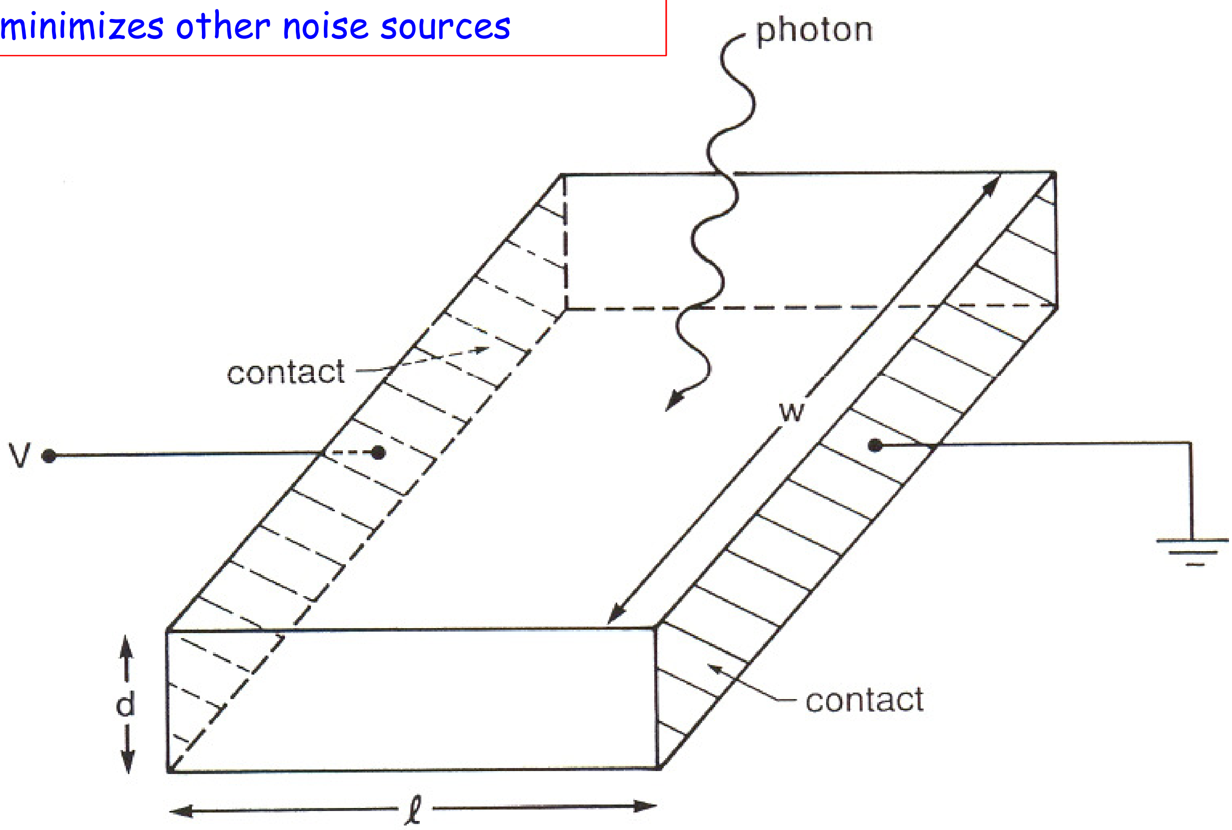
- Lifts e- into conduction band
- E- / hole pair migrate through the material

Operation:

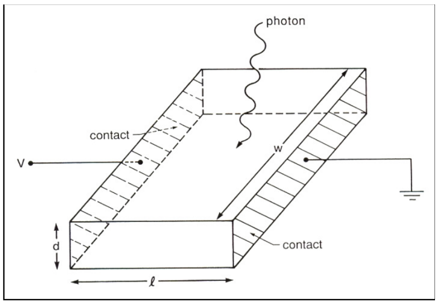
- few charge carriers → high resistance
- electric field applied → $\bar{E}$ drives charge carriers to electrodes

- high resistance material
- allows large voltage → large signals
- minimizes other noise sources

Basic Principle



Some Math …



Goal: Derive the dependency between conductivity σ and photon arrival rate

Ohm's law: $R_d = \frac{V_b}{I_d}$

The conductivity σ [$\Omega^{-1}cm^{-1}$] is related to R_d via: $\sigma = \frac{1}{R_d}\frac{l}{A} \Rightarrow R_d = \frac{1}{\sigma}\frac{l}{wd}$

where: $\sigma = \sigma_{th} + \sigma_{ph} \approx \sigma_{ph}$ (`th' denotes the thermal ("dark") current)

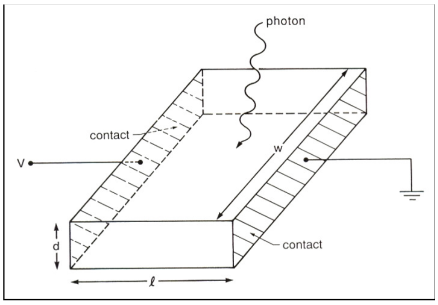
The current density is: $J_x = q_c n_0 \langle v_x \rangle$

where q_c is the electrical charge and n_o the carrier density

But also: $J_x = \frac{I}{A} = \frac{I_d}{wd} = \frac{V_b}{R_d wd} = \frac{\sigma V_b}{l} = \sigma E_x$

and we get: $q_c n_0 \langle v_x \rangle = \sigma E_x$

Electron Mobility



Conductivity: $\sigma \overset{q_c=-q}{=} \frac{-q n_0 \langle v_x \rangle}{E_x} \overset{-\mu_n = \frac{\langle v_x \rangle}{E_x}}{=} q n_0 \mu_n$

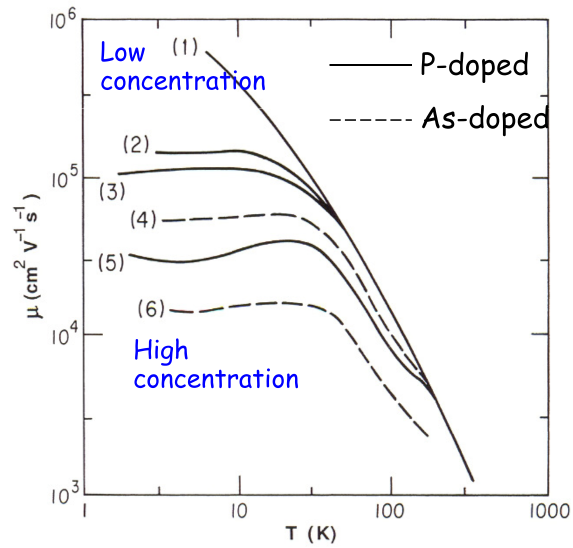
where $-\mu_n$ is the electron mobility.

Mobility ~ mean time between collisions

low T → impurities dominate
ionized impurities: $\mu_n \sim T^{3/2}$
neutral impurities: $\mu_n \sim$ const

high T → crystal lattice dominates
$\mu_n \sim T^{-3/2}$

Astronomical detectors usually operate in the low T regime.



Electron Mobility (2)

Carrier mobilities at room temperature, in $cm^2/V\text{-}s$

Crystal	Electrons	Holes	Crystal	Electrons	Holes
Diamond	1800	1200	GaAs	8000	300
Si	1350	480	GaSb	5000	1000
Ge	3600	1800	PbS	550	600
InSb	800	450	PbSe	1020	930
InAs	30000	450	PbTe	2500	1000
InP	4500	100	AgCl	50	—
AlAs	280	—	KBr (100 K)	100	—
AlSb	900	400	SiC	100	10–20

Some Math … (2)

To the total conductivity, both electrons and holes contribute:

$$\sigma_{ph} = q(\mu_n n + \mu_p p)$$

(n and p are the negative and positive charge carrier concentrations)

Consider the incoming photon flux φ [γ/s]

→ number of charge carriers in equilibrium is $\varphi\eta\tau$, where η is the quantum efficiency and τ is the mean lifetime before recombination. Typically, $\tau \sim$ (impurity concentration)$^{-1}$

Number of charge carriers per unit volume: $n = p = \dfrac{\varphi\eta\tau}{wdl}$

Hence, the resistance is:

$$R_d = \frac{1}{\sigma}\frac{l}{wd} = \frac{1}{q(\mu_n n + \mu_p p)}\frac{l}{wd} = \frac{1}{q(\mu_n + \mu_p)}\frac{wdl}{\varphi\eta\tau}\frac{l}{wd} = \frac{l^2}{q(\mu_n + \mu_p)\varphi\eta\tau}$$

Some Math … (3)

$$R_d = \frac{l^2}{q(\mu_n + \mu_p)\varphi\eta\tau}$$

- R ~ 1/σ
- 1/R ~ I ~ φ → detector is linear

$$\boxed{\text{Responsivity } S \equiv \frac{\text{electrical output signal}}{\text{input photon power}}}$$

The "photon power" falling on the detector is: $P_{ph} = \varphi h\nu = \frac{\varphi hc}{\lambda}$

Photoconductive Gain $G \equiv \frac{\tau\mu E_x}{l}$

τ·μ/l = lifetime × mobility / pathlength
E_x = "amplifying" electric field

The responsivity S is thus:

$$S = \frac{I_{ph}}{P_{ph}} \stackrel{Ohm}{=} \frac{V_b}{R_{ph}P_{ph}} \stackrel{E=V/l}{=} \frac{E_x l}{R_{ph}P_{ph}} = \frac{E_x l}{l^2} q\varphi\eta\tau(\mu_n + \mu_p)\frac{\lambda}{\varphi hc} = G\frac{q\eta\lambda}{hc}$$

The "photo current" is: $\boxed{I_{ph} = \frac{\eta\lambda q G}{hc}P_{ph} = \eta q\varphi G}$

The Photoconductive Gain

(1) Time for an e⁻ to drift from one electrode to the other: $\tau_t = -\frac{l}{\langle v_x \rangle}$

(2) Recall the electron mobility: $\mu = -\frac{\langle v_x \rangle}{E_x}$

Combining (1) and (2): $\tau_t = -\frac{l}{\mu E_x}$

→ Photoconductive Gain: $G = \frac{\tau\mu E_x}{l} = \frac{\tau}{\tau_t}$

τ is the mean carrier lifetime before recombination. Hence:
The photoconductive gain is the ratio of carrier lifetime to carrier transit time.

G quantifies the probability that a generated charge carrier will traverse the extent of the detector and reach an electrode.

The Photoconductive Gain (2)

Since the photoconductive gain is determined via: $I_{ph} = q\varphi\eta G$
, the observed current is degraded by G (for G <1).

$$G = \frac{\tau}{\tau_t}$$

$G \ll 1$ ⇔ $\tau_t \gg \tau$ ⇔ charge carriers recombine before reaching an electrode
$G \sim 1$ ⇔ $\tau_t \sim \tau$ ⇔ all charge carriers have a good chance of reaching an electrode
$G > 1$ is possible if charge multiplication occurs.

Optimizing G:
- make detector as this as possible
- increase the bias voltage (E_x)
- eliminate defects and impurities

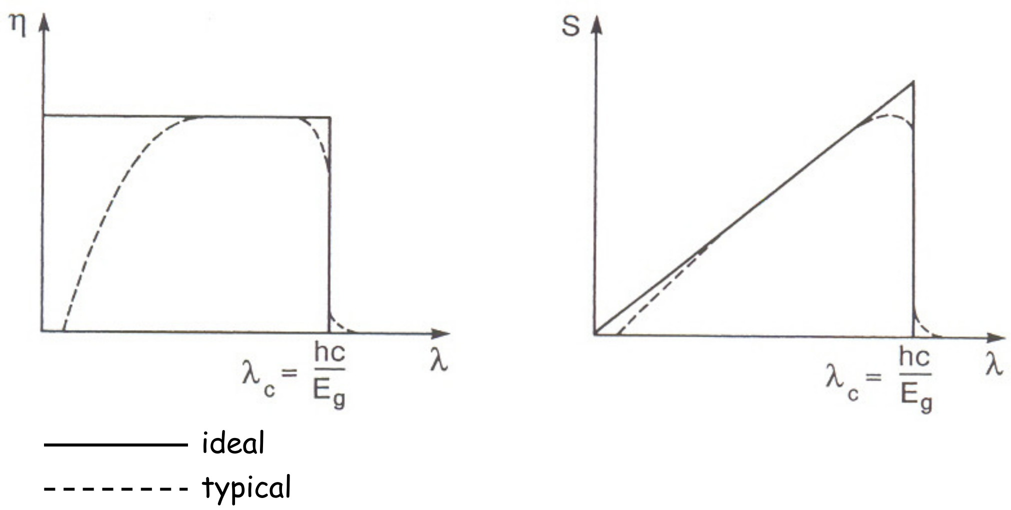
The product ηG describes the probability that an incoming photon will produce an electric charge that will penetrate to an electrode.

QE and Responsivity

Let's assume an *ideal* photoconductor:

The quantum efficiency η is percentage of photons hitting the detector surface that will produce an electron–hole pair (η~const)! It is independent of wavelength up to the cutoff at λ_c.

The responsivity S increases proportional with wavelength: $S = G\frac{q\eta\lambda}{hc}$
Since $E_\gamma = h\nu$ → S is not constant with wavelength.



Noise

The Noise Current

Goal: Estimate the total noise in the system

Assumption: all statistical noise sources are Poisson distributed

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

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

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

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

one gets:

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

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 $U(\xi)$ is the normalized electrical response (current or voltage)

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

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

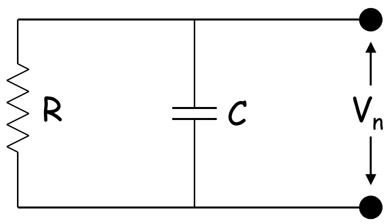
The noise current $\langle I^2_{G-R} \rangle$ can now be rewritten as:

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

Other Noise Sources: 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.

Other Noise Sources: kTC noise

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

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

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

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

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 $\langle I_N^2 \rangle = \langle I_{G-R}^2 \rangle + \langle I_J^2 \rangle + \langle I_{1/f}^2 \rangle$

Noise currents vary randomly in phase → noises are added quadratically

Signal currents are correlated in phase → signals are added linearly