Photodetectors are widely used in optical communication systems. In this application, detectors receive the transmitted optical pulses and convert them, with as little loss as possible, into electronic pulses that can be used by a telephone, a computer, or other terminal at the receiving end.

Typically, ~ 10 Gb/s operation is required in optical communication links. The performance requirements for the detectors are high sensitivity, low noise, wide bandwidth, high reliability, and low cost.

Photodetectors in high-speed communications

• A photodetector is an optoelectronic device that absorbs optical signals and converts them into electrical signals.
Optical processes used in photodetectors

Different mechanisms of photodetection: (a) for intrinsic light ($h\nu \geq \mathcal{E}_g$); (b) for extrinsic light utilizing a deep level; and (c) for extrinsic light utilizing intersubband transitions in a quantum well.
The quantum efficiency $\eta$ of photodetectors

The external quantum efficiency

$$\eta = \frac{\text{the number of electron-hole pairs per second contributing the photocurrent } I_{\text{ph}}}{\text{the number of incident photons per second}}$$

$$\eta = \frac{I_{\text{ph}}/q}{P_{\text{inc}}/h\nu} = \frac{I_{\text{ph}}}{q} \cdot \frac{h\nu}{P_{\text{inc}}}$$

$P_{\text{inc}}$ is the incident optical power.
The responsivity $R$ of photodetectors (compare to the responsivity of the LEDs)

$$
\eta = \frac{I_{ph}/q}{P_{inc}/hv} = \frac{I_{ph}}{q} \cdot \frac{hv}{P_{inc}}
$$

$$
\bar{R} = \frac{I_{ph}}{P_{inc}}
= \frac{\eta q}{hv}
= \frac{\eta \lambda(\mu m)}{1.24} (A/W)
$$
Different types of high-speed photodetectors

The three main types of detectors are

1. Photoconductors,
2. Junction photodetectors (Schottky diodes, PIN diodes, MSM diodes) and
3. Avalanche photodiodes.

The first and the third types have *internal gain*.

Junction photodetectors have no internal gain but they can have very large bandwidths and low noise levels.
I. Photoconductors

The concentration of electron and hole pairs consists of the equilibrium (dark) concentration and that of the photoexcited carriers:

\[ I = I_D + I_{ph} \]

\[ I = abq(\nu \mu_n + p \mu_p) \frac{V}{L} \]

\[ n = n_0 + n_{ph}; \quad p = p_0 + p_{ph}; \]

Correspondingly,

\[ I = I_D + I_{ph} \]

\[ I_D \] – the “dark” current; \( I_{ph} \) – the “photo” current
Quantum efficiency and gain of the photoconductor

The number of photons absorbed in the semiconductor per second per unit volume (the absorption rate) is equal to

\[ R_{\text{abs}} = \frac{P_{\text{inc}}}{h \nu / V_v} . \]

This photon flux creates a certain carrier generation rate, G. If all the light is absorbed, then, the internal quantum efficiency,

\[ \eta_i = \frac{G}{R_{\text{abs}}} = \frac{G V_v}{P_{\text{inc}} / h \nu} \]

where V_v is the volume of the semiconductor.
Absorption coefficient and quantum efficiency

Some light can be transmitted through the slab, after absorption in the material:

\[ P(\alpha) = P_{\text{inc}} \cdot e^{-\alpha \alpha} \]

In this case,

\[ GV_v = \eta_i \frac{P_{\text{inc}} - P(\alpha)}{h \nu} = \eta_i \frac{P_{\text{inc}}}{h \nu} \cdot (1 - e^{-\alpha \alpha}) \]

and the quantum efficiency (external) can be expressed as

\[ \eta = \eta_i \cdot (1 - e^{-\alpha \alpha}) \]
Photocurrent and Gain

Actual device photocurrent (and the gain) depends on what happens to the photogenerated carriers.

If all the carriers are swept out before recombining and if there is no replenishment by reinjection,

\[ I_{ph} = qGV \]

In this case, there is no gain or loss, and the gain, \( \Gamma_G = 1 \)

In general, the gain \( \Gamma_G \neq 1 \), and

\[ I_{ph} = qGV_l \Gamma_G \]

The gain \( \Gamma_G \) can be either > 1 (gain) or <1 (loss)
Gain mechanisms in photoconductors

Effect of electrons and holes life time $t$ on the gain

1) The voltage applied to the slab is very small. The carriers can recombine BEFORE they reach the contact.

\[
\Gamma_G = \frac{(\text{path traveled by electron}) + (\text{path traveled by hole})}{L} = \frac{\mu_e \frac{V}{L} \tau + \mu_h \frac{V}{L} \tau}{L}
\]

- $\tau$ is the $e/h$ pair life time
- $V$ is the voltage drop across the slab

\[
= \frac{\mu_e + \mu_h \tau}{\mu_e} \frac{\tau}{t_{tr}^e} = \frac{L}{\mu_e} \frac{L^2}{\nu_e} \mu_e V
\]

$\bullet \ t_{tr}^e = \frac{L}{\nu_e} = \frac{L^2}{\mu_e V}$ is the electron transit time

Since generally $\mu_e \gg \mu_h$,

\[
\Gamma_G = \frac{\tau}{t_{tr}^e} < 1
\]
2) When the voltage $V$ is made larger:

Electrons travel faster than holes, therefore the situation may be described by the conditions

$$t_{e_{fr}}^e < \tau, \ t_{h_{fr}}^h > \tau.$$

In this case, the Gain,

$$\Gamma_G = \frac{\tau}{t_{e_{fr}}^e} > 1 \quad \text{Why?}$$

3) The bias voltage $V$ is very large,

$$t_{e_{fr}}^e < \tau \text{ and } t_{h_{fr}}^h < \tau.$$

$$\Gamma_G = 1$$
Time response of the photoconductor (AC behavior)

The incident power, \[ P_{\text{inc}} = P_0 + P_1 e^{j\omega t} \]

The generation rate, \[ \hat{G} = G_0 + \hat{G}_1 e^{j\omega t} \]

The time dependent electron concentration, \[ \frac{dn}{dt} = \hat{G} - \frac{n}{\tau} \]

The solution for this equation, \[
\Delta n = G_0\tau (1 - e^{-t/\tau}) + \frac{\hat{G}_1\tau}{1 + j\omega \tau} (e^{j\omega t} - e^{-t/\tau})
\]

For the steady-state conditions, \( t >> \tau \), \[
\Delta n = G_0\tau + \frac{G_1\tau}{1 + j\omega \tau} e^{j\omega \tau}
\]
The photocurrent, \( I_{ph} \),

\[ I_{ph} = q GV_I \Gamma_G = qP_{inc} \frac{\eta}{h \nu} \Gamma_G; \]

\[ i_{ph} = qP_0 \frac{\eta}{h \nu} \frac{\tau}{t_{ir}^e} + qP_1 \frac{\eta}{h \nu} \frac{\tau}{t_{ir}^e} \frac{1}{1 + j \omega \tau} e^{j \omega \tau} \]

\[ = I_0 + i_1 \]

The AC component of the photocurrent has a factor \((1 + j \omega \tau)^{-1}\), therefore, it is \textit{frequency dependent}.

Consider an important case of very high frequencies,

\[ j \omega \tau \gg 1 \]

Then \( i_1 \) is inversely proportional to \( t_{ir}^e = \frac{L^2}{\mu_e V} \).

Hence, for the high frequency operation, \( L \) has to be small and the voltage applied \( V \) has to be large.
The cut-off frequency and AC gain

The cut-off frequency, \( f_c \), is defined as the frequency at which \( \omega \tau = 1 \).

\[
f_c = \frac{1}{2\pi \tau}
\]

The gain at low frequencies, \( \Gamma_G(0) = \frac{\tau}{t_{tr}^*} > 1 \) for small \( L \) values.

However, the gain decreases with the frequency \( f \).

The gain-bandwidth product of the photoconductor is defined as

\[
\Gamma_G f_c = \frac{\tau}{t_{tr}} \cdot \frac{1}{2\pi \tau} = \frac{1}{2\pi t_{tr}}
\]
Interdigitated high-speed photoconductor

Very short transit time \( t_{tr}^c = \frac{L^2}{\mu_e V} \) achieved using small electrode spacing.
Metal-semiconductor-metal photodetector concept

The device consists of two (or more) identical Schottky contacts deposited on the top surface of semiconductor layer.

An external voltage applied between two electrodes biases one of them in forward and another one in reverse direction.
Metal- semiconductor-metal photodetector concept

**Schottky detector**

At zero bias Schottky detector produces photocurrent

**MSM detector**

At zero bias MSM structure is symmetrical; The electric field in the center is zero. Photoexcited electrons are "TRAPPED" in the "potential well" The net photocurrent is ZERO
**Metal-semiconductor-metal photodetector concept: non-zero bias**

The potential barrier at the forward bias contact decreases. There is an electric field between the Schottky electrodes. The majority of photoexcited electrons are "TRAPPED" in the "potential well". Photoexcited holes cannot leave the active region due to the charge of the "trapped" electrons. The net photocurrent is very small.
Metal-semiconductor-metal photodetector concept: punch-through bias

Potential barrier for photo-electrons disappears
Metal-semiconductor-metal photodetector concept: punch-through bias

As the reverse voltage applied to the left Schottky contact increases, the width of the depletion region also increases;
If the reverse voltage is high enough, the depletion region reaches the opposite (right) electrode.
The electric field in the depletion region COMPENSATES the built-in electric field at the forward biased (right) Schottky contact.
As the voltage increases beyond this punch-through value, the potential barrier at the right contact disappear - the flat-band voltage
Metal-semiconductor-metal photodetector concept: punch-through bias

Flat-band conditions for MSM photodetector

Consider reverse-biased (left) electrode.

As the bias increases, the depletion region width, \( W \), increases:

\[
V_d = \phi_b - \frac{E_{Fs}}{q} - V_f = \frac{qN_D W^2}{2\varepsilon_s\varepsilon_0}
\]

At a certain applied voltage, \( V_f \), the depletion region width, \( W = L \), where \( L \) is the electrode spacing:

\[
V_{FB} = \frac{qNW^2}{2\varepsilon_s\varepsilon_0}
\]
Metal-semiconductor-metal photodetector concept: punch-through bias

Why and when the barrier at forward biased electrode disappears?

\[ E(x) \]

Flat-band field distribution

\[ V \text{ increases} \]
Metal-semiconductor-metal photodetector concept: punch-through bias

Voltage distribution in the MSM diode

What portion of the applied voltage drops across the left and the right electrodes?

The answer can be found by considering current continuity through the diode:

\[ V = V_1 (I) + V_2 (I) \]

Non-linear load line approach
Electric field distribution between the MSM electrodes

Due to planar device structure, the field distribution is not uniform.

- The electric field penetrates into the depth of the semiconductor material.
- This characteristic depth is about the electrode spacing.
- The characteristic depth has to be equal about 3 times the light absorption length.
Current-voltage characteristics of MSM diode

At zero bias, both the dark and the photo currents are zero
Capacitance-voltage characteristics of MSM diode

The capacitance is low due to the PLANAR device geometry

\[ C_o = \varepsilon_o (1 + \varepsilon_s) \frac{K(k)}{K(k')} \]

where \( \varepsilon_s \) is the dielectric constant of the semiconductor and \( K \) is the complete elliptic integral of the first kind with

\[ k = \tan^2 \left( \frac{\pi L}{4(L + W)} \right) \quad \text{and} \quad k' = (1 - k^2)^{1/2} \]
Large area multi-finger MSM diode

For $N$ fingers, $C = (N - 1)C_0 l$
MSM capacitance calculation:
complete elliptic integral of the first kind

\[
K = F \left( \frac{\pi}{2}, k \right) = \int_0^{\pi/2} \frac{1}{\sqrt{1 - k^2 \sin^2 \theta}} d\theta = \int_0^1 \frac{1}{\sqrt{(1 - \nu^2)(1 - \nu^2)}} d\nu
\]

\[
= \frac{\pi}{2} \left[ 1 + \left( \frac{1}{2} \right)^2 k^2 + \left( \frac{1}{2} \cdot \frac{3}{4} \right)^2 k^4 + \left( \frac{1}{2} \cdot \frac{3}{4} \cdot \frac{5}{6} \right)^2 k^6 + \ldots \right]
\]

\[
M(k) = \frac{K(k)}{K(k')} \]

![Graph showing the relationship between K(k) and M(k)]
Advantages of MSM photodetectors

- Strong electric field in the active area
  - pure drift photocurrent, no diffusion component
  - very fast photoresponse, determined by saturation velocity, $v_S$
- No need for Ohmic contacts $\rightarrow$ the material can be low-doped.
- Dark current is very low (two back-to-back Schottky contacts)
- Very low capacitance $\rightarrow$ very small RC time - constant