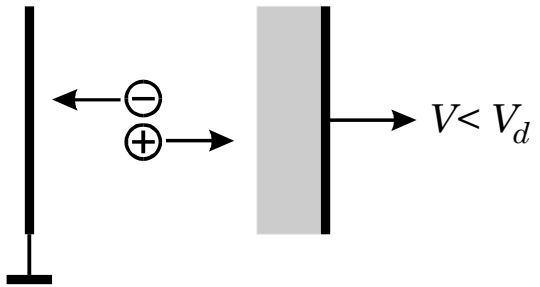
Sensor Physics – Part II

Charge Collection

Mobile electrons and holes formed by radiation move under the influence of the electric field in the junction.

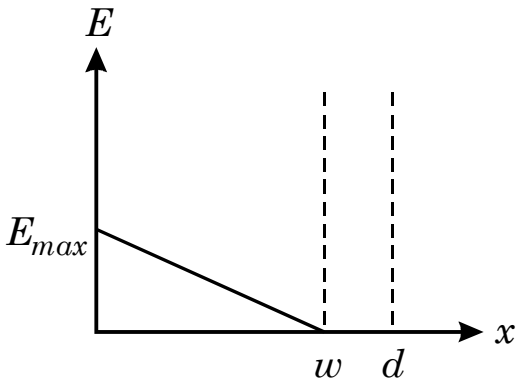
Although electrons and holes move in opposite directions, their contribution to the signal current is of the same polarity.

The time required for a charge carrier to traverse the sensitive volume is called the collection time.



Using the depletion width eq. 13 one can rewrite eq. 2 for the electric field

$$E(x) = \frac{2(V_b + V_{bi})}{w}\left(1 - \frac{x}{w}\right) \qquad (14)$$



The detector bulk is completely depleted of mobile charge when $W = d$, the thickness of the substrate. This occurs at the externally applied depletion voltage

$$V_d = \frac{q_e N_d W^2}{2\varepsilon} - V_{bi} \,. \qquad (15)$$

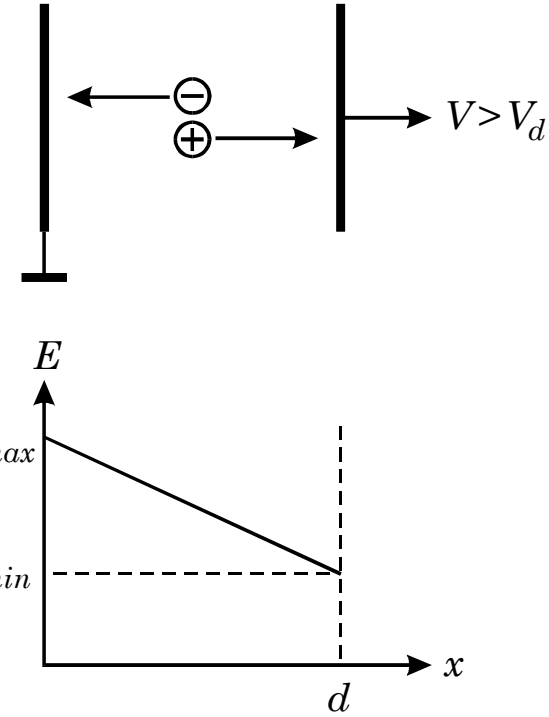
The field drops linearly from its maximum value at the junction to zero at the opposite contact.

Overbias

Increasing the bias beyond the depletion voltage adds a uniform field due to the voltage beyond depletion, yielding a distribution

$$E(x) = \frac{2V_{di}}{d}\left(1 - \frac{x}{d}\right) + \frac{V_b - V_{di}}{d} \qquad (16)$$

where $V_{di} \equiv V_d + V_{bi}$ has been defined as the internal depletion voltage.



First consider a detector operated at partial depletion $V_b > V_d$. The field

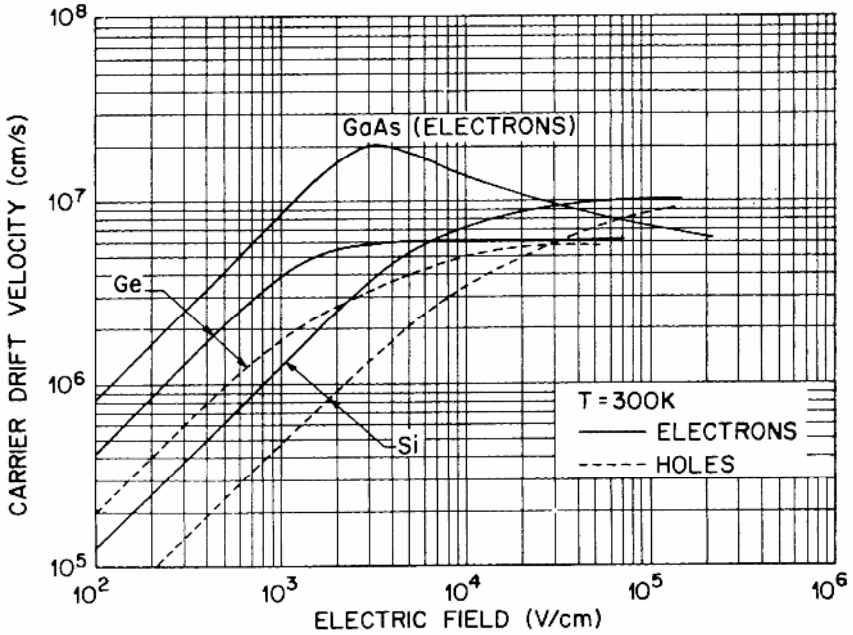
$$E(x) = -\frac{q_e N_d}{\varepsilon}(w - x) \equiv E_0(w - x) \qquad (17)$$

The local velocity of a charge carrier $\quad v(x) = \mu E(x) = \mu E_0(w - x) \qquad (18)$

Note that the velocity does not depend on the time during which the charge carrier is accelerated, as in normal ballistic motion, since the charge carrier also interacts with the crystal lattice, exciting lattice vibrations (phonons). Since the characteristic times for phonon excitation are much smaller than the transport times, the carrier is always in equilibrium with the lattice, so the velocity is only a function of the electric field, at every position in the depletion region.

In Si at 300K the mobility at low fields is 1350 cm^2/ Vs for electrons and 480 cm^2/ Vs for holes.

The mobility is constant up to about 10^4 V/cm, but then increased phonon emission reduces the energy going into electron motion, so the mobility decreases. At high fields E > 10^5 V/cm the mobility $\mu \propto 1/E$ and carriers attain a constant drift velocity of 10^7 cm/s.



(from Sze)

The time required for a charge originating at x_0 to reach a point x is

$$t(x) = \int_{x_0}^{x} \frac{1}{v(x)} dx = \frac{1}{\mu E_0} \int_{x_0}^{x} \frac{1}{w-x} dx = -\frac{1}{\mu E_0} \left[\ln(w-x) \right]_{x_0}^{x}$$

$$t(x) = -\frac{1}{\mu E_0} \ln \frac{w-x}{w-x_0} = \frac{\varepsilon}{\mu q_e N_d} \ln \frac{w-x}{w-x_0} \qquad (19)$$

Consider a hole drifting toward the high-field region and collected at the p-electrode x= 0. Using the hole mobility μ_p eq. 19 yields

$$t(x_0) = -\frac{1}{\mu_p E_0} \ln \frac{w}{w-x_0} = \frac{\varepsilon}{\mu_p q_e N_d} \ln \frac{w}{w-x_0} \qquad (20)$$

If we define a characteristic collection time $\tau_p \equiv \frac{\varepsilon}{\mu_p q_e N_d}$,

then

$$t(x_0) = \tau_p \ln \frac{w}{w-x_0} \qquad (20a)$$

For example,

$$t(x_0 = 0.5w) = 0.7\tau_p$$

and

$$t(x_0 = 0.95w) = 3.0\tau_p .$$

For the electrons drifting toward the low-field electrode $x = W$, eq. 19 does not yield a solution. However, it can be rewritten to yield the position as a function of time

$$x(t) = w - (w - x_0)\, e^{-t/\tau_n} \qquad (21)$$

where τ_n has been defined analogously to τ_p.

For a charge originating at the metallurgical junction $x_0 = 0$ and drifting toward $x = w$

$$x(t) = w(1 - e^{-t/\tau_n}) \; . \qquad (22)$$

In this simple picture, a charge drifting toward the low field region is never collected (in reality this is accomplished by diffusion), although after a time $t = 3\tau_n$ the carrier will have traversed 95% of the detector. Note that in a partially depleted detector the collection time constants τ_n and τ_p are independent of the applied bias voltage (and depletion thickness), but determined only by the doping concentration of the bulk material and the carrier mobility.

τ_n is numerically equal to the dielectric relaxation time of the n-type bulk

$$\tau = \rho\varepsilon = \varepsilon_{Si}\ \varepsilon_0\ \rho = 1.05\left[\frac{ns}{k\Omega\cdot cm}\right]\ \rho\ . \qquad (23)$$

In n-type silicon of 10 kΩ·cm resistivity τ_n= 10.5 ns and τ_p= 31.5 ns, and typical collection times in partially depleted detectors are about 30 and 90 ns, respectively.

Voltage bias beyond depletion (overbias)

The collection time can be reduced by operating the detector at bias voltages exceeding the depletion voltage.

The field distribution was given in eq. 16, which can be rewritten as

$$E(x) = E_0 \left(1 - \frac{x}{d}\right) + E_1 \ . \tag{24}$$

This yields a collection time

$$t(x) = \int_{x_0}^{x} \frac{1}{v(x)} dx = \frac{1}{\mu} \int_{x_0}^{x} \frac{1}{E_0 \left(1 - \frac{x}{d}\right) + E_1} dx$$

$$t(x) = -\frac{d}{\mu E_0} \left[\ln(E_0 + E_1 - E_0 \frac{x}{d} \right]_{x_0}^{x}$$

$$t(x) = \frac{d}{\mu E_0} \ \ln \frac{E_0 + E_1 - E_0 \frac{x}{d}}{E_0 + E_1 - E_0 \frac{x_0}{d}} \ . \tag{25}$$

For holes originating at $x_0 = d$ and drifting to the p-electrode $x = 0$

$$t_{cp} = \frac{d}{\mu_p E_0} \ln\left(1 + \frac{E_0}{E_1}\right). \qquad (26a)$$

The corresponding result obtains for electrons originating at $x_0 = 0$ and drifting to the n-electrode $x = d$

$$t_{cn} = \frac{d}{\mu_n E_0} \ln\left(1 + \frac{E_0}{E_1}\right). \qquad (26b)$$

For large overbias $E_1 \gg E_0$: $\ln\left(1 + \frac{E_0}{E_1}\right) \approx \frac{E_0}{E_1}$

and $t_{cp} = \frac{d}{\mu_p E_1}$

as expected for a uniform field.

Rewritten in terms of voltages, eqs. 26a and 26b become $t_{cp} = \frac{d^2}{2\mu_p V_{di}} \ln\left(\frac{V_b + V_{di}}{V_b - V_{di}}\right)$

$$\text{and} \quad t_{cn} = \frac{d^2}{2\mu_n V_{di}} \ln\left(\frac{V_b + V_{di}}{V_b - V_{di}}\right) \qquad (27)$$

Example:

For n-type silicon of 10 kΩ·cm resistivity,

a detector thickness of 300 μm, and

a reverse bias voltage V_b= 60V= 2V_d (i.e. E_0=2·10^3 and E_1=10^3 V/cm)

Collection times for

Electrons: 12 ns

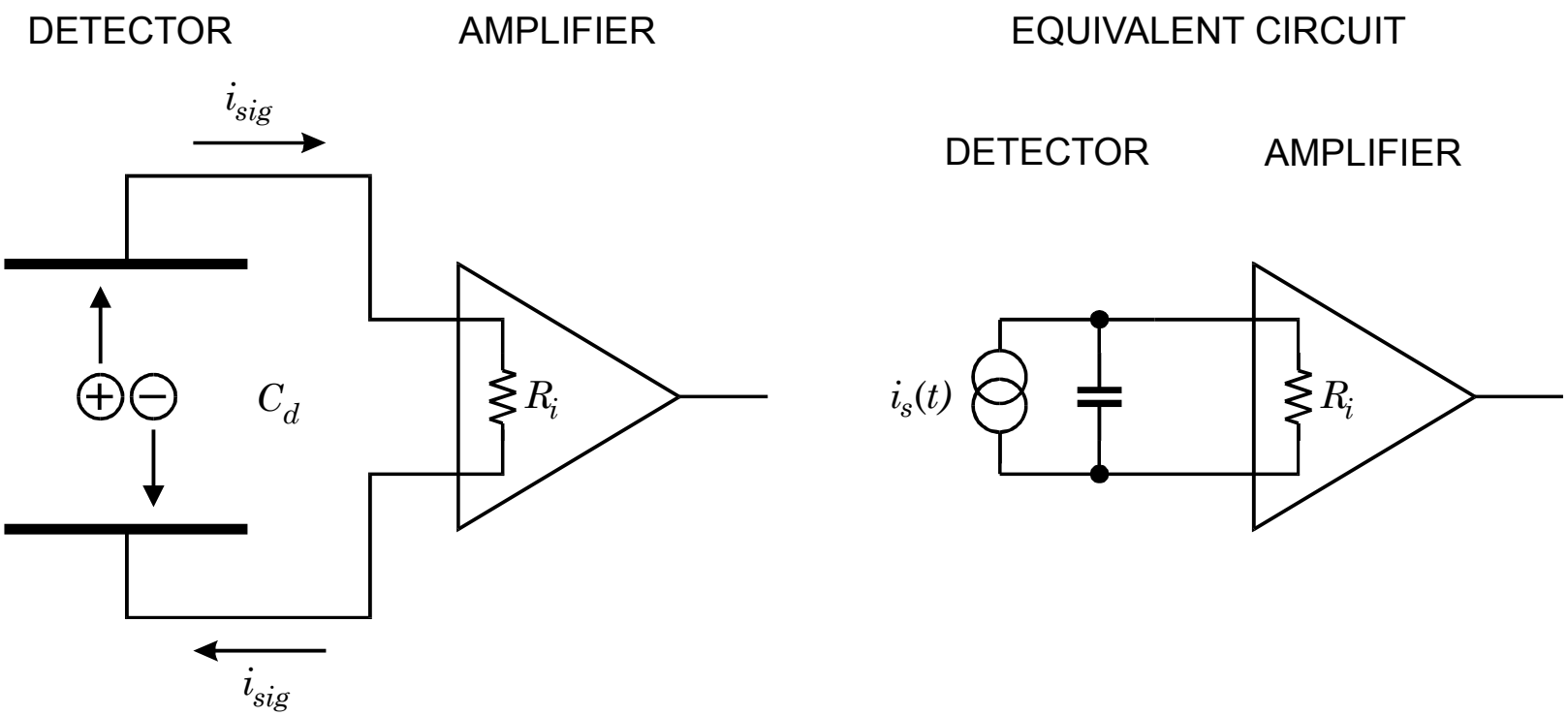
Holes: 36 ns.

This is substantially less than in the partially depleted device, where collection times for

Electrons: 30 ns

Holes: 90 ns.

Time Dependence of the Signal Current



When does the signal current begin?

a) when the charge reaches the electrode?

or

b) when the charge begins to move?

Although the first answer is quite popular (encouraged by the phrase “charge collection”), the second is correct.

When a charge pair is created, both the positive and negative charges couple to the electrodes. As the charges move the induced charge changes, i.e. a current flows in the electrode circuit.

The following discussion applies to ALL types of structures that register the effect of charges moving in an ensemble of electrodes, i.e. not just semiconductor or gas-filled ionization chambers, but also resistors, capacitors, photoconductors, vacuum tubes, etc.

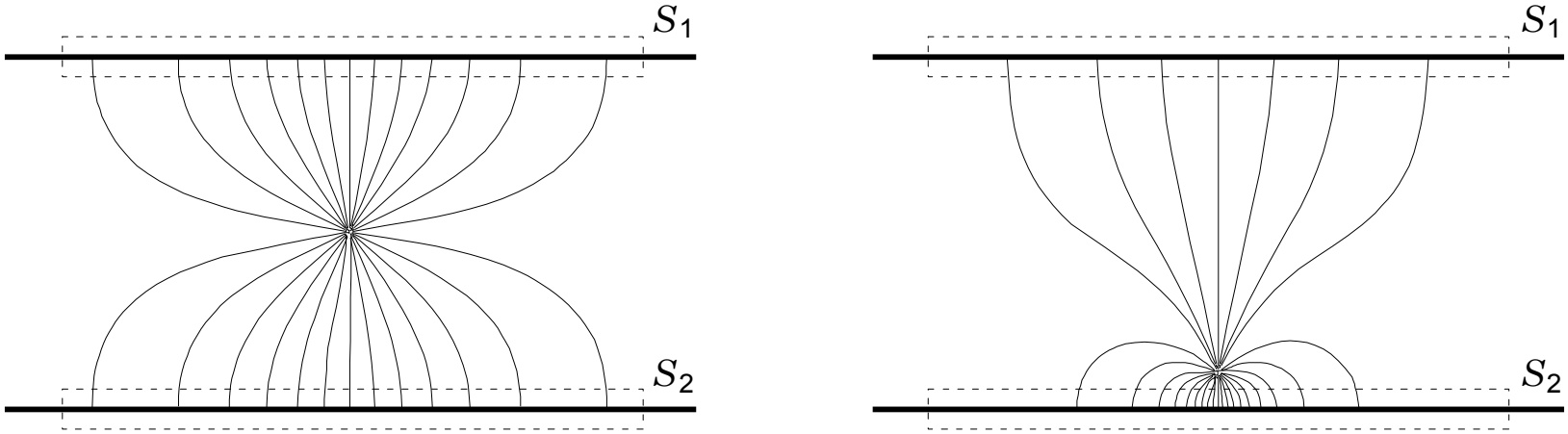
The effect of the amplifier on the signal pulse will be discussed in the Electronics part.

Induced Charge

Consider a charge q in a parallel plate capacitor:

When the charge is midway between the two plates, the charge induced on one plate is determined by applying Gauss' law. The same number of field lines intersect both S_1 and S_2, so equal charge is induced on each plate (= q / 2).

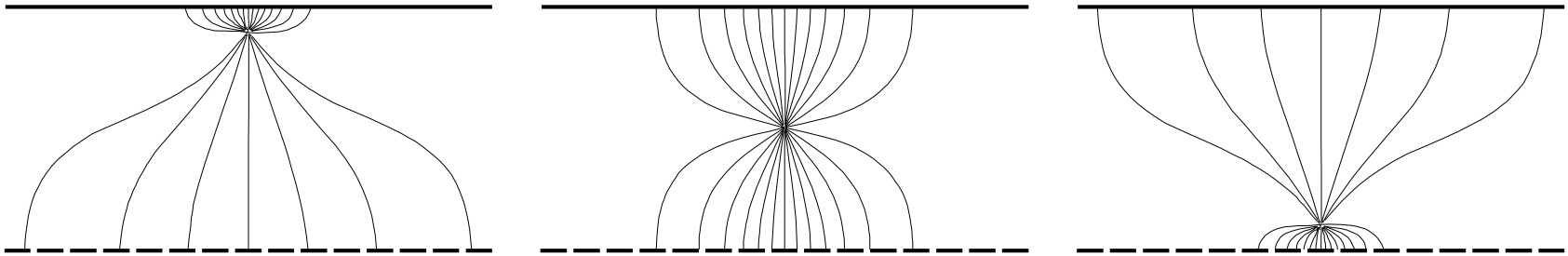
When the charge is close to one plate, most of the field lines terminate on that plate and the induced charge is much greater.



As a charge traverses the space between the two plates the induced charge changes continuously, so current flows in the external circuit as soon as the charges begin to move.

Induced Signal Currents in a Strip Detector

Consider a charge originating near the upper contiguous electrode and drifting down towards the strips.



Initially, charge is induced over many strips.

As the charge approaches the strips, the signal distributes over fewer strips.

When the charge is close to the strips, the signal is concentrated over few strips

The magnitude of the induced current due to the moving charge depends on the coupling between the charge and the individual electrodes.

Mathematically this can be analyzed conveniently by applying Ramo's theorem.

Induced Charge – Ramo's Theorem

W. Shockley, J. Appl. Phys. **9** (1938) 635
S. Ramo, Proc. IRE **27** (1939) 584

Consider a mobile charge in the presence of any number of grounded electrodes.

Surround the charge q with a small equipotential sphere. Then, if V is the potential of the electrostatic field, in the region between conductors

$$\nabla^2 V = 0$$

Call V_q the potential of the small sphere and note that $V = 0$ on the conductors. Applying Gauss' law yields

$$\int_{\substack{\text{sphere's}\\ \text{surface}}} \frac{\partial V}{\partial n} ds = 4\pi q$$

Next, consider the charge removed and one conductor A raised to unit potential.

Call the potential V_1, so that

$$\nabla^2 V_1 = 0$$

in the space between the conductors, including the site where the charge was situated. Call the new potential at this point V_{q1}.

Green's theorem states that

$$\int_{\substack{\text{volume between}\\ \text{boundaries}}} (V_1 \nabla^2 V - V\ \nabla^2 V_1)\ dv = \quad - \int_{\substack{\text{boundary}\\ \text{surfaces}}} \left[V_1 \frac{\partial V}{\partial n} - V \frac{\partial V_1}{\partial n} \right] ds\ .$$

Choose the volume to be bounded by the conductors and the tiny sphere.

Then the left hand side is 0 and the right hand side may be divided into three integrals:

1. Over the surfaces of all conductors except A. This integral is 0 since on these surfaces $V = V_1 = 0$.

2. Over the surface of A. As $V_1 = 1$ and $V = 0$ this reduces to

$$- \int_{\text{surface A}} \frac{\partial V}{\partial n} ds\ .$$

3. Over the surface of the sphere.

$$-V_{q1} \int_{\substack{\text{sphere's}\\ \text{surface}}} \frac{\partial V}{\partial n} ds \quad + \quad V_q \int_{\substack{\text{sphere's}\\ \text{surface}}} \frac{\partial V_1}{\partial n} ds\ .$$

The second integral is 0 by Gauss' law, since in this case the charge is removed.

Combining these three integrals yields

$$0 = -\int_{\text{surface A}} \frac{\partial V}{\partial n} ds \quad - \quad V_{q1} \int_{\substack{\text{sphere's} \\ \text{surface}}} \frac{\partial V}{\partial n} ds = 4\pi\ Q_A - 4\pi\ q V_{q1}$$

or $Q_A = q V_{q1}$.

If the charge q moves in direction x, the current on electrode A is

$$i_A = \frac{dQ_A}{dt} = q \frac{dV_{q1}}{dt} = q \left(\frac{\partial V_{q1}}{\partial x} \ \frac{dx}{dt} \right) .$$

Since the velocity of motion

$$\frac{dx}{dt} = v_x \ ,$$

the induced current on electrode A is $i_A = q\ v_x \frac{\partial V_{q1}}{dx}$,

where V_{q1} is the “weighting potential” that describes the coupling of a charge at any position to electrode A.

The weighting potential is for a specific electrode is obtained by setting the potential of the electrode to 1 and setting all other electrodes to potential 0.

- If a charge q moves along any path s from position 1 to position 2, the net induced charge on electrode k is

$$\Delta Q_k = q(V_{q1}(2) - V_{q1}(1)) \equiv q\left(\Phi_k(2) - \Phi_k(1)\right)$$

- The instantaneous current can be expressed in terms of a weighting field

$$i_k = -q\ \vec{v} \cdot\ \overrightarrow{F_k}$$

  The weighting field is determined by applying unit potential to the measurement electrode and 0 to all others. For this calculation the electrodes are assumed to be in a vacuum or a uniform dielectric.

- It is not affected by the presence of space charge, as the electric field in a semiconductor detector.

Note that the electric field and the weighting field are distinctly different.

- The electric field determines the charge trajectory and velocity.
- The weighting field depends only on geometry and determines how charge motion couples to a specific electrode. It is field with the unit 1/length (no voltage!) that describes the coupling from the charge at a given position to a specific electrode and has noting to do with work or energy.
- Only in 2-electrode configurations are the electric field and the weighting field of the same form.
- **The detector signal originates as a current!**

  Signal charge is a secondary quantity, obtained by integrating the signal current: $Q_s = \int i_s(t)dt$.

Example 1: Parallel plate geometry with uniform field

(semiconductor detector with very large overbias)

Assume a voltage V_b applied to the detector. The distance between the two parallel electrodes is d.

The electric field that determines the motion of charge in the detector is

$$E = \frac{V_b}{d}$$

Assume that the velocity of the charge carriers is collision limited, so the velocity of the charge

$$v = \mu E = \mu \frac{V_b}{d}$$

The weighting field is obtained by applying unit potential to the collection electrode and grounding the other,

$$E_Q = \frac{1}{d}$$

so the induced current

$$i = qvE_Q = q\mu \frac{V_b}{d}\frac{1}{d} = q\mu \frac{V_b}{d^2}$$

Since both the electric field and the weighting field are uniform throughout the detector, the current is constant until the charge reaches its terminal electrode.

Assume that the charge is created at the opposite electrode and traverses the detector thickness d.

The required collection time, i.e. the time required to traverse the detector thickness d

$$t_c = \frac{d}{v} = \frac{d}{\mu \frac{V_b}{d}} = \frac{d^2}{\mu V_b}$$

The induced charge

$$Q = it_c = q\mu \frac{V_b}{d^2} \frac{d^2}{\mu V_b} = q$$

Next, assume an electron-hole pair formed at coordinate x from the positive electrode.

The collection time for the electron

$$t_{ce} = \frac{x}{v_e} = \frac{xd}{\mu_e V_b}$$

and the collection time for the hole

$$t_{ch} = \frac{d-x}{v_h} = \frac{(d-x)d}{\mu_h V_b}$$

Since electrons and holes move in opposite directions, they induce current of the same sign at a given electrode, despite their opposite charge.

The induced charge due to the motion of the electron

$$Q_e = q_e \mu_e \frac{V_b}{d^2} \frac{xd}{\mu_e V_b} = q_e \frac{x}{d}$$

whereas the hole contributes

$$Q_h = q_e \mu_h \frac{V_b}{d^2} \frac{(d-x)d}{\mu_h V_b} = q_e \left(1 - \frac{x}{d}\right)$$

Assume that $x = d/2$. After the collection time for the electron

$$t_{ce} = \frac{d^2}{2\mu_e V_b}$$

it has induced a charge $q_e/2$.

At this time the hole, due to its lower mobility $\mu_h \approx \mu_e/3$, has induced $q_e/6$, yielding a cumulative induced charge of $2q_e/3$.

After the additional time for the hole collection, the remaining charge $q_e/3$ is induced, yielding the total charge q_e.

In this configuration

- Electrons and holes contribute equally to the currents on both electrodes
- The instantaneous current at any time is the same (although of opposite sign) on both electrodes

The continuity equation (Kirchhoff's law) must be satisfied:

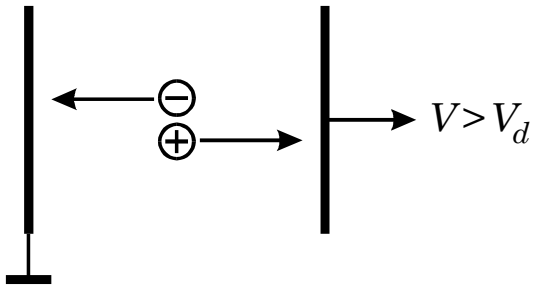
$$\sum_k i_k = 0$$

Since k=2: $$i_1 = -i_2$$

A Common Fallacy

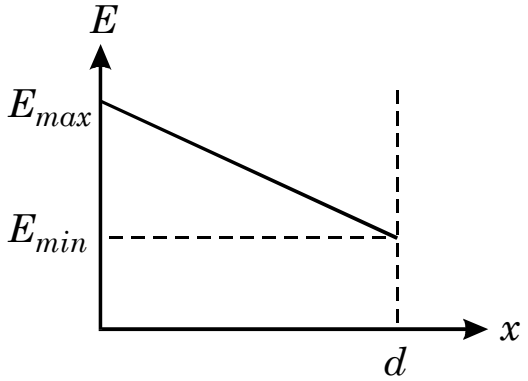
A widespread derivation of induced charge is based on energy balance, where it is postulated that the energy gained by the particle in traversing the sensor equals the change in potential on the capacitor plates.

This predicts the incremental charge $dQ = q\frac{dV}{V}$



Because the field in a semiconductor detector isn't constant, the potential has a quadratic term, which yields a different pulse shape than derived from electrostatics,

$$dQ = q\frac{dx}{d}.$$



The fundamental error in the energy balance concept is that it assumes that all energy imparted by the field goes into carrier motion, i.e. ballistic transport.

However, most of the energy goes into other modes (phonons). The energy balance approach is false for all collision-limited transport, i.e. in solids, liquids, and gases.

- The induced charge described by Ramo's theorem applies the correct physics for all materials and electrode configurations.

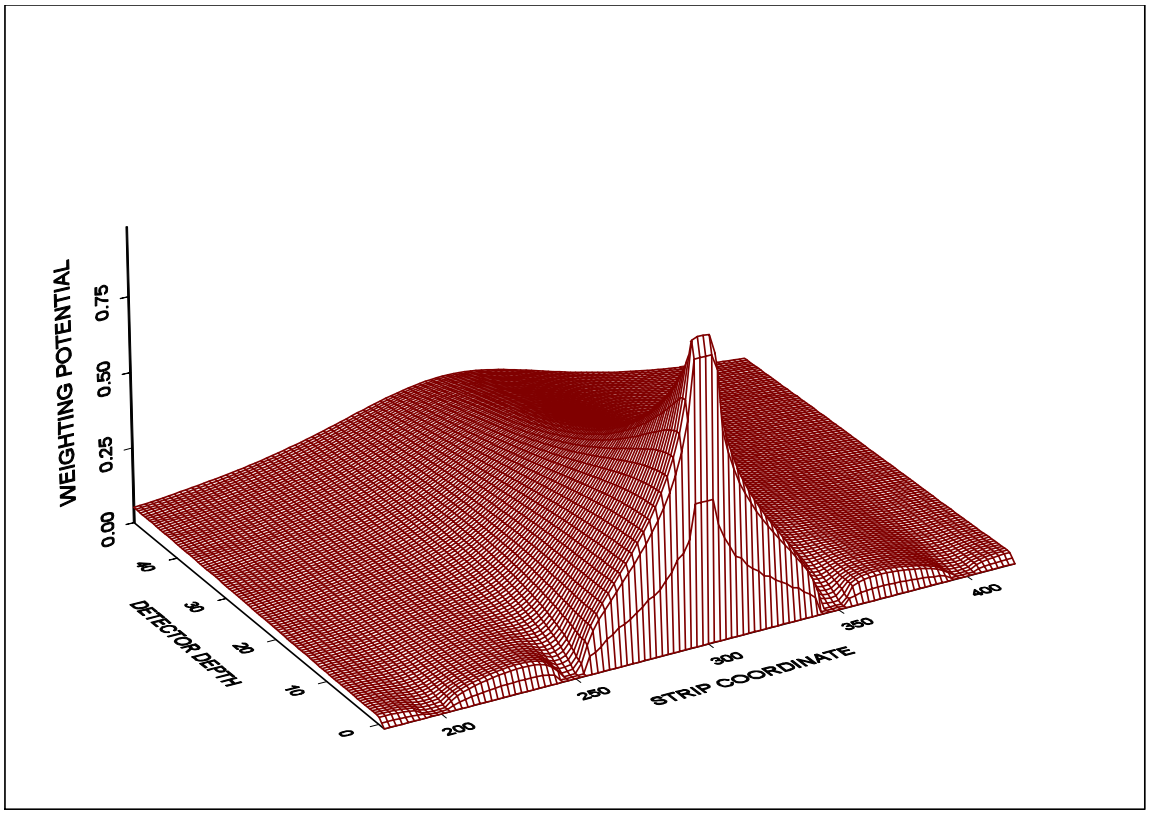
Example 2: Double-Sided Strip Detector

The strip pitch is assumed to be small compared to the thickness.

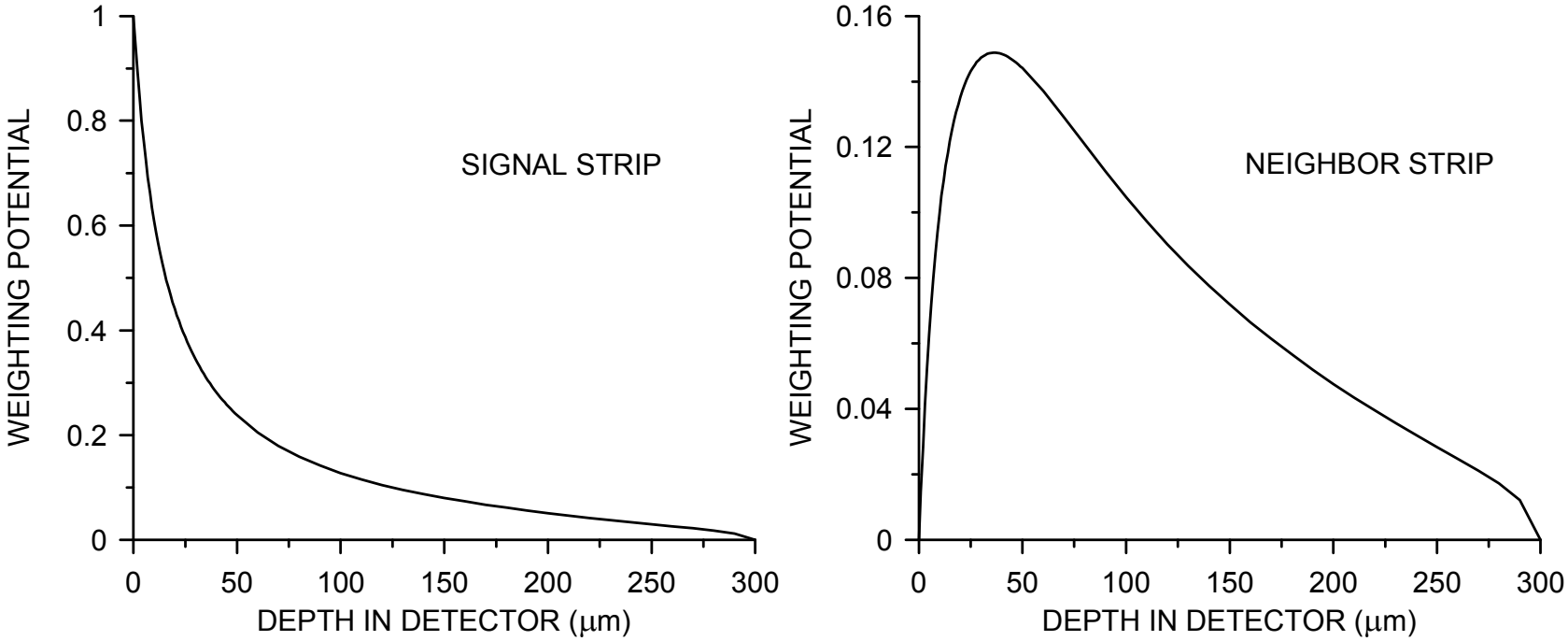
The electric field is similar to a parallel-plate geometry, except in the immediate vicinity of the strips.

The signal weighting potential, however is very different.

Weighting potential for a 300 μm thick strip detector with strips on a pitch of 50 μm. Only 50 μm of depth are shown.



Cuts through the weighting potential



Consider an electron-hole pair q_n, q_p originating on a point x_0 on the center-line of two opposite strips of a double-sided strip detector. The motion of the electron towards the n-electrode x_n is equivalent to the motion of a hole in the opposite direction to the p-electrode x_p. The total induced charge on electrode k after the charges have traversed the detector is

$$Q_k = q_p[\Phi_{Qk}(x_p) - \Phi_{Qk}(x_0)] + q_n[\Phi_{Qk}(x_n) - \Phi_{Qk}(x_0)]$$

since the hole charge $q_p = q_e$ and $q_n = -q_e$

$$Q_k = q_e[\Phi_{Qk}(x_p) - \Phi_{Qk}(x_0)] - q_e[\Phi_{Qk}(x_n) - \Phi_{Qk}(x_0)]$$
$$Q_k = q_e[\Phi_{Qk}(x_p) - \Phi_{Qk}(x_n)]$$

If the signal is measured on the p-electrode, collecting the holes,

$$\Phi_{qk}(x_p) = 1$$
$$\Phi_{qk}(x_n) = 0$$

and $Q_k = q_e$.

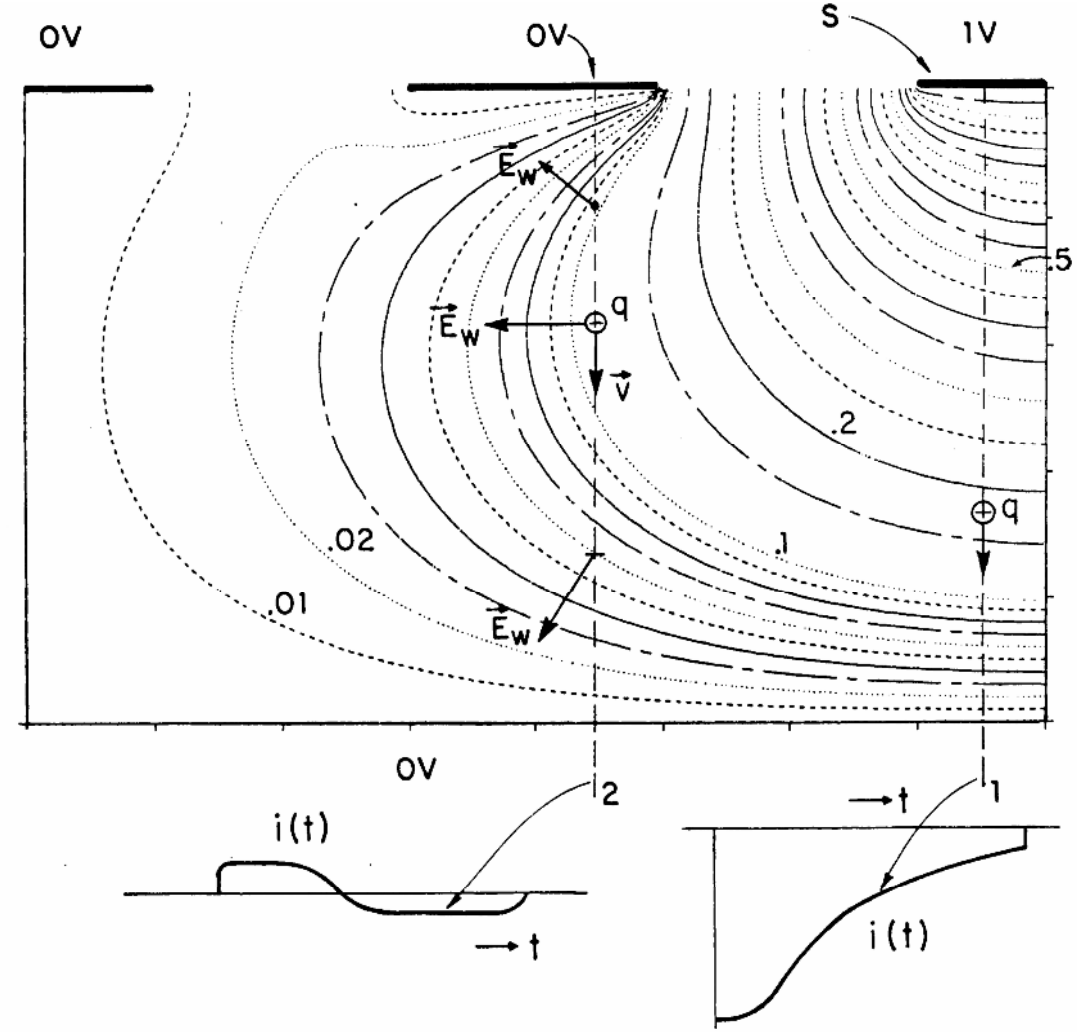
If, however, the charge is collected on the neighboring strip $k+1$, then

$$\Phi_{Q(k+1)}(x_n) = 0$$
$$\Phi_{Q(k+1)}(x_p) = 0$$

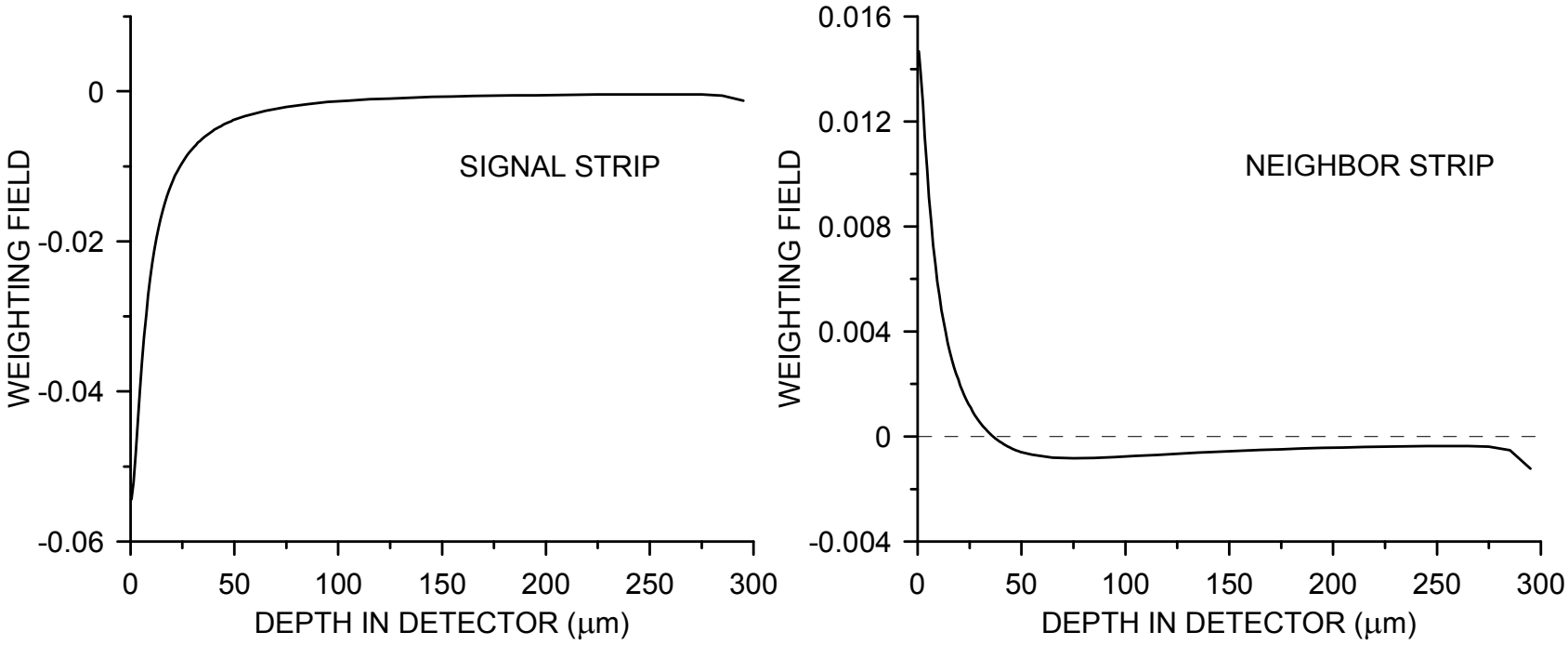
and $Q_{k+1} = 0$.

In general, if moving charge does not terminate on the measurement electrode, signal current will be induced, but the current changes sign and integrates to zero.

This is illustrated in the following schematic plot of the weighting field in a strip detector (from Radeka)



Cuts through the Weighting Field in a Strip Detector
(d= 300 μm, p= 50 μm)



Note, however, that this charge cancellation on “non-collecting” electrodes relies on the motion of both electrons and holes.

Assume, for example, that the holes are stationary, so they don't induce a signal. Then the first term of the first equation above vanishes, which leaves a residual charge

$$Q_k = q_e[\Phi_{Qk}(x_0) - \Phi_{Qk}(x_n)]$$

since for any coordinate not on an electrode

$$Q_k(x_0) \neq 0$$

although it may be very small.

An important consequence of this analysis is that one cannot simply derive pulse shapes by analogy with a detector with contiguous electrodes (i.e. a parallel plate detector of the same overall dimensions as a strip detector). Specifically,

1. the shape of the current pulses can be quite different,

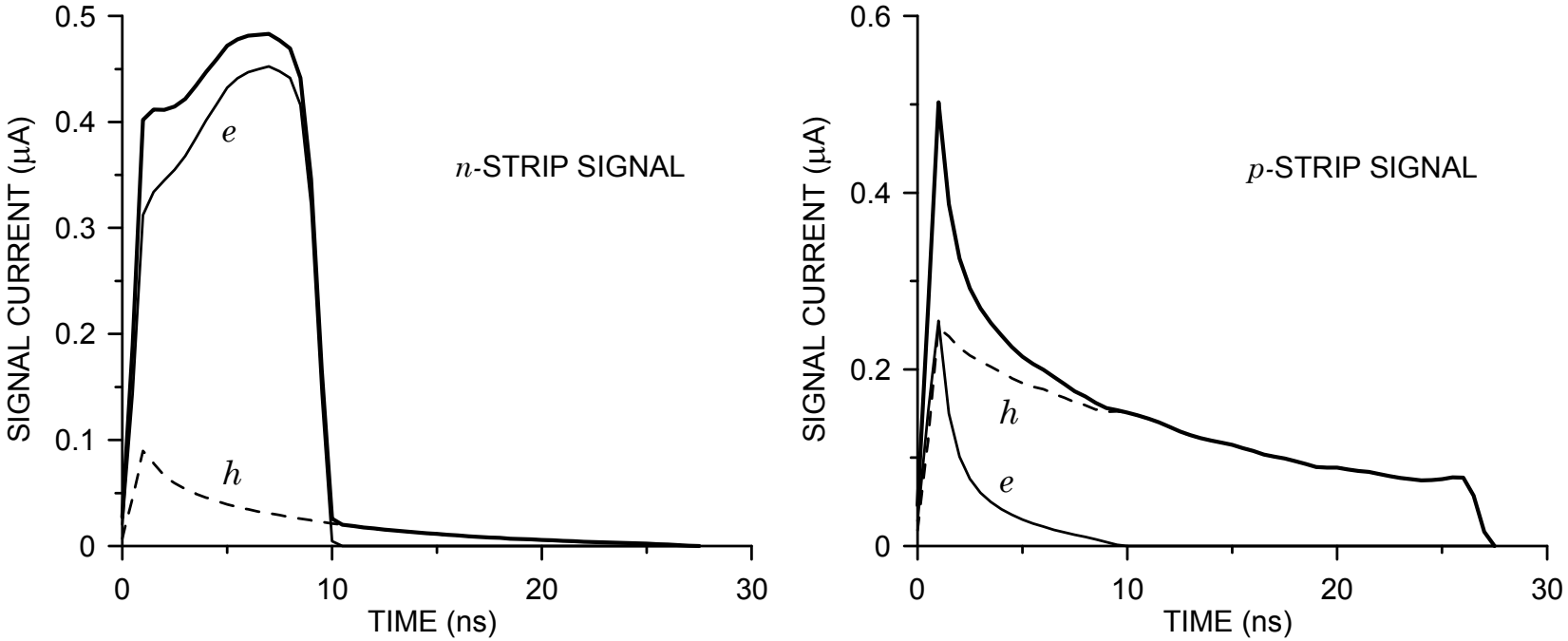
2. the signals seen on opposite strips of a double-sided detector are not the same (although opposite in sign), and

3. the net induced charge on the p- or n-side is not split evenly between electrons and holes.

   - Because the weighting potential is strongly peaked near the signal electrode, most of the charge is induced when the moving charge is near the signal electrode.

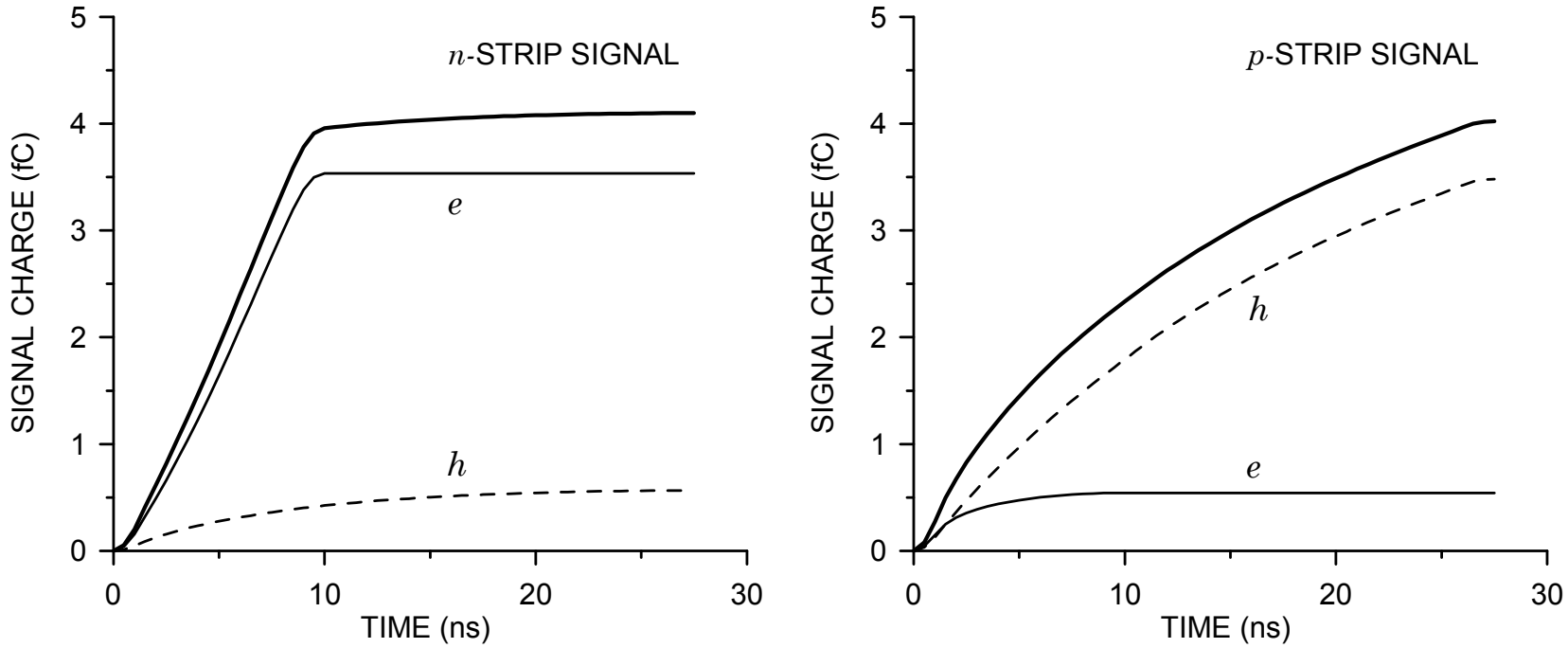
   - As a result, most of the signal charge is due to the charge terminating on the signal electrode.

Current pulses in strip detectors (track traversing the detector)



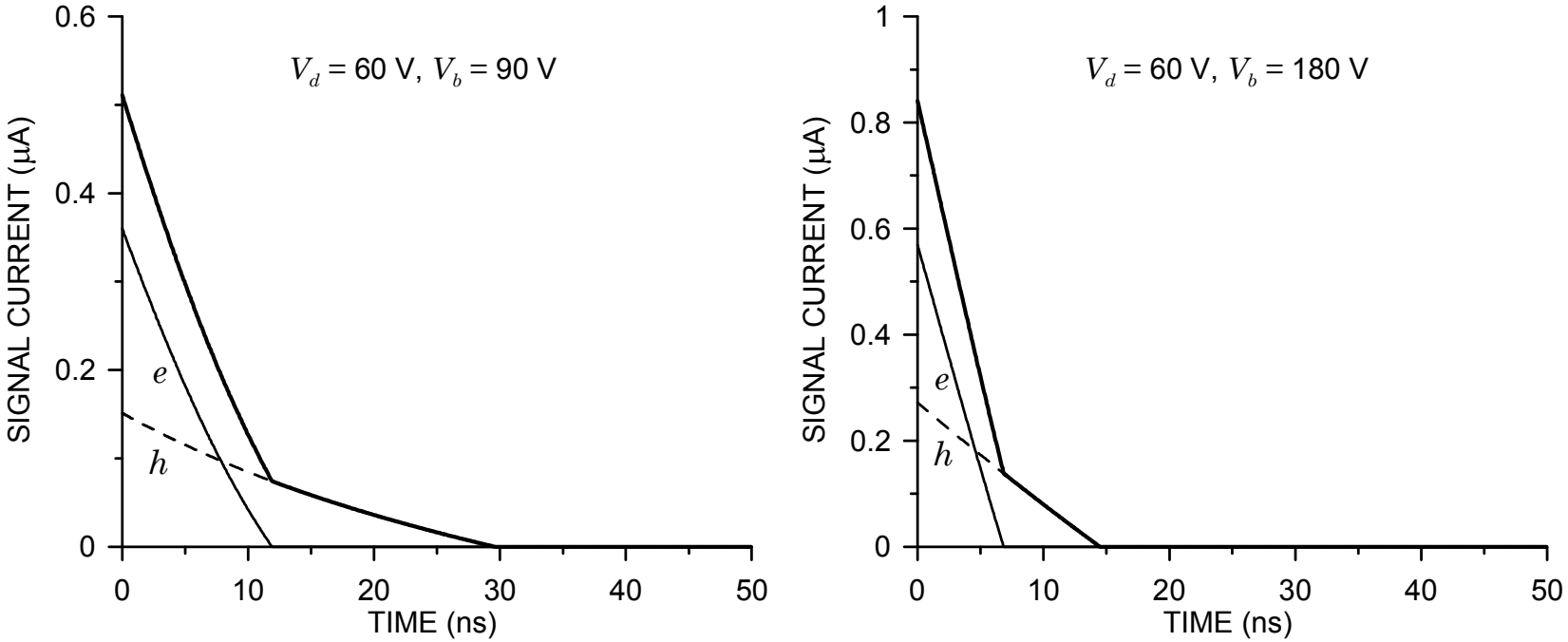
The duration of the electron and hole pulses is determined by the time required to traverse the detector as in a parallel-plate detector, but the shapes are very different.

Strip Detector Signal Charge Pulses



For comparison:

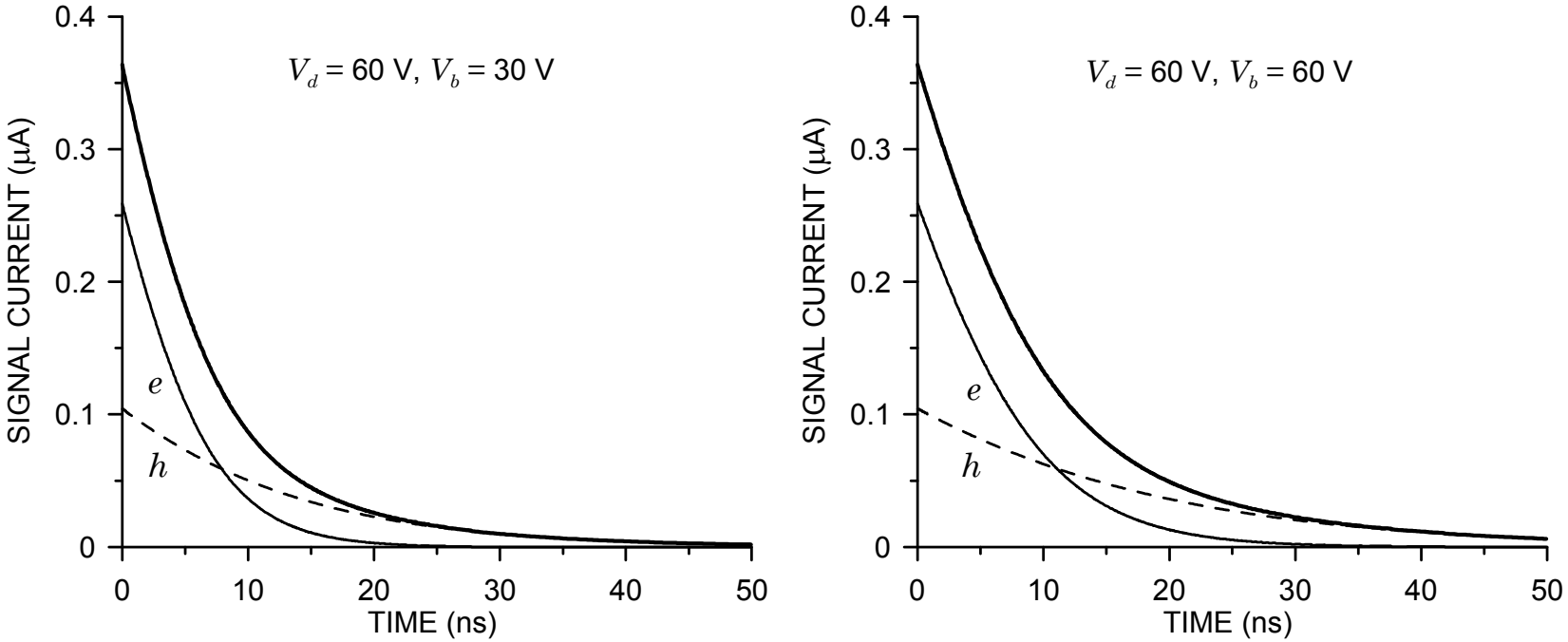
Current pulses in pad detectors (track traversing the detector)



For the same depletion and bias voltages the pulse durations are the same as in strip detectors, although the shapes are very different.

Overbias decreases the collection time.

Operation at or below full depletion leads to long “tails” from the low-field region.



Charge Collection in the Presence of Trapping

Practical semiconductor crystals suffer from imperfections introduced during crystal growth, during device fabrication, or by radiation damage.

Defects in the crystal

- impurity atoms
- vacancies
- structural irregularities (e.g. dislocations)
- radiation damage

introduce states into the crystal that can trap charge.

Charge trapping is characterized by a carrier lifetime τ, the time a charge carrier can "survive" in a crystal before trapping or recombination with a hole.

Trapping removes mobile charge available for signal formation.

Depending on the nature of the trap, thermal excitation or the externally applied field can release the carrier from the trap, leading to delayed charge collection.

Given a lifetime τ, a packet of charge Q_0 will decay with time: $Q(t) = Q_0 e^{-t/\tau}$

In an electric field the charge will drift. The time required to traverse a distance x is

$$t = \frac{x}{v} = \frac{x}{\mu E},$$

after which the remaining charge is

$$Q(x) = Q_0 e^{-x/\mu E\tau} \equiv Q_0 e^{-x/L}.$$

Since the drift length $L \equiv \mu\tau E$ is proportional to the mobility-lifetime product, $\mu\tau$ is often used as a figure of merit.

Assume a detector with a simple parallel-plate geometry. For a charge traversing the increment dx of the detector thickness d, the induced signal charge is

$$dQ_s = Q(x)\frac{dx}{d},$$

so the total induced charge

$$Q_s = \frac{1}{d}\int_0^d Q(x)dx = \frac{1}{d}\int_0^d Q_0 e^{-x/L}dx$$

$$Q_s = Q_0 \ \frac{L}{d} \ \left(1 - e^{-d/L}\right)$$

The magnitude of the recovered signal depends on the drift length relative to the width of the sensor's sensitive region.

$$d \gg L: \qquad \frac{Q_s}{Q_0} \approx \frac{L}{d}$$

$$d = 3L: \qquad \frac{Q_s}{Q_0} = 0.95$$

In high quality silicon detectors: $\tau \approx$ 10 ms

$\mu_e =$ 1350 V/cm·s^2

$E =$ 10^4 V/cm $\Rightarrow$ $L \approx$ 10^4 cm

In amorphous silicon $L \approx$ 10 μm (short lifetime, low mobility).

In diamond, however, $L \approx$ 100 – 200 μm (despite high mobility).

In CdZnTe at 1 kV/cm, $L \approx$ 3 cm for electrons, 0.1 cm for holes

Carrier lifetime also important for efficiency of solar cells!

Semiconductor Materials

Material	E_g (eV)	E_i (eV)	ε	μ_e	μ_h	$(\mu\tau)_e$	$(\mu\tau)_h$	ρ	$\langle Z \rangle$
Si	1.12	3.6	11.7	1350	450	>1	>1	2.33	14
Ge	0.67	2.96	16	3900	1900	>1	>1	5.33	32
GaAs	1.43	4.2	12.8	8000	400	$8 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	5.32	31.5
Diamond	5.5	13	5.7	1800	1200	*	*	3.52	6
4H-SiC	3.26	8	9.7	1000	115	$4 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	3.21	10
GaN	3.39	8 – 10		1000	30			6.15	19
InP	1.35	4.2	12.4	4600	150	$5 \cdot 10^{-6}$	$<10^{-5}$	4.78	32
CdTe	1.44	4.43	10.9	1100	100	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	5.85	50
$Cd_{0.9}Zn_{0.1}Te$	1.572	4.64	10	1000	120	$4 \cdot 10^{-3}$	$1.2 \cdot 10^{-4}$	5.78	49.1
HgI2	2.15	4.2	8.8	100	4	$3 \cdot 10^{-4}$	$4 \cdot 10^{-5}$	6.4	62
TlBr	2.68	6.5	30	30	4	$5 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	7.56	58
a-Si	1.9	6	12	1 – 4	0.05	$2 \cdot 10^{-7}$	$3 \cdot 10^{-8}$	2.3	14

* In diamond the maximum drift length is typically specified. Typically grown by thin-film deposition, material quality depends on the growth rate, with 200 μm drift length obtained for optimal growth.

Si and Ge provide the best overall properties for precision spectroscopy.

Higher Z materials would provide higher absorption, but typically suffer from limited carrier lifetime.

Currently, CdZnTe provides the best performance of the compound semiconductors, but spectral quality is still inferior to Ge.

In HEP tracking detectors the power dissipation in the front-end electronics is an important consideration.

The magnitude of the signal increases with decreasing ionization energy E_i ($\propto$bandgap).

The signal-to-noise ratio improves with reduced capacitance, i.e. dielectric constant ε.

$\Rightarrow$ materials with small εE_i could be advantageous.

Other consideration at high luminosity colliders: radiation damage

Currently, Si is still the material of choice.

Photodiodes

Although photomultiplier tubes still dominate in scintillation detectors, silicon photodiodes are also widely used.

Scintillator light:
$\lambda =$ 200 – 500 nm
($E =$ 6.2 – 2.5 eV)

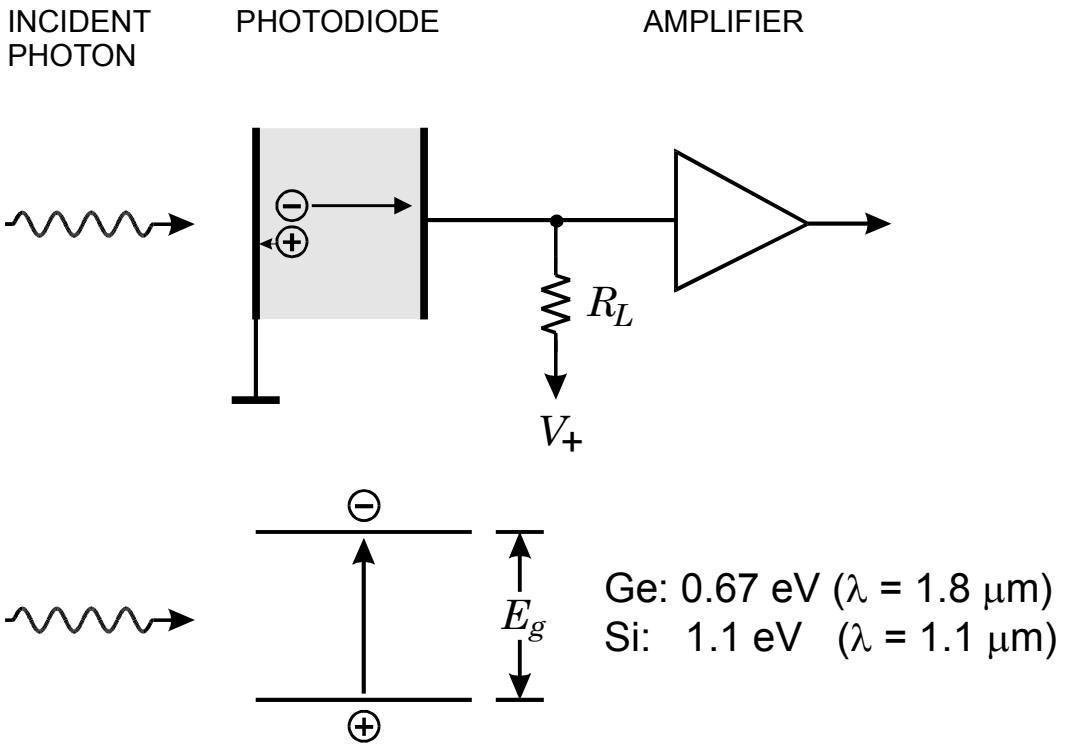
Si photodiodes offer

a) high quantum efficiency
(70 - 90% instead of
10 – 30% for PMTs)

b) insensitivity to magnetic fields

c) small size

d) low bias voltage



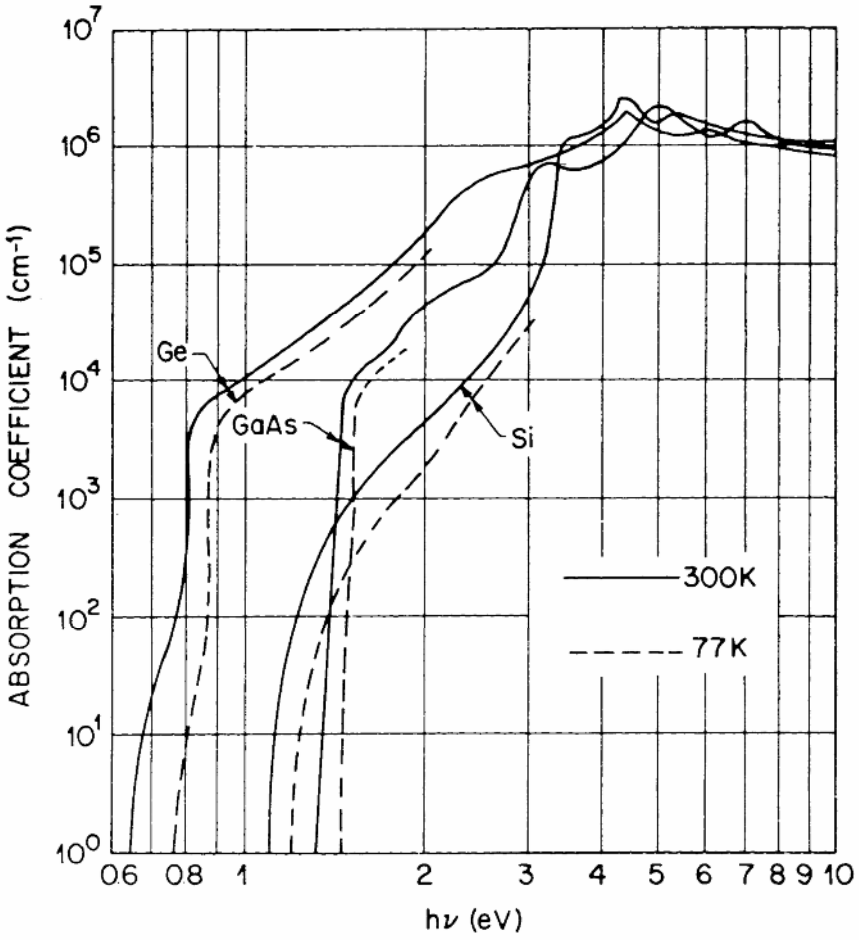
All semiconductor diodes are light sensitive.

For high quantum efficiency they must be designed to avoid significant dead layers at the surface, as most of the photons in the visible range are absorbed within about 1 μm of the surface.

The number of absorbed photons

$$N_{abs} = N_0 \int e^{-\mu x} dx$$

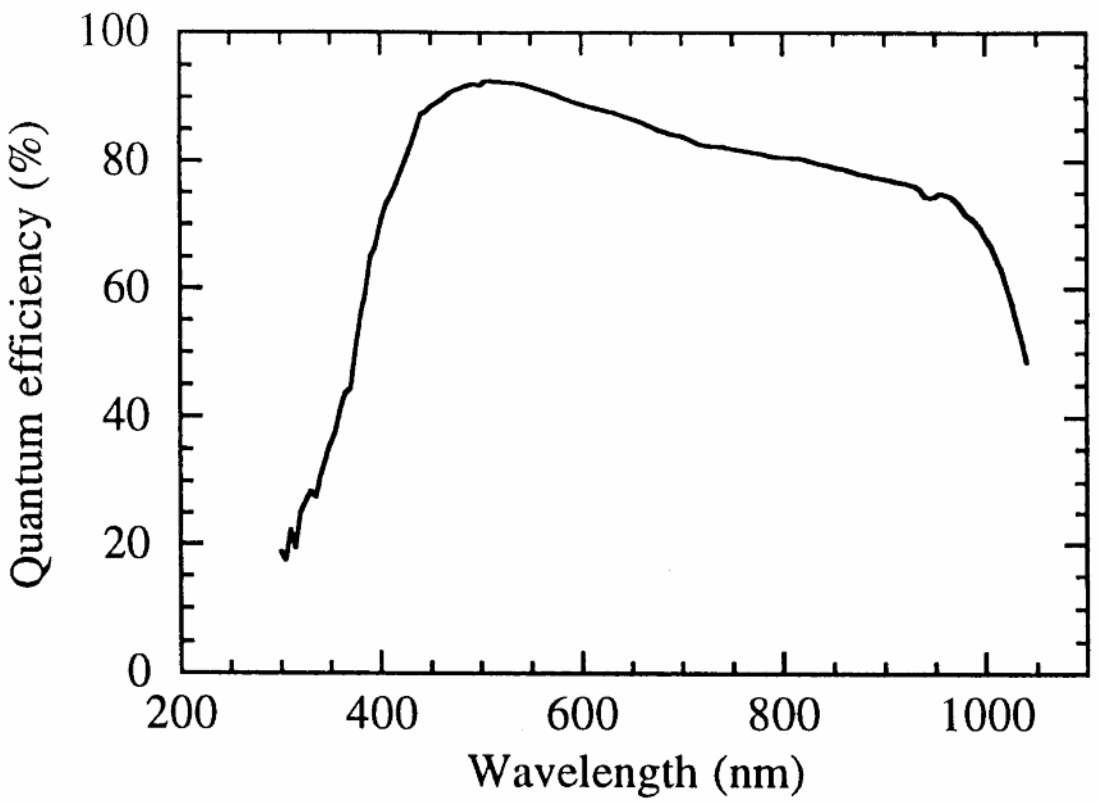
If the absorption coeficient $\mu = 10^4$ cm^{-1}, dead layers must be < 100 nm to avoid significant losses (<10%).



Quantum efficiency of well-designed photodiodes is 2 – 3 times better than of PMTs.

Measured data of photodiodes fabricated in LBNL Microsystems Lab
(N. Wang + S. Holland)

Used in high-resolution PET scanner,



However, for visible light photodiodes yield only one electron-hole pair per incident photon, so signals are small.

Photomultiplier tubes provide high gain without introducing significant electronic noise, whereas photodiode systems depend critically on low noise electronics.

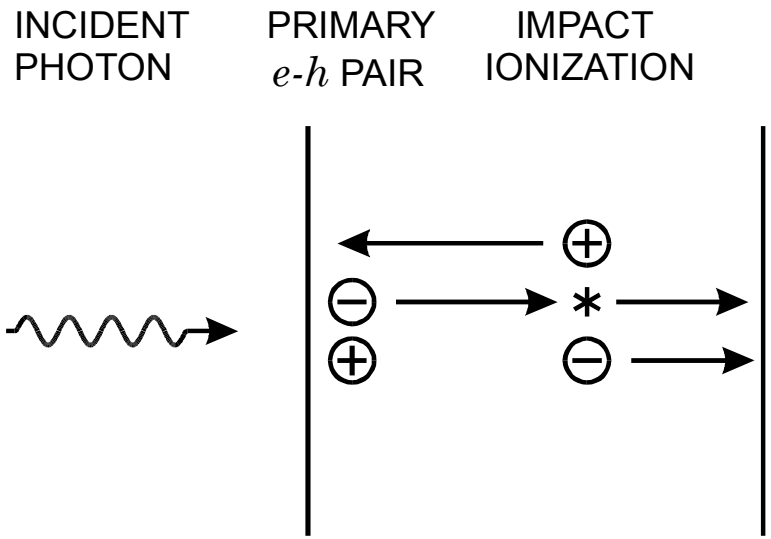
Unlike PMT systems, photodiode readouts must be very carefully optimized.

$\Rightarrow$ Reduce demands on electronics by developing photodiodes with internal gain,

- avalanche photodiodes (APDs).

Principle of an Avalanche Photodiode

An electron-hole pair is created at the left-most electrode by incident light.



Under the influence of the electric field the electron drifts towards the right, gaining sufficient energy for ionization, i.e. formation of an additional electron-hole pair.

The gain of this process

$$G_n = e^{\alpha_n d}$$

where the electron ionization coefficient

$$\alpha_n = \alpha_{n0} \exp(-E_n / E)$$

is a function of the electric field E. The parameters α_{n0} and E_n are material constants.

The ionization coefficient is also strongly temperature dependent.

The secondary hole can also ionize and form additional electron-hole pairs.

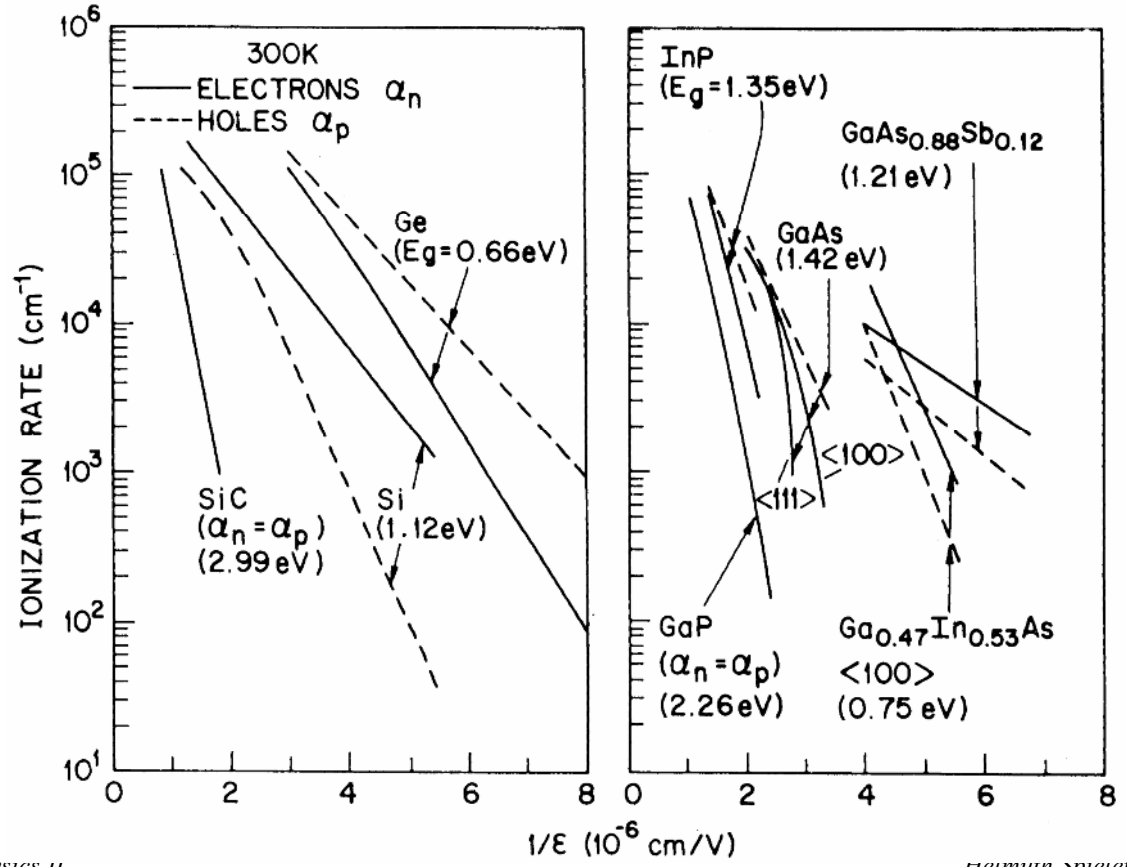
This is a positive feedback process, i.e. when the partial gain due to holes

$$G_p \geq 2$$

the combined multiplication of electrons and holes leads to a sustained avalanche, i.e. breakdown.

Since the hole mobility is less than the electron mobility, higher fields are required than for same electron ionization.

In silicon the ratio of electron to hole ionization coefficients is field dependent, so the sensitivity to breakdown is reduced at low fields.



The ratio of electron to hole ionization coefficients is an exponential function of field:

$$\frac{\alpha_n}{\alpha_p} = 0.15 \cdot \exp\left(\frac{1.15 \cdot 10^6}{E}\right)$$

This leads to the following limits of gain and detector thickness vs. electric field

$E = 2 \cdot 10^5$ V/cm	$G_n = 2.2 \cdot 10^3$	$d = 520$ μm	$V_b = 10$ kV
$E = 3 \cdot 10^5$ V/cm	$G_n = 50$	$d = 5$ μm	$V_b = 150$ V
$E = 4 \cdot 10^5$ V/cm	$G_n = 6.5$	$d = 0.5$ μm	$V_b = 20$ V
$E = 5 \cdot 10^5$ V/cm	$G_n = 2.8$	$d = 0.1$ μm	$V_b = 5$ V

To achieve gains in the range 100 – 1000 requires

- a depletion region of several hundred microns thick
- bias voltages in the range 500 – 1000 V
- excellent control of the field distribution
  provide stable operation without local breakdown
  reduce avalanche noise

Many different device structures have been used for APDs, but the optimum structure is the "reach-through" APD.

Lightly doped p-type material is used for the bulk.

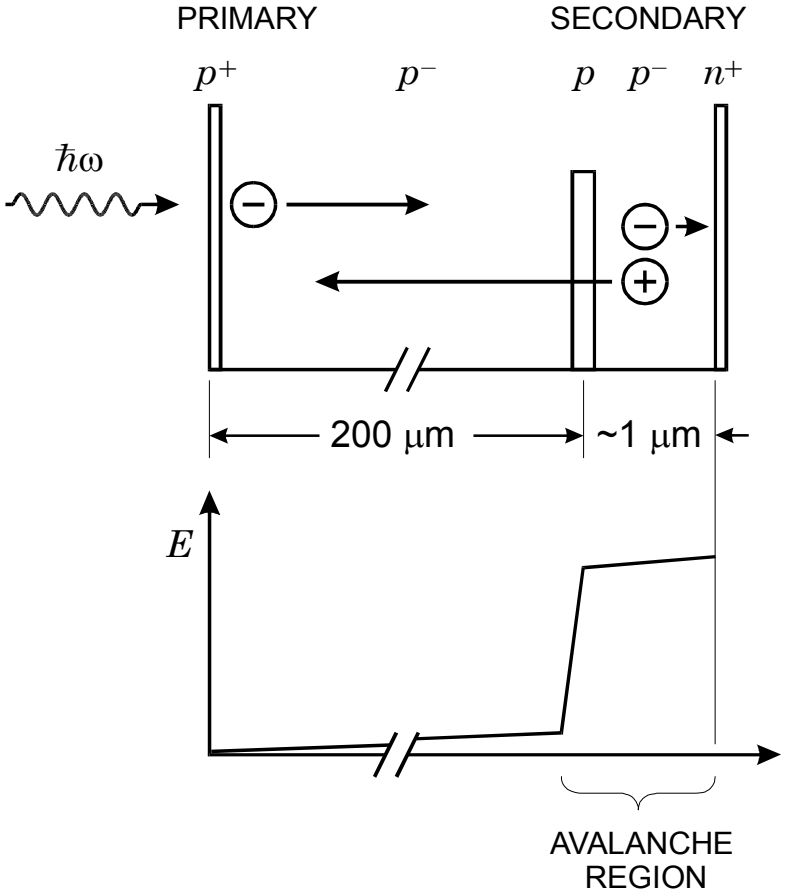
A local high-field region is created by introducing an intermediate p-layer through deep diffusion.

When a depletion voltage is applied, the diode depletes from the right-hand side. Initially the depletion region progresses with voltage until the intermediate p-layer is reached. Since this layer is more highly doped, the voltage required to deplete the intermediate layer is rather high.
As a result, a high field is set up in the region between the junction and the p-layer.

Depletion beyond the p-layer requires less voltage, due to low doping.

Photons impinge on the left surface. Electrons drift towards the high field region, where they avalanche.

Secondary holes drift through the low-field region, contributing most of the induced signal



The advantage of this structure is that the primary holes remain in the low-field region. Secondary holes drift into the low-field region, thus reducing the hole partial gain and the risk of breakdown.

Silicon Photomultipliers (SiPM)

At high gains APDs go into a sustained avalanche mode.

This can be triggered by an incident photon. Typical gain ~10^6.

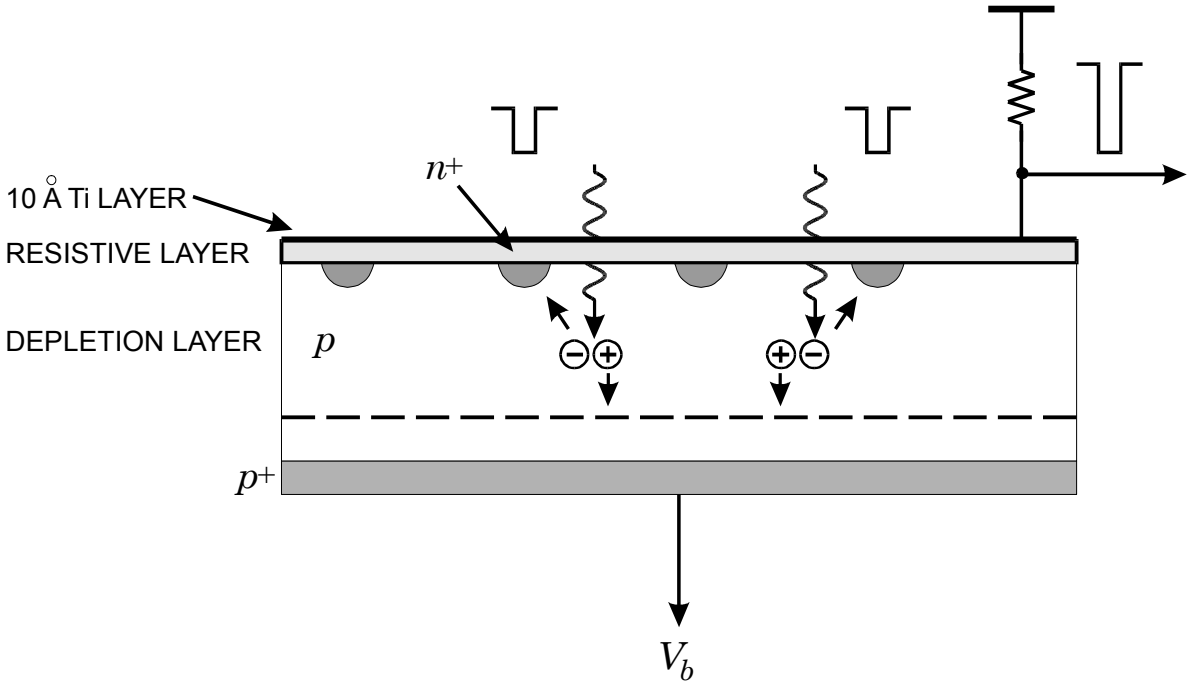
If the current and time duration of the sustained avalanche are limited, the diode does not suffer damage.

Inserting a sufficiently resistance into the bias “quenches” the avalanche, as the momentary high current increases the voltage drop and reduces the diode bias to a stable level (analogous to Geiger mode).

This yields a short current pulse of uniform magnitude for each incident photon.

However, all intensity information of the incident scintillation light is lost.

The silicon photomultiplier subdivides the APD into many small pixels (~50 μm), so that individual pixels are struck by only one scintillation photon.



Summing the current pulses from all pixels ⇒ signal proportional to the number of photons.

Advantage: single photon sensitivity, fast response (~100 ns)
Downside: electrons due to diode reverse bias current initiate avalanches, so dark current rates are ~10^5 s^{-1}.

In experiments with external triggers or coincidence conditions the dark counts can be suppressed.