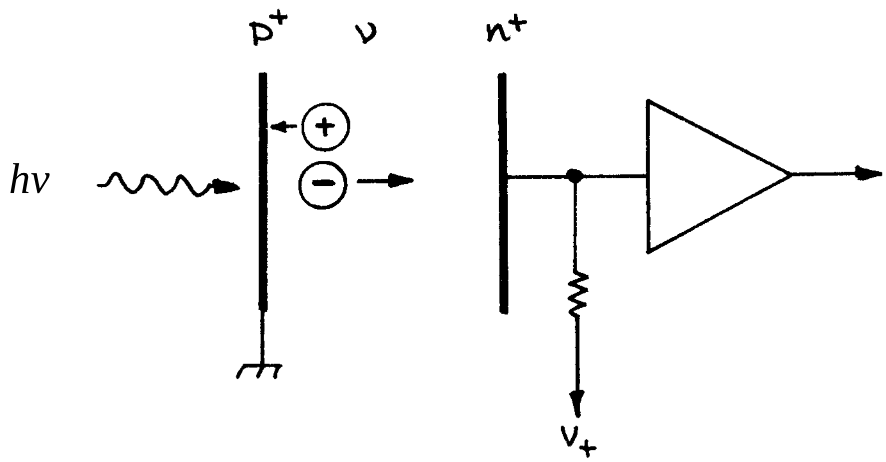
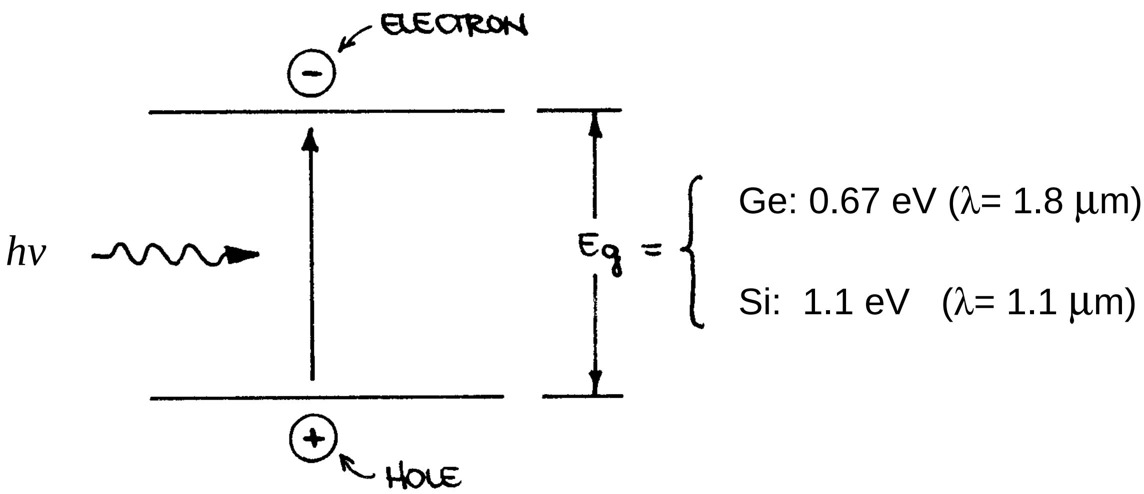
XI. Photodiodes

Although photomultiplier tubes still dominate in scintillation detectors, silicon photodiodes are becoming increasingly popular.





Scintillation light: λ = 200 – 500 nm (E = 6.2 – 2.5 eV)

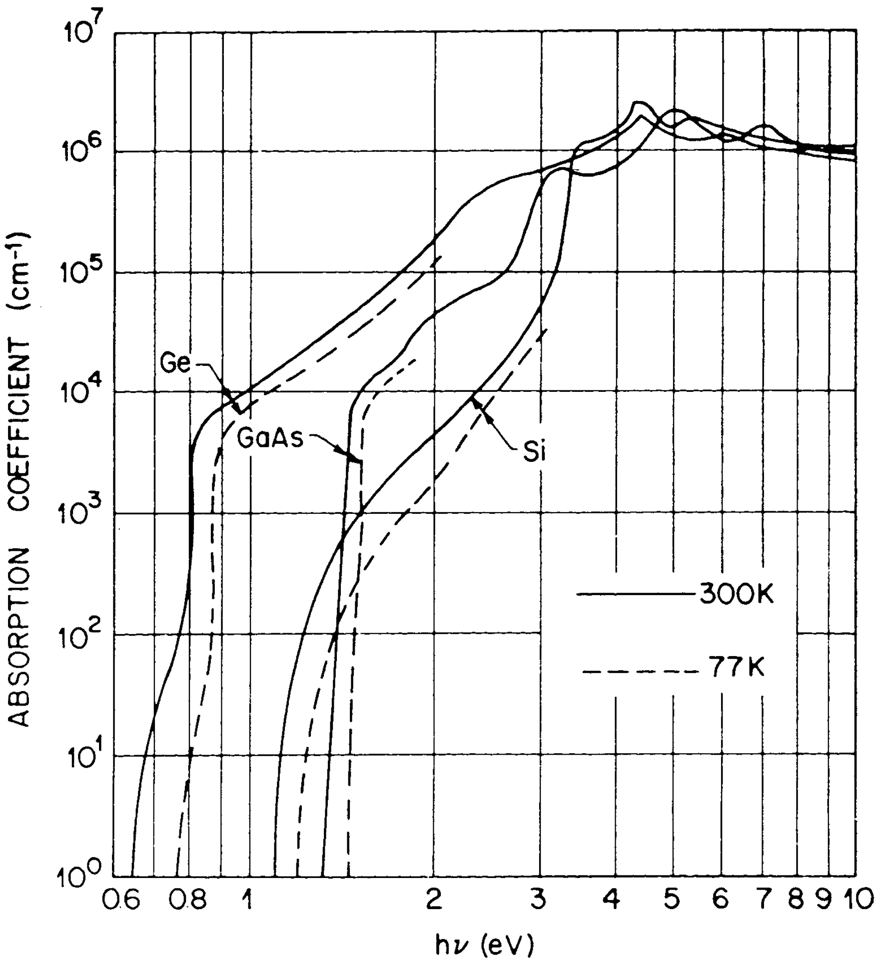
Semiconductor photodiodes offer

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

b) insensitivity to magnetic fields

c) small size

Although 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.



(from Sze)

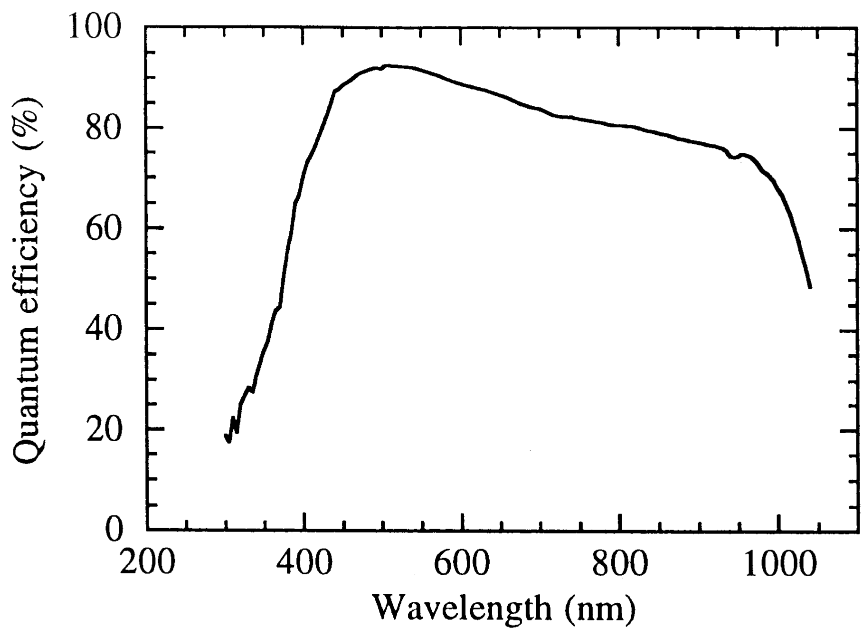
The number of absorbed photons

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

If the absorption coeficient $\alpha = 10^4$ cm, dead layers must be < 0.1 μm 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 (used for medical imaging, N. Wang + S. Holland)



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

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

Example:

Photodiode coupled to a NaI(Tl) scintillator crystal.

PMT:

The photon yield for 511 keV gammas is about 15000 at the photocathode. The resolution obtained in a PMT system is about 2% rms, i.e. 10 keV.

For the photodiode assume a quantum efficiency of 80%, i.e. 80% of the incident scintillation photons create an electron-hole pair. The signal charge

$$Q_s = 0.8 \text{ x } 15000 \text{ el} = 12000 \text{ el}$$

If the photodiode is to replace a standard phototube, its diameter must be 2”, i.e. the area is 2000 mm^2.

If we use p-type Si with 10 kΩcm resistivity, a 1 mm thick diode requires a depletion voltage of 1000 V, which is possible.

The capacitance of a 1 mm thick diode with an area of 2000 mm^2 is about 200 pF.

Voltage Noise:

For an optimally matched input transistor and a shaping time of 1 μs the voltage noise would be about 60 el rms, or 210 eV.

Current Noise:

The reverse bias current of the photodiode, assuming 1 nA/cm^2, is 20 nA, leading to a noise contribution of 500 el, or 1.8 keV.

The problem with the above estimate is that FETs that capacitively match the photodiode are prohibitively large.

More realisitic is a device with a noise level of 0.5 nV/Hz$^{1/2}$, which yields a noise level of 720 el or 2.6 keV for the FET alone, which now dominates the noise level.

Together with the detector shot noise this yields a total noise of 3.2 keV.

In practice, the 1 mm thick diode is much more expensive than a PMT, so the photodiode will probably have about 1/3 the depletion thickness, which brings the noise level to about the same level as the PMT.

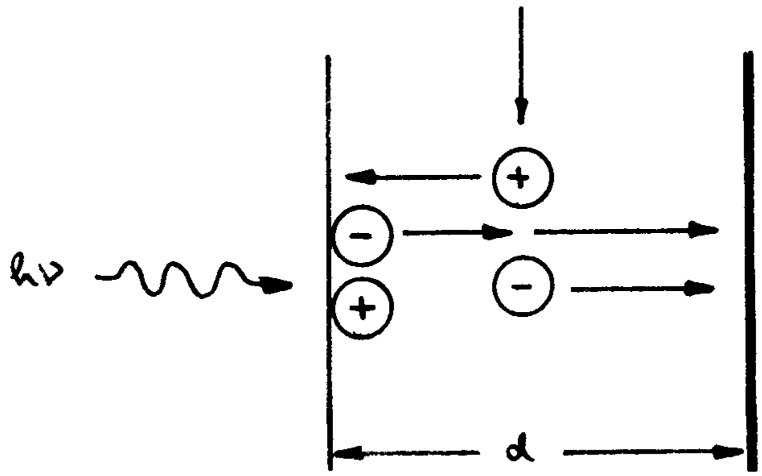
Unlike PMT systems, photodiode readouts must be very carefully optimized.

$\Rightarrow$ Reduce demands on electronics by developing photodiodes with internal gain, avalanche photodiodes (APDs).

Principle of an APD

Charge carriers are accelerated sufficiently to form additional electron-hole pairs.

Impact Ionization



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

$$\alpha_n = \alpha_{n0} e^{-E_n/|E|}$$

is a function of the electric field. 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. Since the hole mobility is less than the electron mobility, higher fields are required than for same electron ionization.

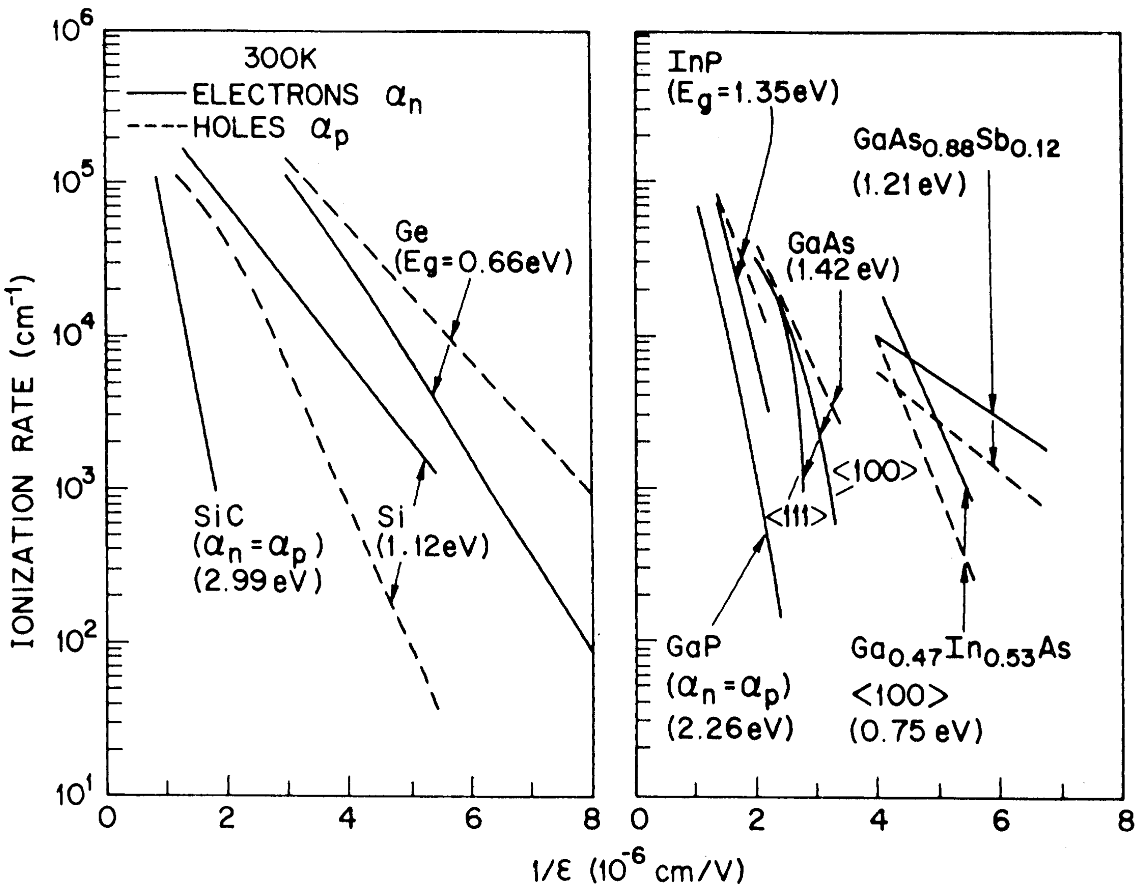
This is fortunate, since the formation of secondary holes is a positive feedback process, i.e. when the partial gain due to holes

$$G_p \geq 2$$

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

In silicon the ratio of electron to hole ionization coefficients is field dependent.

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



(from Sze)

This leads to the following combinations of electric field, achievable gain and detector thickness.

$E = 2\cdot 10^5$ 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

At high fields the gain is limited by the increase in ionization due to secondary holes (thickness is limited by the mean free path of holes).

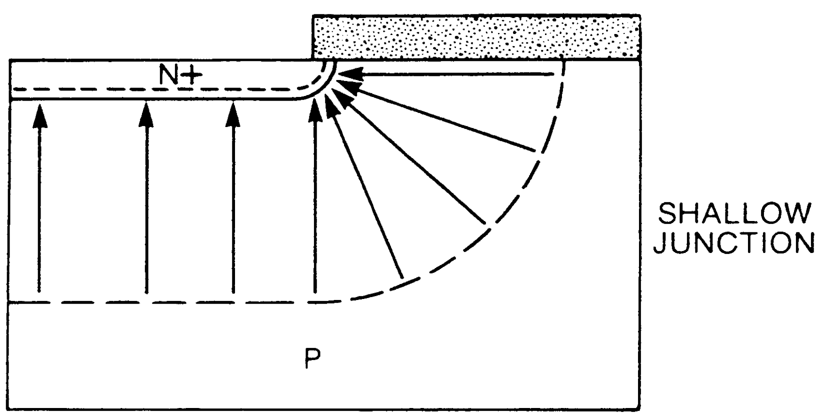
To achieve gains in the range 100 – 1000 requires

a depletion region that is several hundred microns thick

bias voltages in the range 500 – 1000 V

excellent control of the field distribution

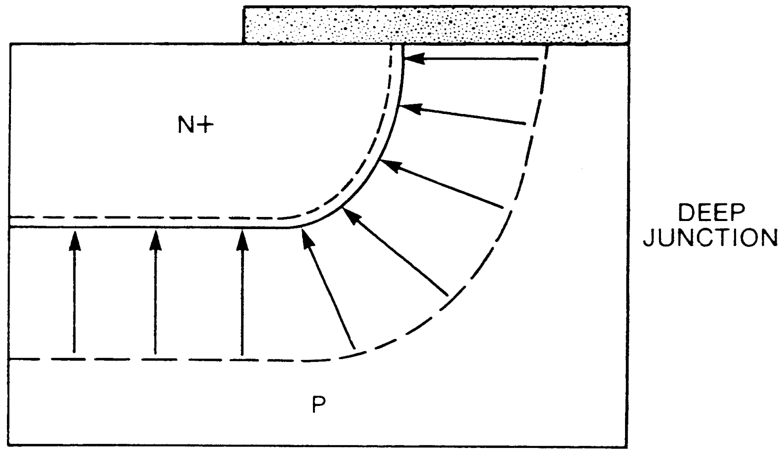
Operation at high voltages is limited by local high-field regions



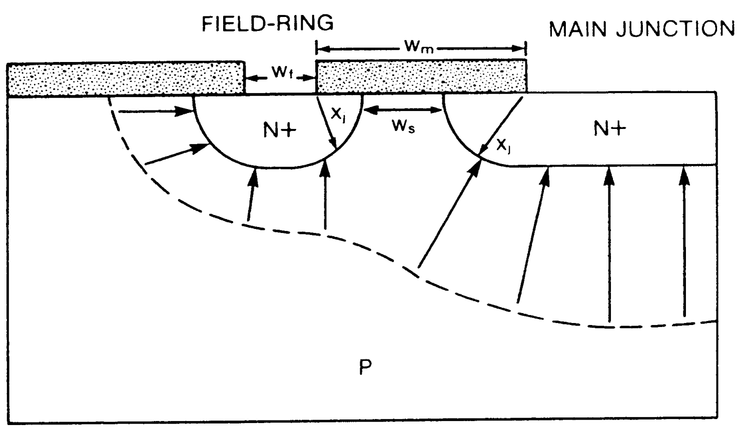
(from Baliga, Modern Power Devices)

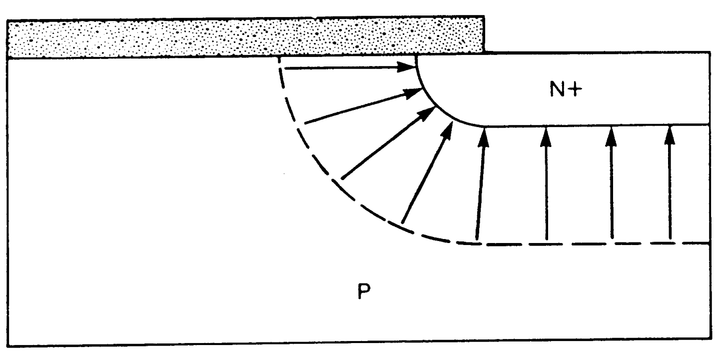
Breakdown will occur at the edge of the junction before the full operating field in the bulk is attained.

This problem can be alleviated by increasing the depth of the n^+ region, i.e. increasing the radius of curverture at the edge.



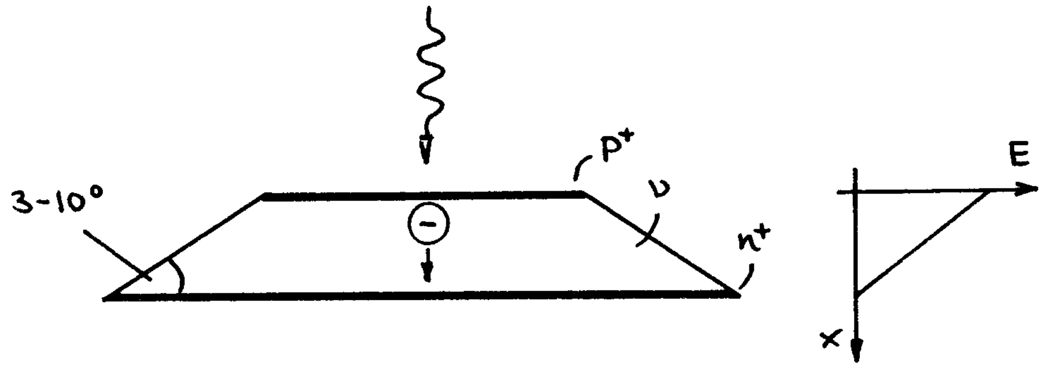
The field can also be reduced by adding a guard ring, which also reduces the field at the edge of the wafer.



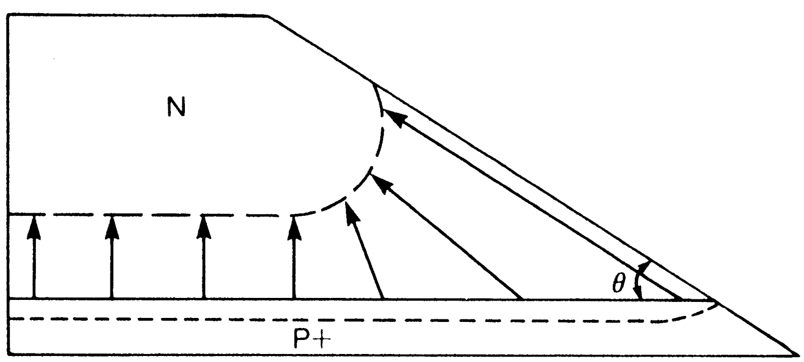


(from Baliga)

Another solution is the beveled diode:



The bevel reduces the field both at the junction edge and at the edge of the wafer.



(from Baliga)

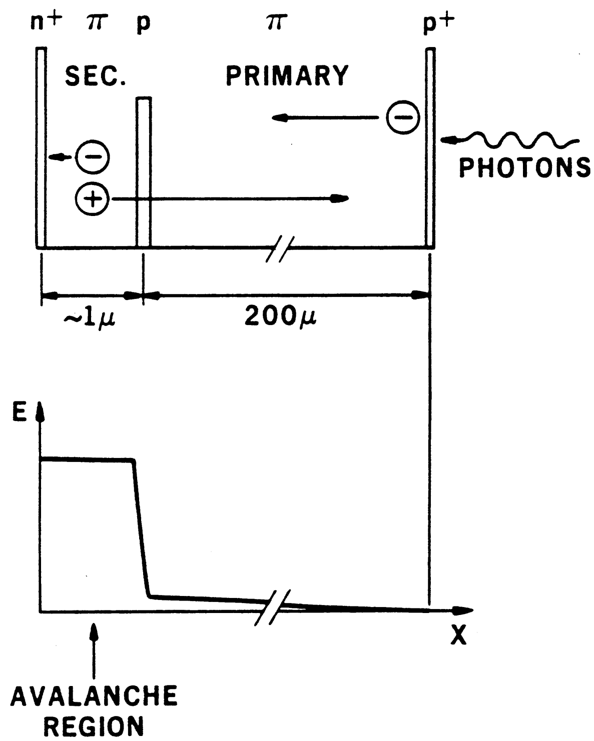
All of these structures require very uniform doping of the bulk material. Typical doping variations are 20% across the wafer.

Solution: neutron transmutation doping

$$^{30}\mathrm{Si}\,(n,\gamma)\,^{31}\mathrm{Si} \xrightarrow[\beta^-,\ 2.6\ \mathrm{h}]{} {^{31}\mathrm{P}} \qquad (n\text{-type dopant})$$

Note: $$^{31}\mathrm{P}\,(n,\gamma)\,^{32}\mathrm{P} \xrightarrow[\beta^-,\ 14.6\ \mathrm{d}]{} {^{32}\mathrm{S}} \qquad \text{(background)}$$

An alternative APD 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 internediate *p*-layer through deep diffusion.

> When a depletion voltage is applied, the diode depletes from the left 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 the low doping level.

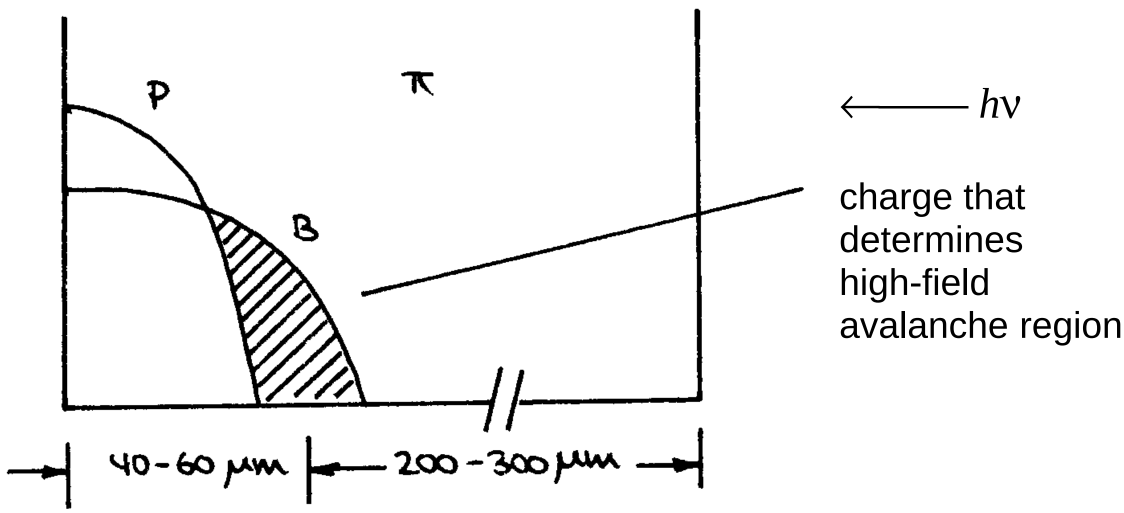
Photons impinge on the right surface. Electrons drift towards the high field region, where they avalanche.

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.

Furthermore, the secondary holes drift into the low-field region, thus reducing the hole partial gain and the risk of breakdown.

Common Implementation of Reach Through Structure



Lightly doped p-type material is doped with two deep diffusions to create a local high-field region.

The deep B diffusion introduces acceptors.

The overlapping P diffusion (shaded) forms a lightly doped p-region due to compensation (N_A - N_D) with a high field determined by the local p^+ doping.

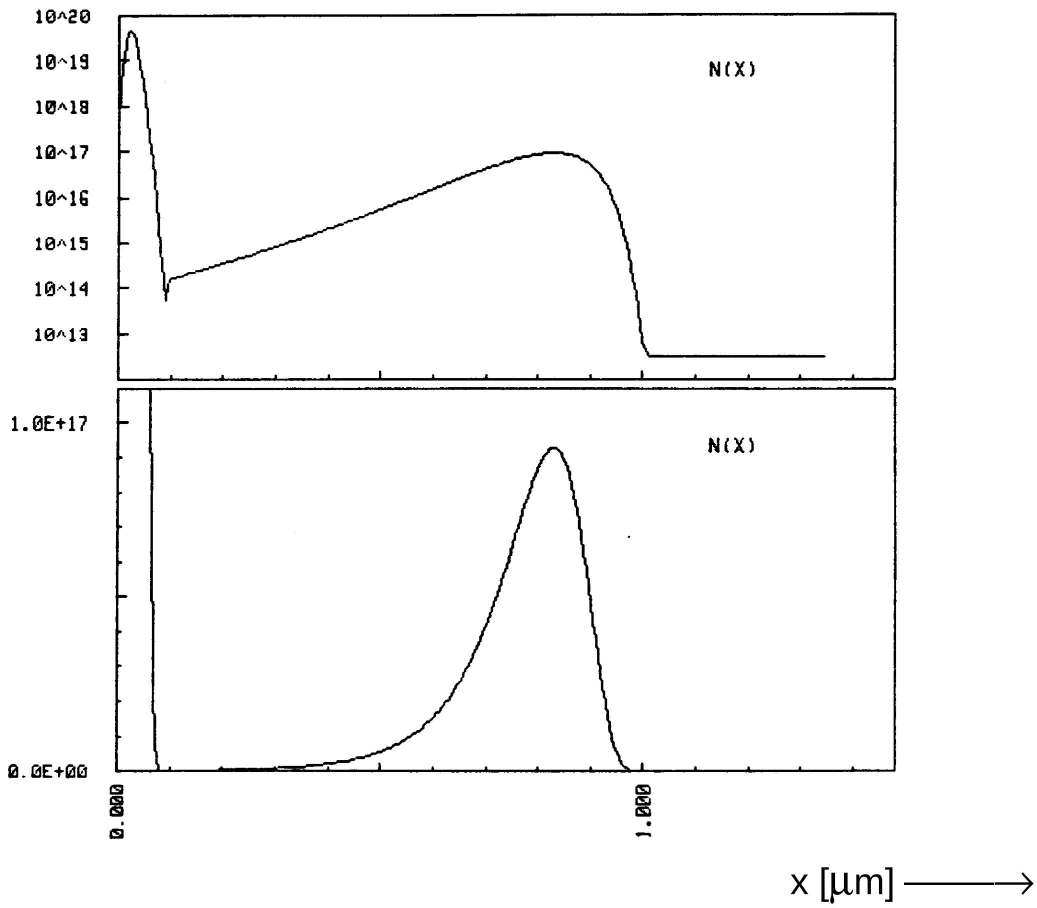
Problem: deep diffusions are difficult to control – low yield

Nevertheless, these devices are commercially available with gains of 10^3 to 10^6.

Often moderate gains (~10) are adequate.

A modified reach-through structure using shallower implants can be utilized. Again, the high field region is formed by two successive diffusions, but only about 1 µm, rather than 50 µm deep.

Dopant Concentration vs. Depth



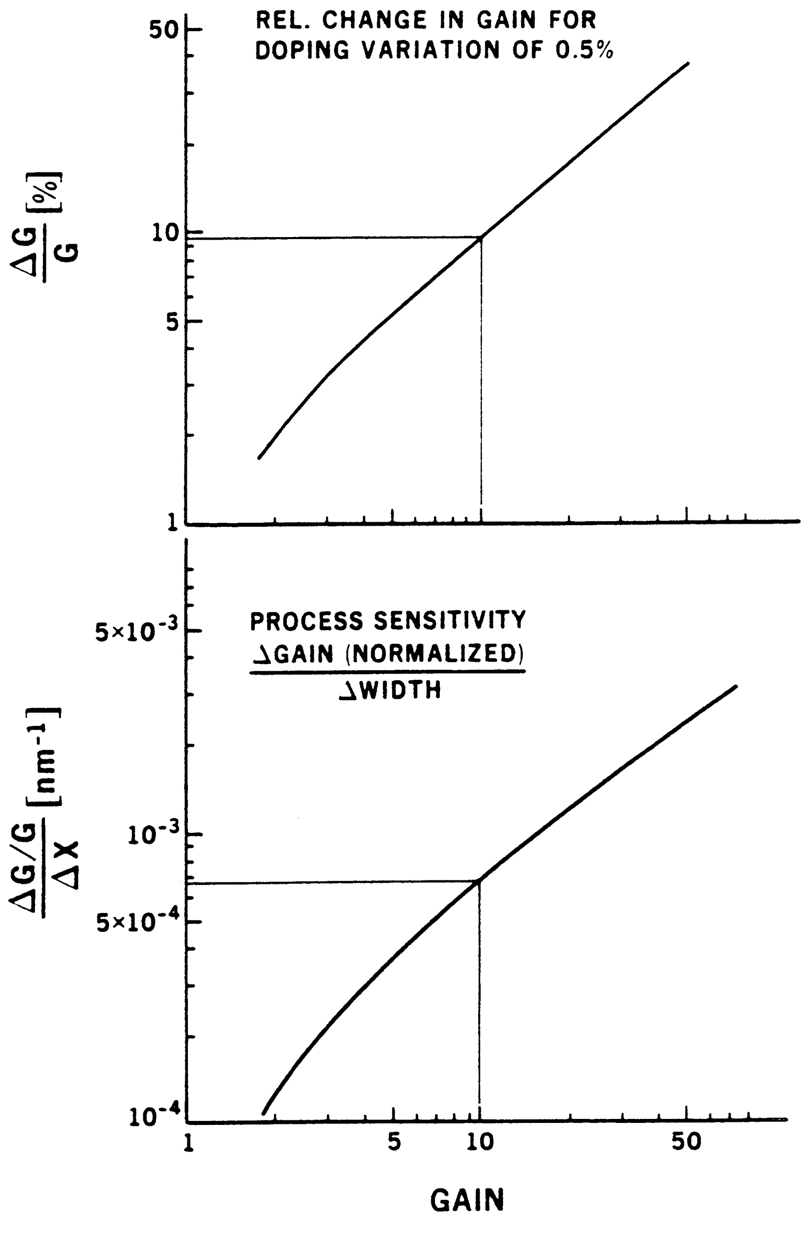
In the upper plot (log scale) the two dopants are clearly visible. The deeper diffusion is B, the shallow diffusion As.

The bottom plot shows the net dopant distribution on a linear scale, showing the lightly doped avalanche region.

Both dopants are introduced by ion-implantation and then diffused, making use of the higher diffusivity of B.

Gain Sensitivity for Realistic Implant Uniformity

The upper plot show the gain variation for a non-uniformity of the implanted ion dose over the diode area of 0.5%. For a gain of 10 the gain variation would be 10 %, increasing to 50% at a gain of 50.



The lower plot shows the variation in gain vs. variations in diffusion depth, e.g. due to material imperfections. Even if the depth of the B diffusion varies by 100 nm (0.1 µm), the gain only changes by 7%.