OPTI510R: Photonics

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Announcements

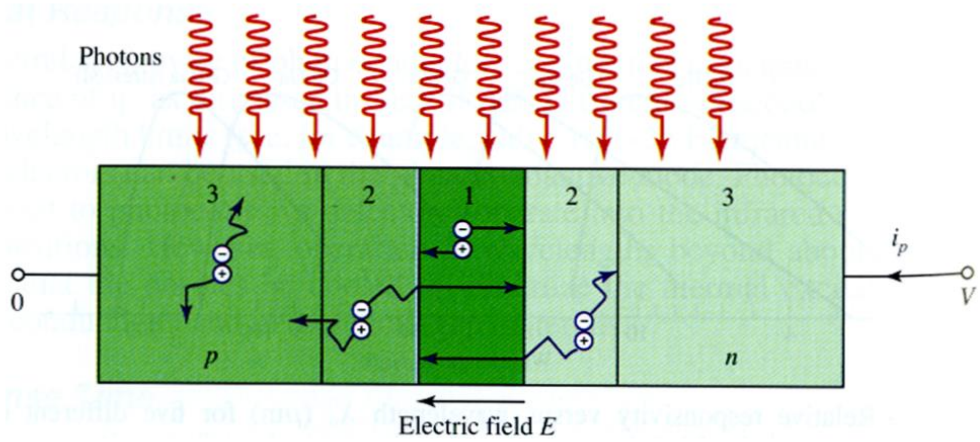
- HW #6 assigned, due April 22
- Final exam May 1

Photodetectors

- p-n photodiode
- Response time
- p-i-n photodiode
- APD photodiode
- Noise
- Wiring
- Arrayed detector (Home Reading)

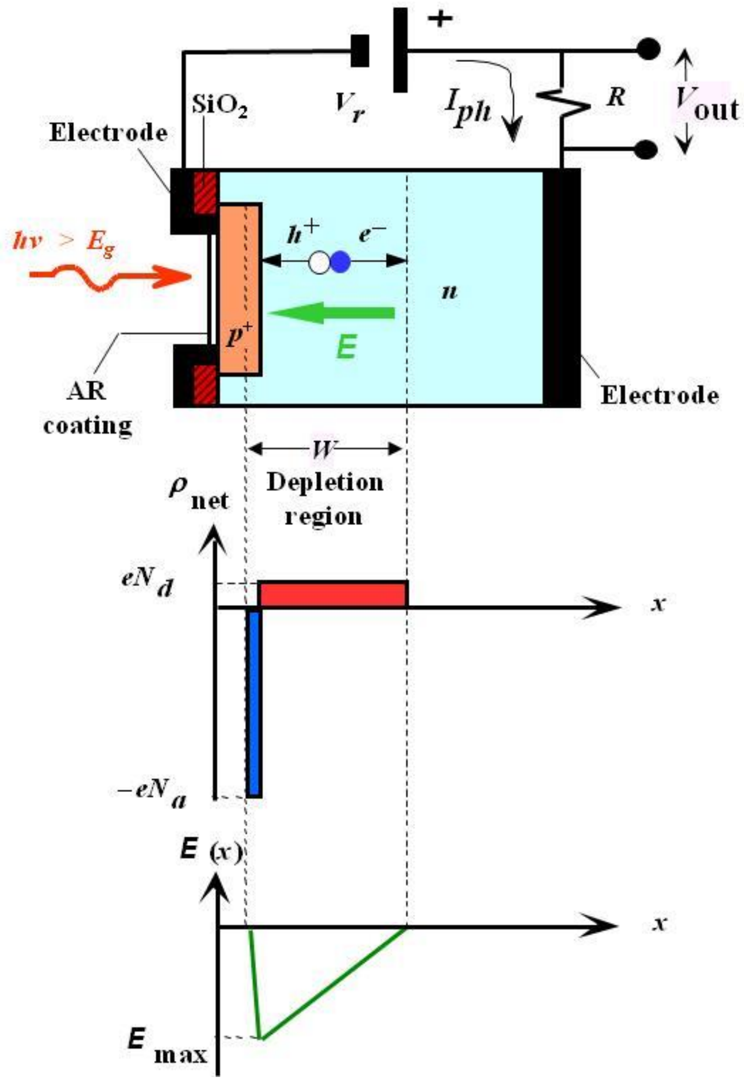
p-n photodetector

Photons are absorbed and e-h are generated everywhere, but only e-h in presence of **E** field is transported. A p-n junction supports an **E** field in the depletion layer.



Region 1: e-h generated in depletion region quickly move in opposite directions under **E**. External current is in reverse direction from n to p direction. Each carrier pair generates a pulse of area e.
Region 2: e-h generated outside the depletion layer have a finite probability in moving into the layer by random diffusion. An electron in the p side and a hole in the n side will be transported to the external circuit. Diffusion is usually slow.
Region 3: e-h generated cannot be transported, wandered randomly, are annihilated by recombination. No signal to external circuit.

p-n photodetector



- Schematic diagram of a **reverse biased** p-n junction photodiode
  - Photocurrent is dependent on number of EHP and drift velocity.
  - The electrodes do not inject carriers but allow excess carriers in the sample to leave and be collected by the battery.
- Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides.
- The field in the depletion region.

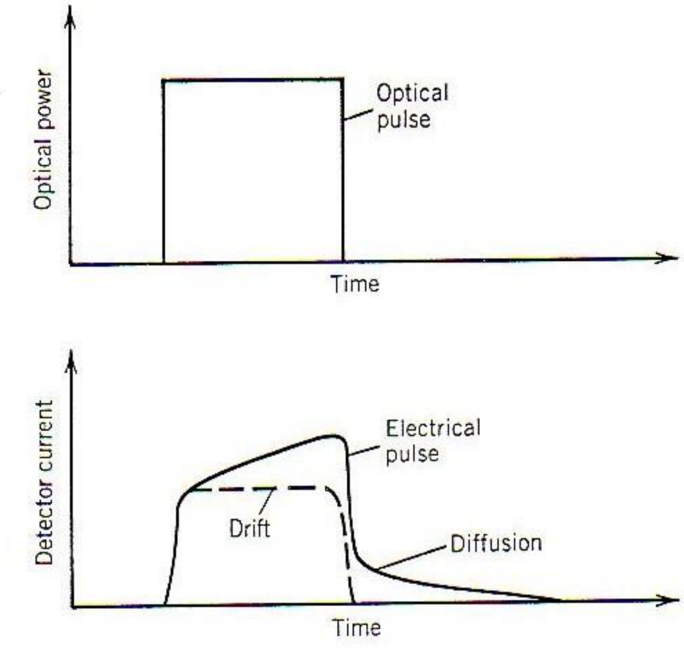
Response time

1) Finite diffusion time: carriers take nanosecond or longer to diffuse a distance of ~ 1 μm.
2) Junction capacitance puts a limit on the intensity modulation frequency

$$\omega = \frac{1}{RC}$$

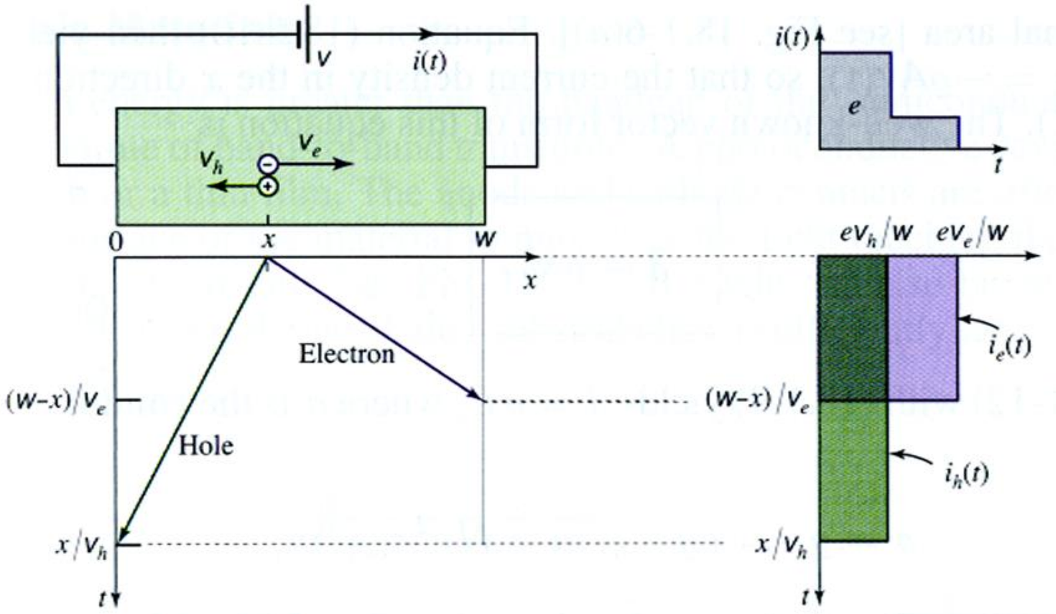
3) Finite transit time of carriers across depletion layer

Illustration of the response of a *p-n* photodiode to an optical pulse when both drift and diffusion contribute to the detector current:



Response time

w_d / v_e	Transit time of electron across depletion layer
w_d / v_h	Transit time of hole across depletion layer



In photodiodes (compared with photoconductor), there is longer time because of diffusion. The transit time should not be greater than the lifetime of the carrier. Nevertheless photodiodes are usually faster because of large **E** field which induces a larger drift velocity.

Response time

The bandwidth of a photodetector is determined by the speed with which it responds to variations in the incident optical power. The speed of a detector is ultimately limited to how long it takes for the carriers to be collected. It also depends on the response time of the electronic circuits to process the photocurrent. If W is the width of the depletion region and v_d is the drift velocity, the collection time of the detector is:

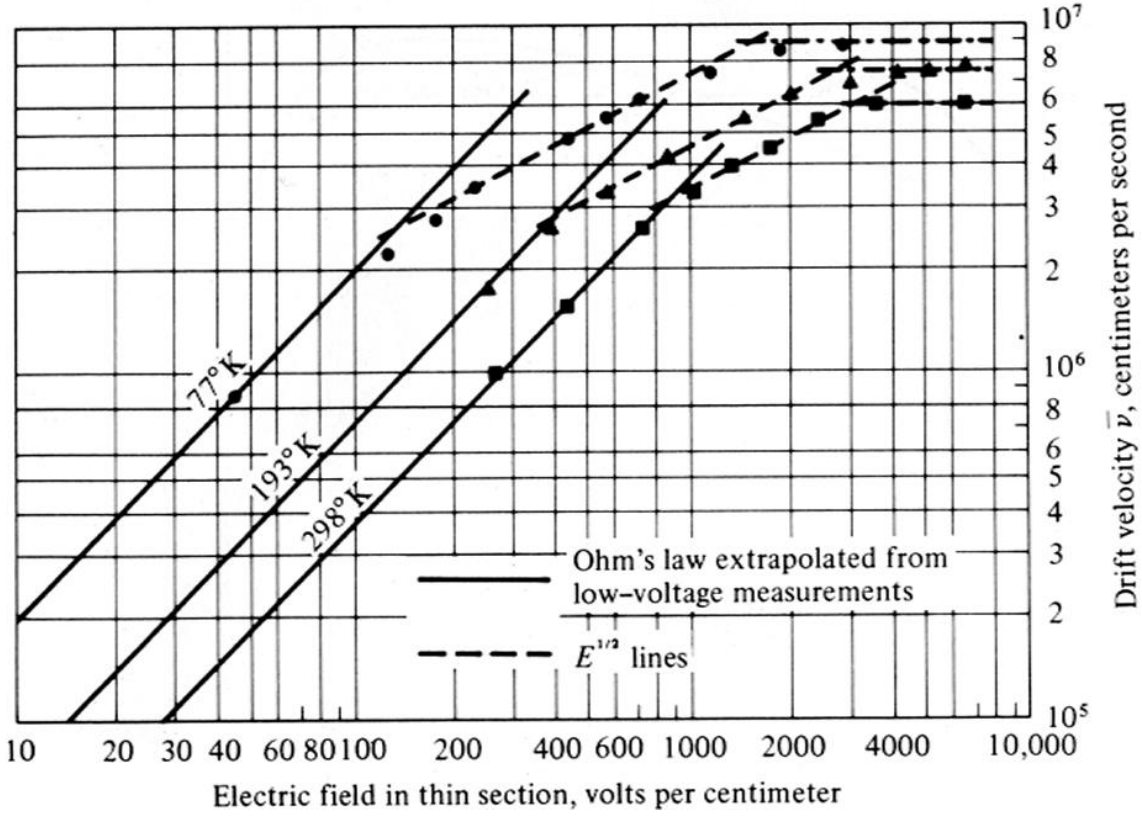
$$\tau = W / v_d .$$

Typically $W \sim 10\ \mu$m and $v_d \sim 10^5$ m/s, so $\tau \sim 100$ ps. Both W and v_d can be optimized to minimize τ. The depletion layer width depends on the donor and acceptor concentrations and the drift velocity on the applied voltage. The drift velocity, however, attains a saturation value, which depends on the material used.

To maximize the speed the capacitance of the junction needs to be minimized. This can be achieved by reducing the detector area (commercial high speed detectors have diameters on the order of 20 μm that is compatible with fibers), and by increasing W (contradicts with the requirement to reduce the collection time).

The modern *p-n* photodiodes are capable of operating at bit rates up to 40 Gbit/s.

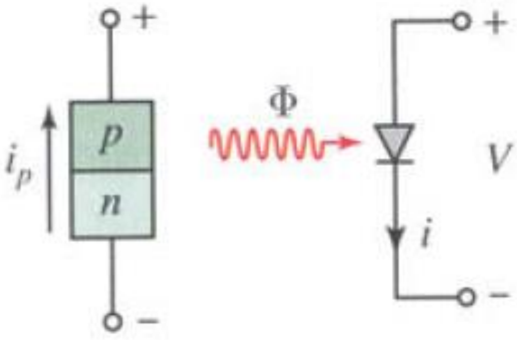
Response time

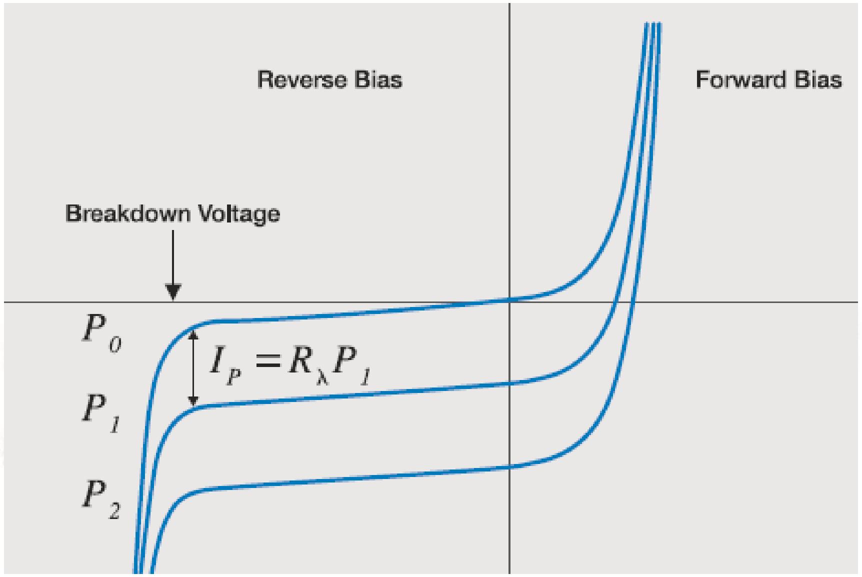


Experimental data showing the saturation of drift velocity of holes in germanium at high electric fields.

Credit: S. Pau

i-V characteristics



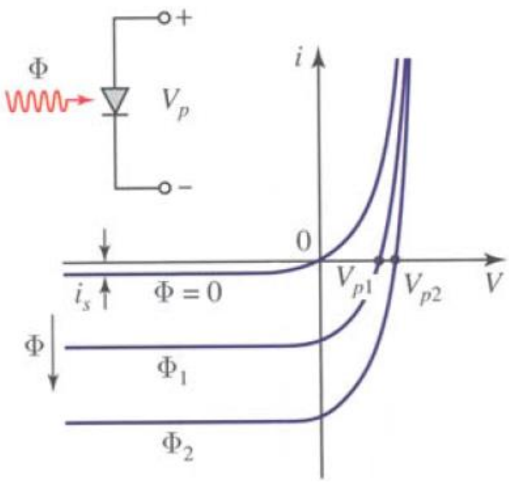


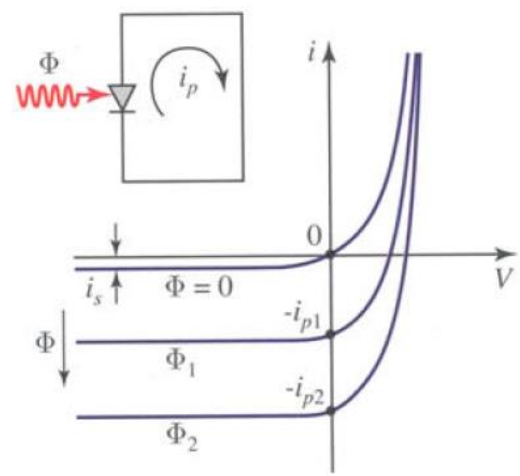
$$i = i_s\left[\exp\left(\frac{eV}{kT}\right) - 1\right] - i_p$$

$-i_p$, photocurrent is proportional to photon flux

Modes of operation

Modes of photodiode operations: (1) open circuit (photovoltaic), (2) short circuit and (3) reverse biased (photoconductive)



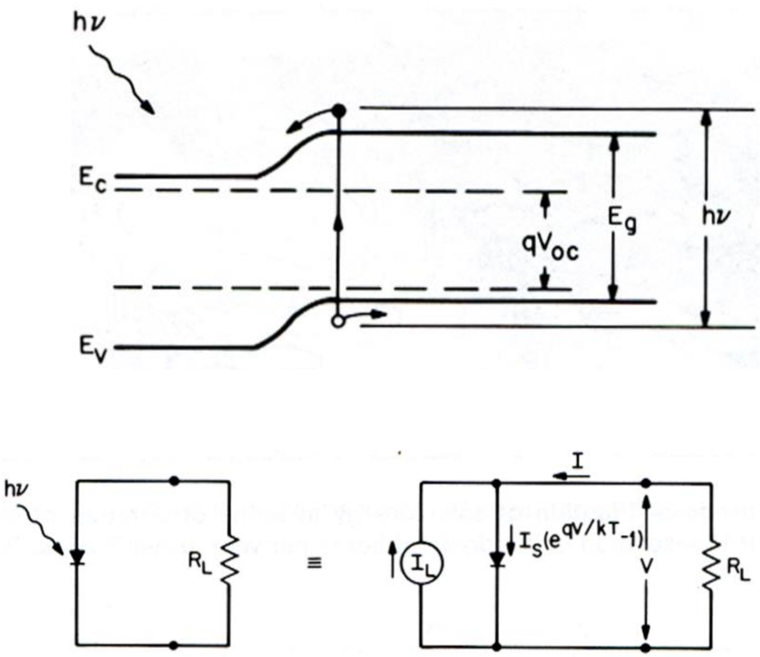


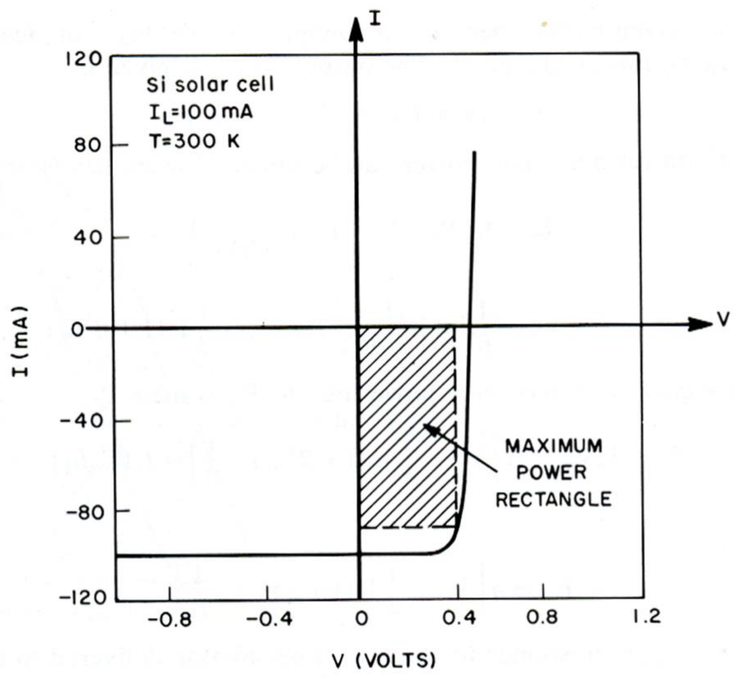
Light generated e-h pair. E field and voltage increase with carrier. Responsivity of photovoltaic cell is measured in V/W.

Short circuit operation. Responsivity is typically measured in A/W.

Photodiode and Photovoltaic

- Unbiased photodiode operates in photovoltaic mode.
- Photodiodes are small to minimize junction capacitance. Solar cell are big.
- Important parameter of photodiode is quantum efficiency, response time.
- Important parameter of photovoltaic is power conversion efficiency.
- By properly choosing a load, close to 80% of $I_{sc}V_{oc}$ can be extracted.

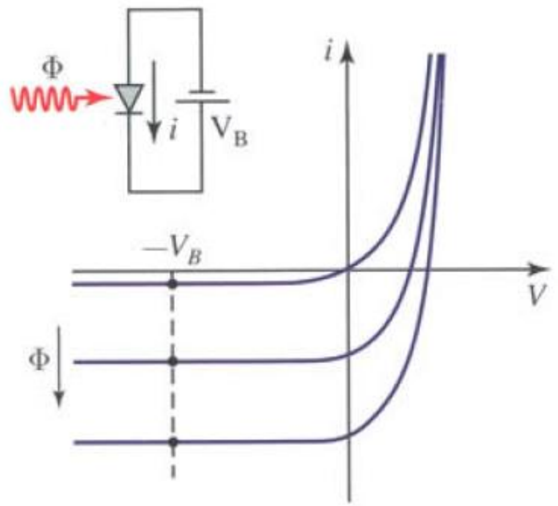




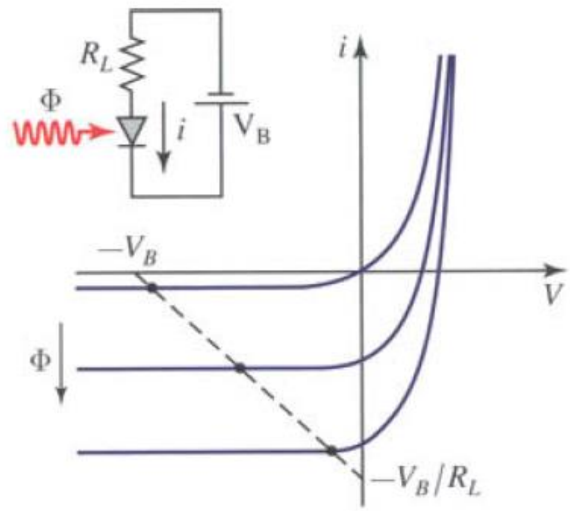
Reversed bias mode

Photodiodes are operated in strongly reversed bias mode because

1) Strong **E** fields give large drift velocity, reducing transit time
2) Strong bias increases depletion width, reducing capacitance
3) Increase depletion layer leads to more light collection

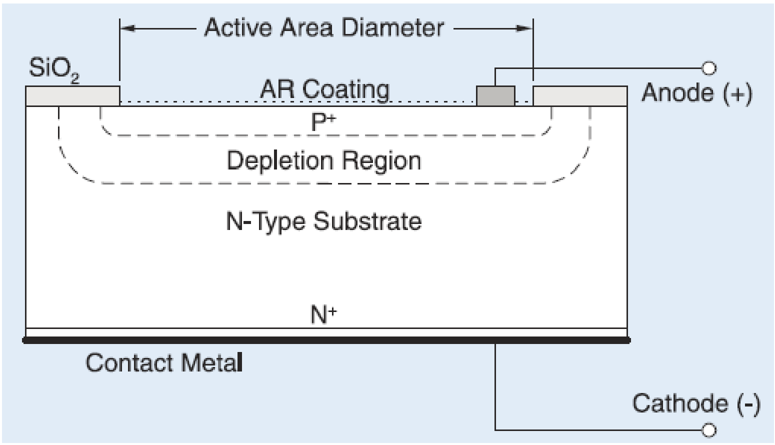


Reversed biased operation of a photodiode without a load resistor.

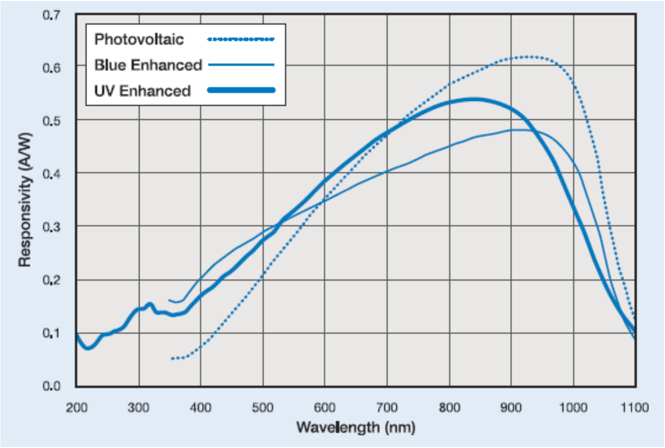


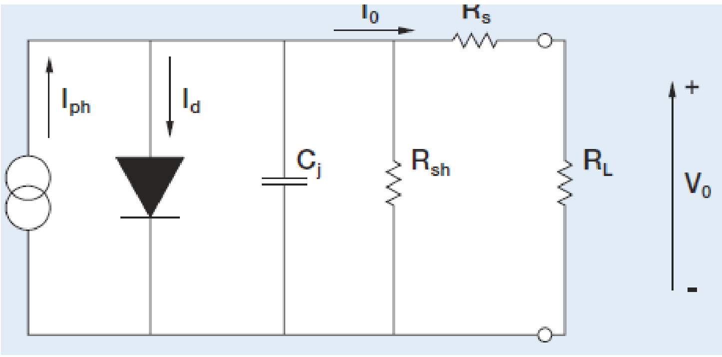
Reversed biased operation of a photodiode with a series load resistor.

Example-silicon photodiode



Planar diffused silicon photodiode





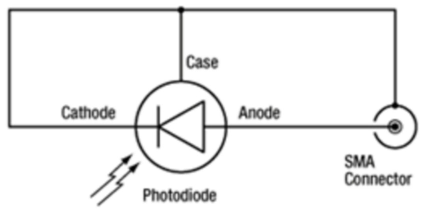
Equivalent circuit

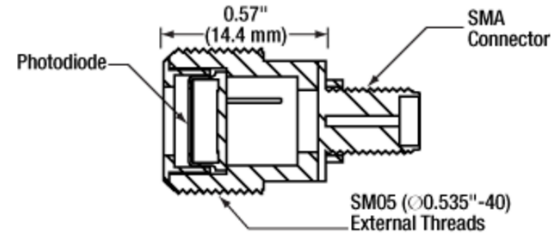
- C_j: junction capacitance
- R_{sh}: shunt resistance
- R_s: series resistance
- R_L: load resistance

Examples of photodiode

SM05-Threaded Mounted Photodiodes, Cathode Grounded

Zoom





Item #	Detector	Rise/Fall Time (Typ.)[a]	Active Area (Dimensions)	NEP ($W/Hz^{1/2}$)	Dark Current	Spectral Range (nm)	Material	Junction Capacitance (Typ.)	Reverse Bias Voltage (Max)	Responsivity Plots
SM05PD7A	FGAP71	55 ns / 55 ns @ 5 V	4.8 mm^2 (2.2 x 2.2 mm)	1.3×10^{-14}	15 pA (Typ.) @ 5 V 40 pA (Max) @ 5 V	150 - 550	GaP	1000 pF @ 0 V	5 V	
SM05PD2A	FDS010	1 ns / 1 ns @ 10 V	0.82 mm^2 (Ø1.02 mm)[b]	5.0×10^{-14}	0.3 nA @ 10 V	200 - 1100	Si	7 pF @ 5 V	30 V	
SM05PD1A	FDS100	10 ns / 10 ns @ 632 nm, 20 V	13 mm^2 (3.6 x 3.6 mm)	1.2×10^{-14}	1.0 pA (Typ.) @ 20 V 20 pA (Max) @ 20 V	350 - 1100	Si	24 pF @ 20 V	25 V	
SM05PD5A	FGA21	14 ns / 14 ns @ 0 V	3.1 mm^2 (Ø2.0 mm)	6.0×10^{-14}	50 nA @ 1 V	800 - 1700	InGaAs	100 pF @ 3 V	3 V	
SM05PD6A	FDG03	600 ns / 600 ns @ 3 V	7.1 mm^2 (Ø3.0 mm)	2.6×10^{-12}	4.0 μA (Max) @ 1 V	800 - 1800	Ge	6 nF @ 1 V 4.5 nF @ 3 V	3 V	
SM05PD4A	FGA10	10 ns / 10 ns @ 5 V	0.8 mm^2 (Ø1.0 mm)	2.5×10^{-14}	1.1 nA @ 5 V	900 - 1700	InGaAs	80 pF @ 5 V	5 V	

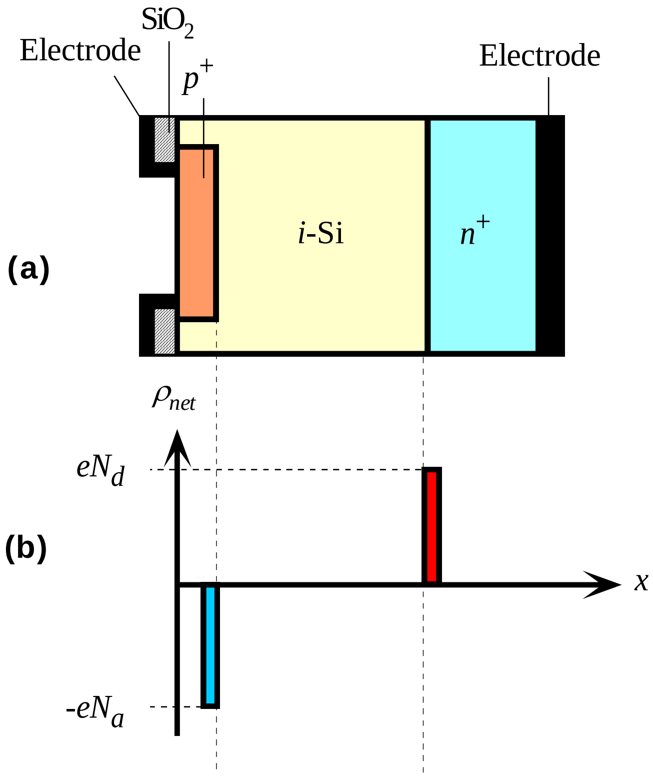
a. R_L = 50 Ω
b. The Ø1 mm active area accounts for the two solder leads found on the photodiode face.

Based on your currency / country selection, your order will ship from Newton, New Jersey

+1	Qty	Docs	Part Number - Universal	Price	Available / Ships
			SM05PD7A Mounted GaP Photodiode, 150-550 nm, Cathode Grounded	$138.00	√ Today
			SM05PD2A Mounted Silicon Photodiode, 200-1100 nm, Cathode Grounded	$87.75	√ Today
			SM05PD1A Large Area Mounted Silicon Photodiode, 350-1100 nm, Cathode Grounded	$73.50	√ Today
			SM05PD5A Mounted InGaAs Photodiode, 800-1700 nm, Cathode Grounded	$300.00	√ Today
			SM05PD6A Large Area Mounted Germanium Photodiode, 800-1800 nm, Cathode Grounded	$182.00	√ Today
			SM05PD4A Mounted InGaAs Photodiode, 900-1700 nm, Cathode Grounded	$211.00	√ Today

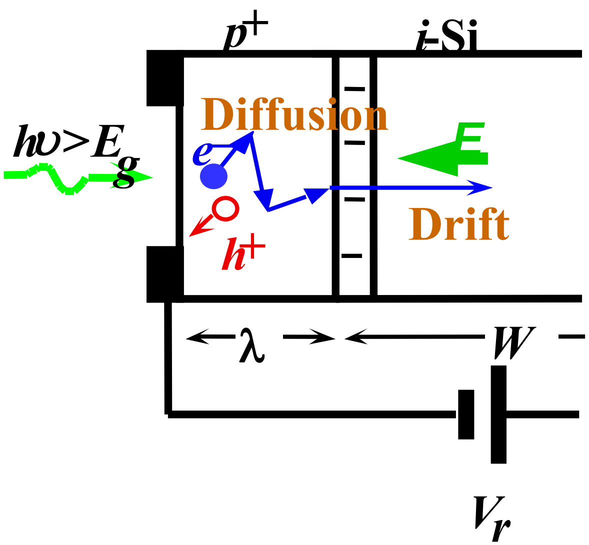
pin photodiode

- The *pn* junction photodiode has two drawbacks:
  - Depletion layer (DL) capacitance is not sufficiently small to allow photodetection at high modulation frequencies (RC time constant limitation).
  - Narrow DL (at most a few microns) → long wavelengths incident photons are absorbed outside DL→ low QE
- The *pin* photodiode can significantly reduce these problems.
- Intrinsic layer has less doping and wider region (5 – 50 μm).



pin photodiode

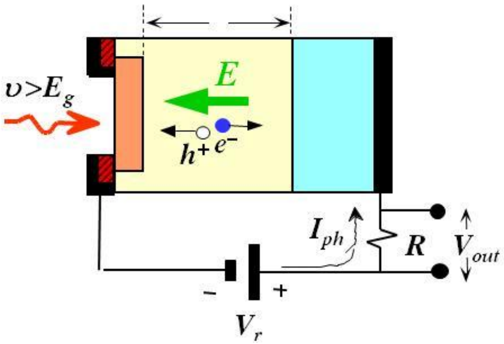
- A reverse biased *pin* photodiode is illuminated with a short wavelength photon that is absorbed very near the surface.
- The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*- layer and drifted across.



Advantages over pin junction photodiode

1) Larger light collection area
2) Reduce junction capacitance and RC time constant. Transit time also increases
3) Reducing ratio between diffusion length and drift length leads to greater proportion of current carried by faster drift process

pin photodiode



❑ Junction capacitance of *pin*

$$C_{dep} = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

- Small capacitance: High modulation frequency
- RC_{dep} time constant is ~ 50 psec.

❑ Electric field of biased *pin*

$$E = E_0 + \frac{V_r}{W} \approx \frac{V_r}{W}$$

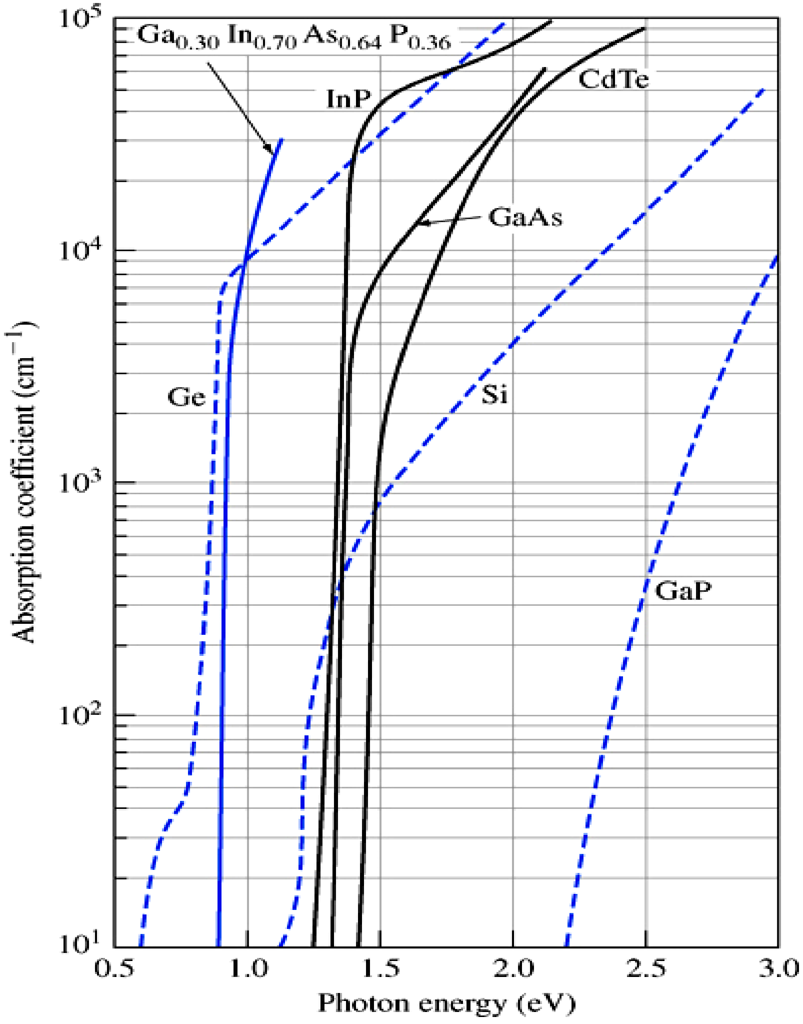
❑ Response time

$$t_{drift} = \frac{W}{\mathrm{v}_d}$$

$$\mathrm{v}_d = \mu_d E$$

- The speed of pin photodiodes are invariably limited by the transit time of photogenerated carriers across the *i*-Si layer.
- For *i*-Si layer of width 10 μm, the drift time is about is about 0.1 nsec.

Photodiode Materials



- Absorption coefficient α is a material property.
- Most of the photon absorption (63%) occurs over a distance 1/α (it is called **penetration depth** δ)

Photodiode Materials

A table below lists operating characteristics of common *p-i-n photodiodes.* In the parameters the dark current is the current generated in a photodiode in the absence of any optical signal. The parameter rise time is defined as the time over which the current builds up from 10 to 90% of its final value when the incident optical power is abruptly changed.

For Si and Ge, *W* typically has to be in the range of 20 – 50 μm to ensure a reasonable quantum efficiency. The bandwidth is thus limited by a relatively long collection time. In contrast, *W* can be as small as 3 – 50 μm for InGaAs photodiodes resulting in higher bandwidths.

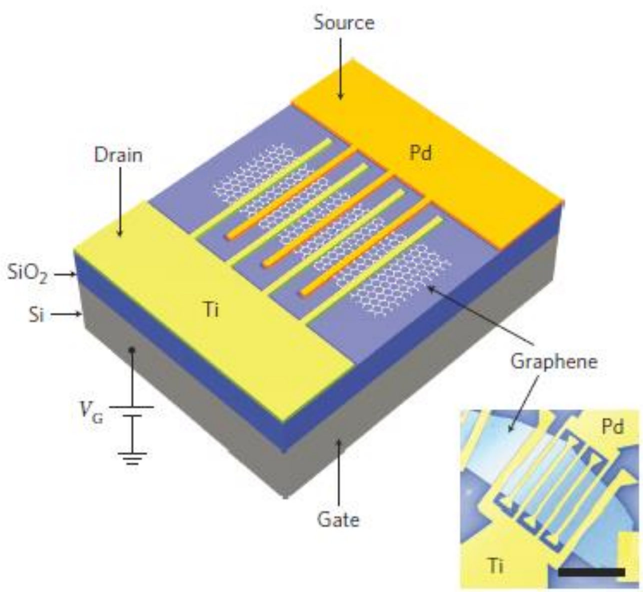
Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	R	A/W	0.4–0.6	0.5–0.7	0.6–0.9
Quantum efficiency	η	%	75–90	50–55	60–70
Dark current	I_d	nA	1–10	50–500	1–20
Rise time	T_r	ns	0.5–1	0.1–0.5	0.02–0.5
Bandwidth	Δf	GHz	0.3–0.6	0.5–3	1–10
Bias voltage	V_b	V	50–100	6–10	5–6

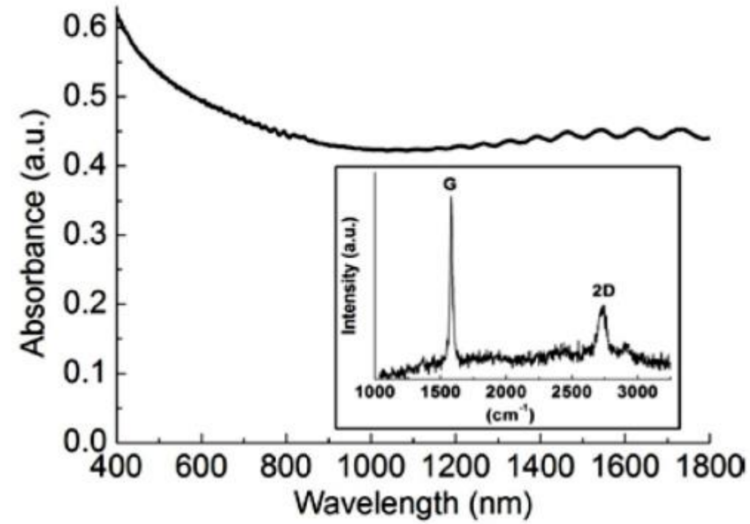
Photodiode based on graphene

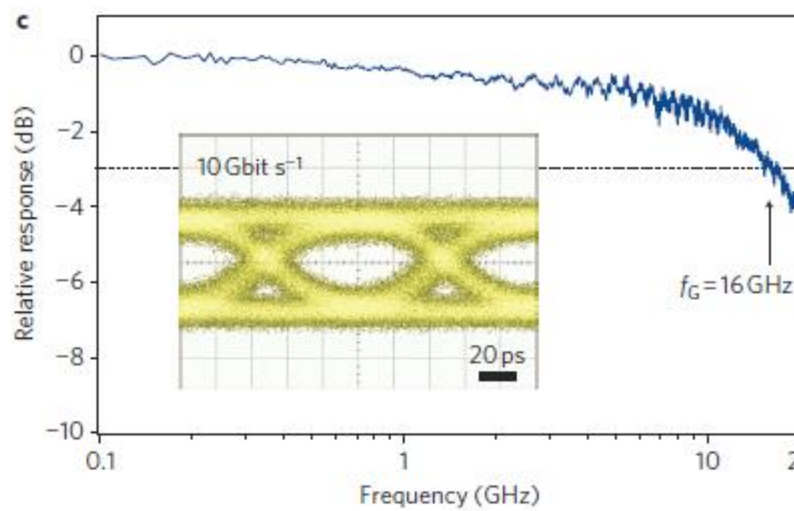
nature photonics LETTERS
PUBLISHED ONLINE: 28 MARCH 2010 | DOI: 10.1038/NPHOTON.2010.40

Graphene photodetectors for high-speed optical communications

Thomas Mueller[†], Fengnian Xia* and Phaedon Avouris*





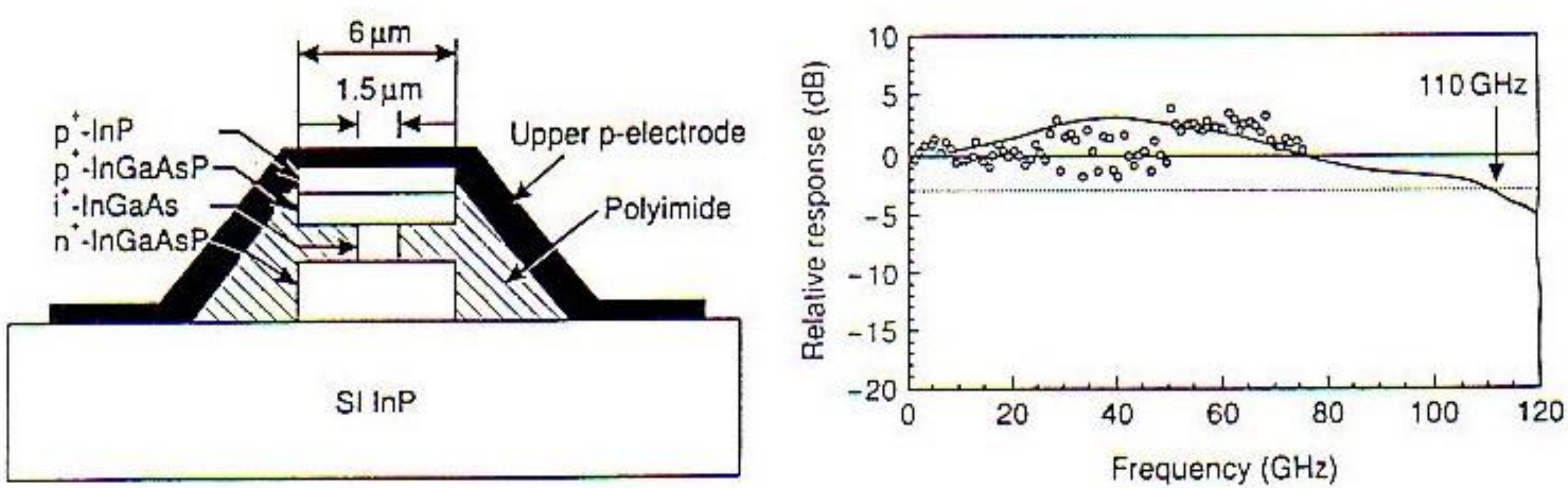


Very high speed *p-i-n* photodiodes

In optical communications systems operating at bit rates 10 Gbit/s or more, the photodiodes need to have very high bandwidths as well. Bandwidths of up to 70 GHz were demonstrated as early as 1986 using a very thin absorption layer (< 1 μm) and reducing the capacitance with a small size. This approach works but with the expense of lower responsivity and quantum efficiency.

Since early 1990s several new approaches have been investigated for high-speed detectors. One example is illustrated in a figure below. The approach uses a channel waveguide-type configuration. Since the absorption takes place along the length of the waveguide (~ 10 μm), the quantum efficiency can be nearly 100%. From bandwidth point of view, the device can be optimized having an ultra-thin absorption layer resulting in very short collection time.

a) Schematic cross section of a waveguide-photodiode and b) its measured frequency response:



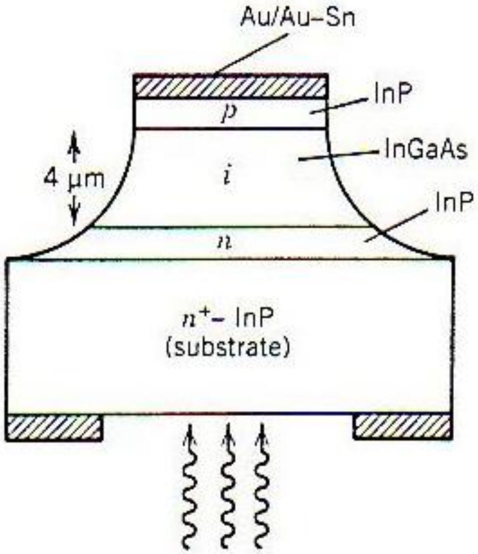
Double heterostructure photodiodes

As with semiconductor laser diodes, the performance of a *p-i-n* photodiode can be significantly improved by using a double-heterostructure design (sketched in figure below). The *i*-region is made of ternary compound $In_{0.53}Ga_{0.47}As$ (lattice matched to InP) and is sandwiched between *n*- and *p*-type InP epitaxial layers. InP has a bandgap of ~ 1.35 eV, so it is transparent at wavelengths above ~ 0.92 μm. The middle InGaAs layer has a bandgap of ~ 0.75 eV, so it absorbs strongly within a wavelength range of about 1.3 – 1.6 μm. Key features:

- The diffusive current component completely eliminated, since all the absorption occurs within the *i*-region.
- Quantum efficiency nearly 100% with 4- 5 μm thick InGaAs layer.

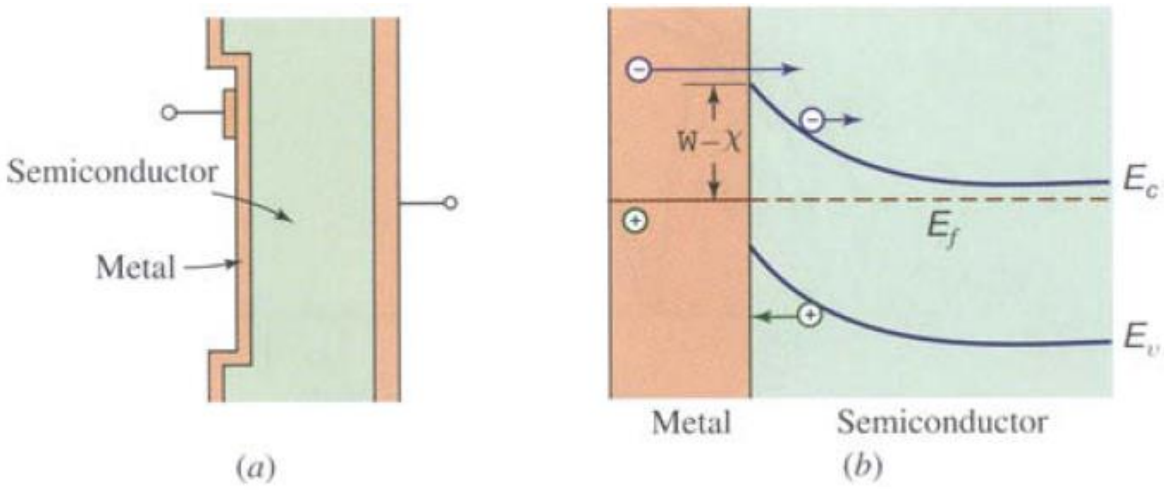
Sketch of an InGaAs photodiode based on double-heterostructure design:

$$E_g(InP) > E_g(InGaAs)$$



Schottky-Barrier Photodiodes

Instead of a p layer, a thin semitransparent metallic film is used.
Below shows (a) the structure and (b) energy band diagram of a Schottky barrier photodiodes. Minimum photon energy is $W - \chi$, difference between the work function and the electron affinity. Examples of metal are Au on n-type Si and PtSi on p type silicon.



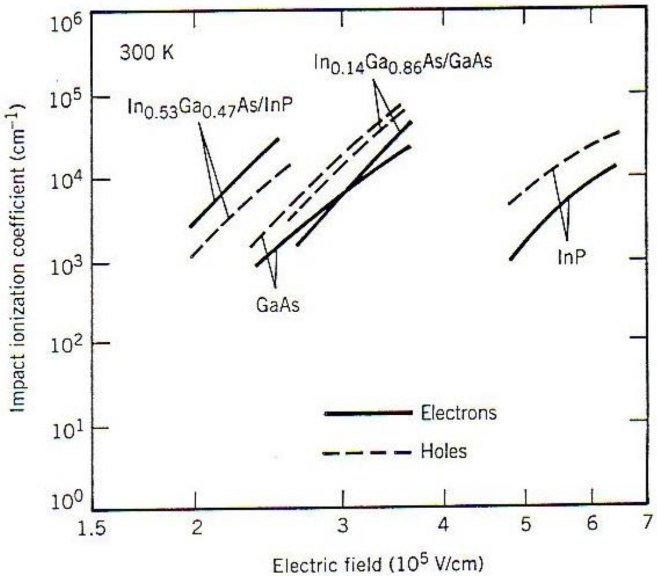
Advantages
1) Not all semiconductors can be made in n and p type form.
2) MS junction has depletion layer at surface, with low surface recombination.
3) Majority carrier device with fast response and bandwidth ~ 100GHz. Low R and low RC because of metal.

Avalanche Photodiode

Avalanche photodiodes (APDs) are preferred when the amount of optical power that can be spared for the receiver is limited. Their responsivity can significantly exceed 1 due to built in gain. The physical phenomenon behind the gain is known as *impact ionization*. Under certain conditions an accelerating electron can acquire sufficient energy to generate a new electron-hole pair. The net result is that a single primary electron creates many secondary electrons and holes, all of which contribute to the current.

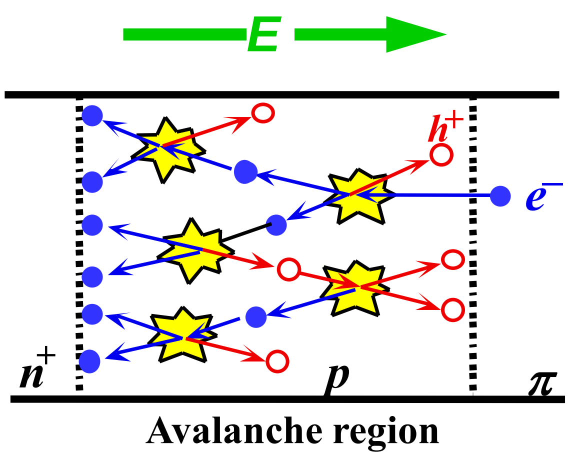
The generation rate is governed by two parameters, α_e and α_h, the *impact-ionization coefficients* for electrons and holes, respectively. Their numerical values depend on the semiconductor material and on the electric field that accelerates electrons and holes. Figure below shows the coefficients for several semiconductors.

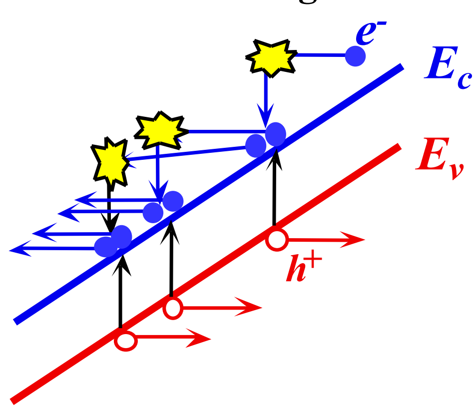
The values for α_e and α_h ~ 1×10^{-4} cm^{-1} are obtained for electric fields in the range of $2 – 4 \times 10^5$ V/m. Such high fields are obtained by applying a high voltage of (~ 100 V) to the APD. These values decreases with increasing temperature.

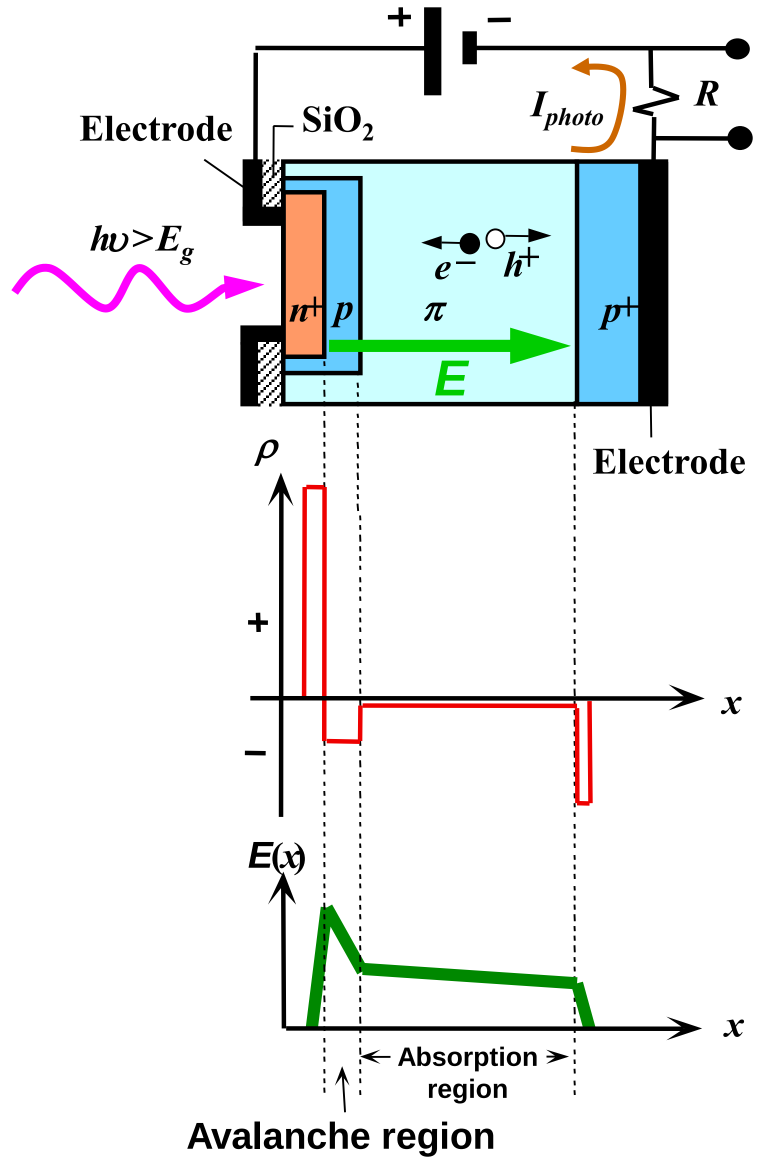


Avalanche Photodiodes

- Impact ionization processes resulting avalanche multiplication







- Impact of an energetic electron's kinetic energy excites VB electron to the CV.

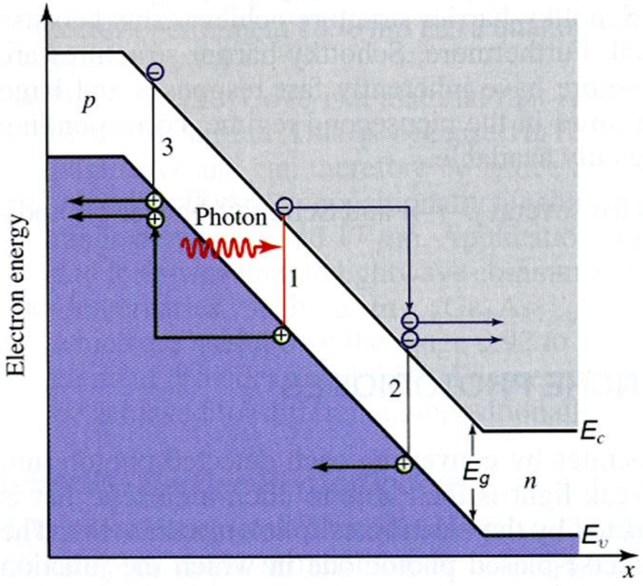
Avalanche Photodiodes

$1/\alpha_e$ average distances between consecutive ionizations of electron

$1/\alpha_h$ average distances between consecutive ionizations of hole

An important parameter for APD is the ionization ratio, $k = \alpha_h/\alpha_e$. For k << 1, most ionization is cause by electrons and avalanching occurs from left to right. For k ~ 1, we have holes to left generating electrons to right, creating a circulating path. This is not good because (1) of long time for carrier to stabilize, (2) of increase random and noise and (3) of increase chance of instability and breakdown.

Ideal case is k=0 or k=infinity, where there is only one type of carrier to impact ionize.



Multiplication factor *M*:

$$M = \frac{I_{APD}}{I_{ph}}$$

$$R_{APD} = MR_0$$

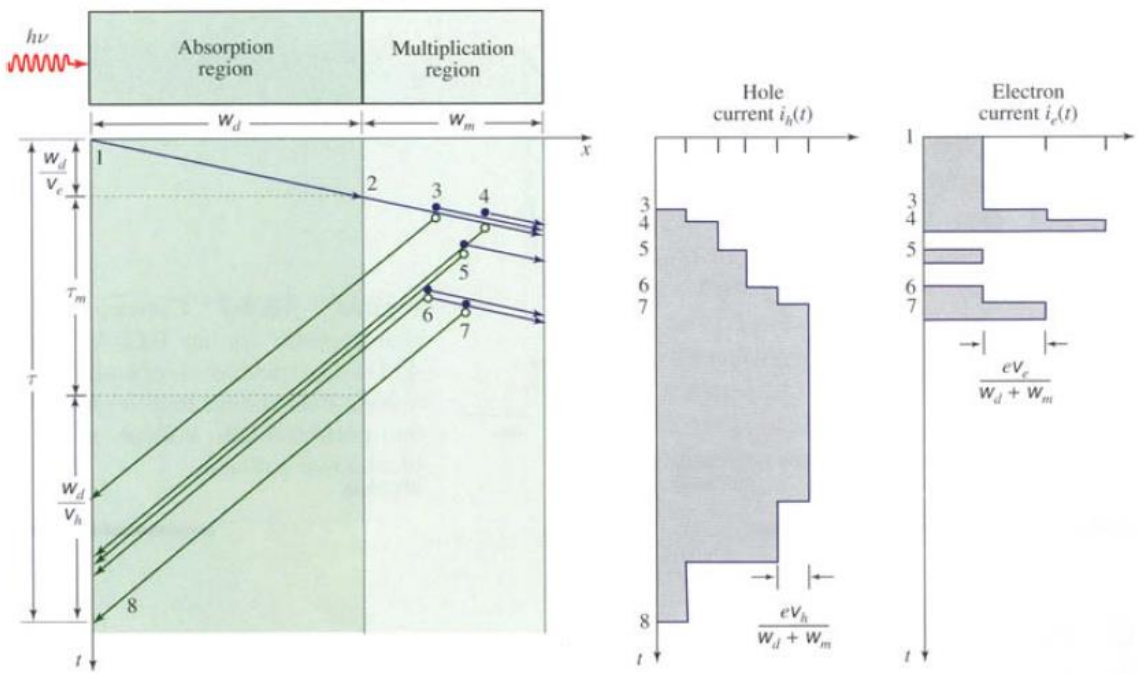
Responsivity R_{APD} (A/W) for common APDs:

Si:	80 – 130
Ge:	3 – 30
InGaAs:	5 – 20

Response time

Response time of APD is determined by the usual transit, diffusion and RC effects. In addition, APD has an avalanche buildup time, τ_m.

$$\tau = \frac{w_d}{v_e} + \frac{w_d}{v_h} + \tau_m$$



τ_m is in general a random statistical variable. For large gain G and for electron injection with 0 < k < 1,

$$\tau_m \sim Gk\frac{w_m}{v_e} + \frac{w_m}{v_h}$$

Response time

Avalanche buildup time in a silicon APD

APD parameters

$$w_d = 50\mu m$$

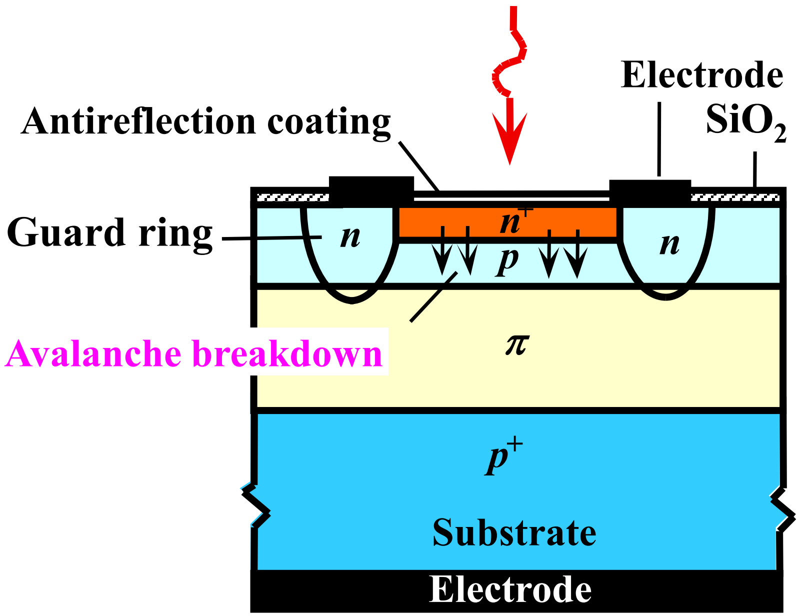
$$w_m = 0.5\mu m$$

$$v_e = 10^7 cm/s$$

$$v_h = 5\times 10^6 cm/s$$

$$G = 100$$

$$k = 0.1$$



$$\tau = \frac{w_d}{v_e} + \frac{w_d}{v_h} + Gk\frac{w_m}{v_e} + \frac{w_m}{v_h} = 1065\,ps$$

Photodetector Noise

Shot noise: Shot noise is related to the statistical fluctuation in both the photocurrent and the dark current. The magnitude of the shot noise is expressed as the root mean square (rms) noise current:

$$I_{sn} = \sqrt{2q(I_P + I_D)\Delta f}$$

q is charge of electron, $1.6*10^{-19}$C

Thermal or Johnson noise: The shunt resistance in a photodetector has a Johnson noise associated with it. This is due to the thermal generation of carriers. The magnitude of this generated current noise is:

$$I_{jn} = \sqrt{\frac{4k_B T\Delta f}{R_{SH}}}$$

k_B is Boltzmann Constant
$k_B = 1.38 *10^{-23}$ J/K

Δf is the operating bandwidth

Photodetector Noise

Total Noise

The total noise current generated in a photodetector is determined by:

$$I_{tn} = \sqrt{I_{sn}{}^2 + I_{jn}{}^2}$$

Noise Equivalent Power (NEP)

Noise Equivalent Power is the amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current. NEP is defined as:

$$NEP = \frac{I_{tn}}{R_\lambda}$$

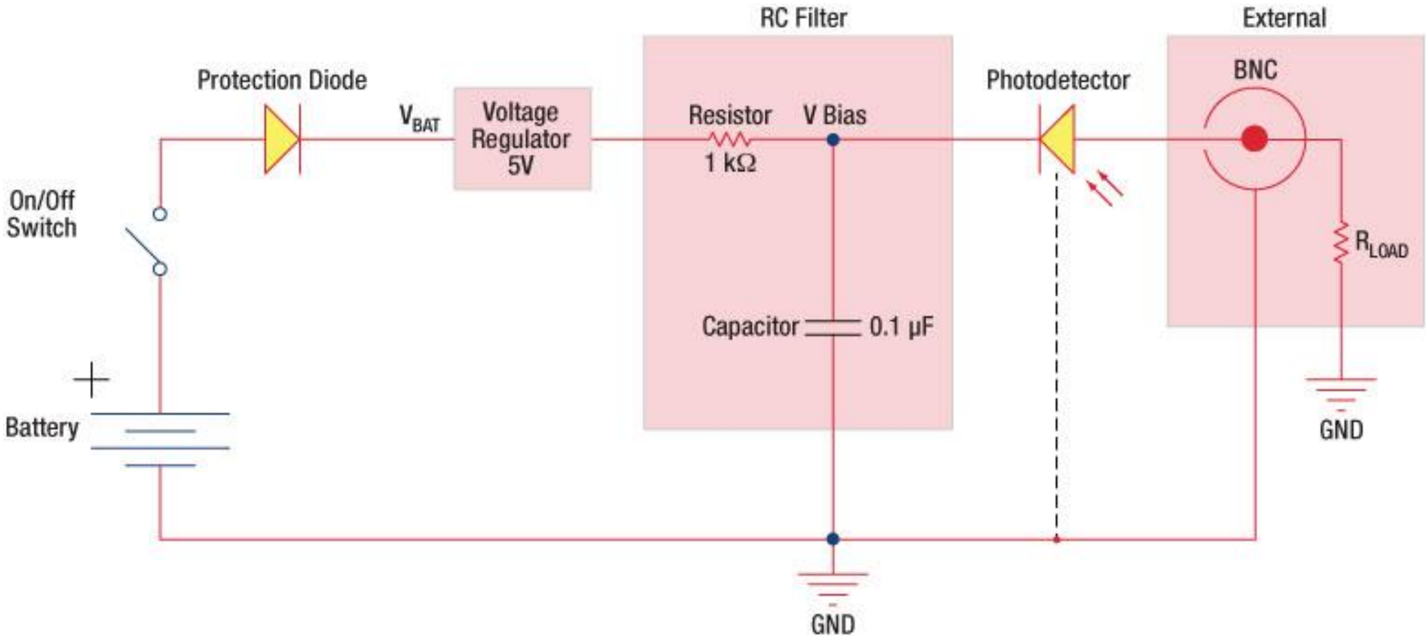
APD example

Item #	APD110C
Detector Type	InGaAs APD
Wavelength Range	900 - 1700 nm
Typical Max Responsivity	9 A/W @ 1500 nm M = 10
Transimpedance Gain	100 kV/A 50 kV/A with 50 Ω Termination
Maximum Conversion Gain	0.9×10^6 V/W
Active Detector Diameter	0.2 mm
CW Saturation Power	4.2 μW
Max Input Power[a]	1 mW
Output Bandwidth (3dB)	DC - 50 MHz
Minimum NEP	0.46 pW/($Hz^{1/2}$)
Electrical Output	BNC, 50 Ω
Max Output Voltage Threshold	3.6 V
DC Offset Electrical Output	<±15 mV
Device Dimensions	2.0" x 3.0" x 1.1" (50.8 mm x 76.2 mm x 27.9 mm)
Power Supply	±12 V @ 200 mA (110/230 VA switchable)

- High-Speed Response up to 1 GHz
- Ultra-High Sensitivity up to 0.9×10^6 V/W
- Wavelength Range of 850 - 1650 nm or 900 - 1700 nm
- SM05 or SM1 Compatible

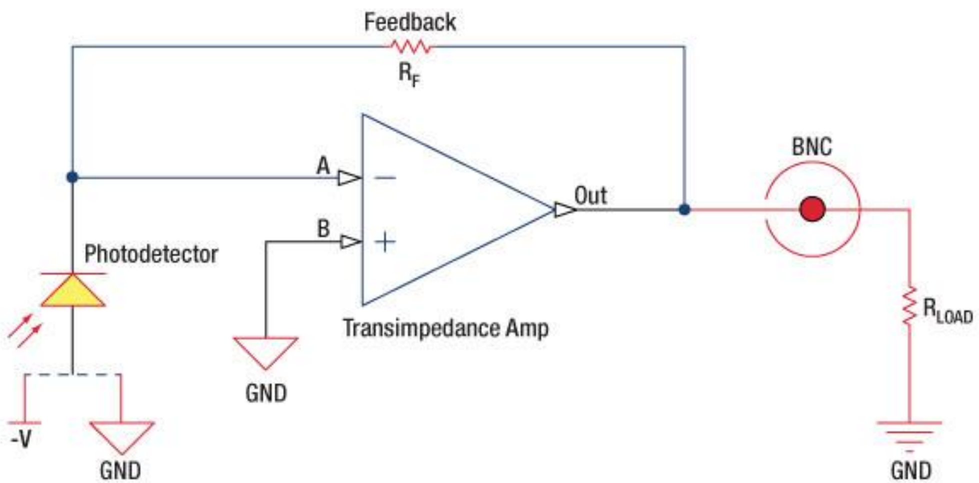
APD110C

Electrical wiring



Reverse biased photodetector

Electrical wiring



Amplified photodetector

Questions for thoughts

Can we detect a single photon?

Can you come up with a new kind of detector that is faster, more sensitive, and have less noise?