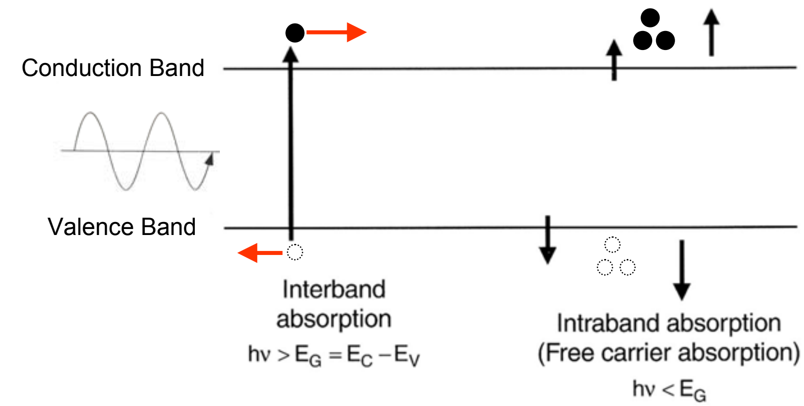
Integrated Photodetectors

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

Fundamental Requirements of Photodetectors

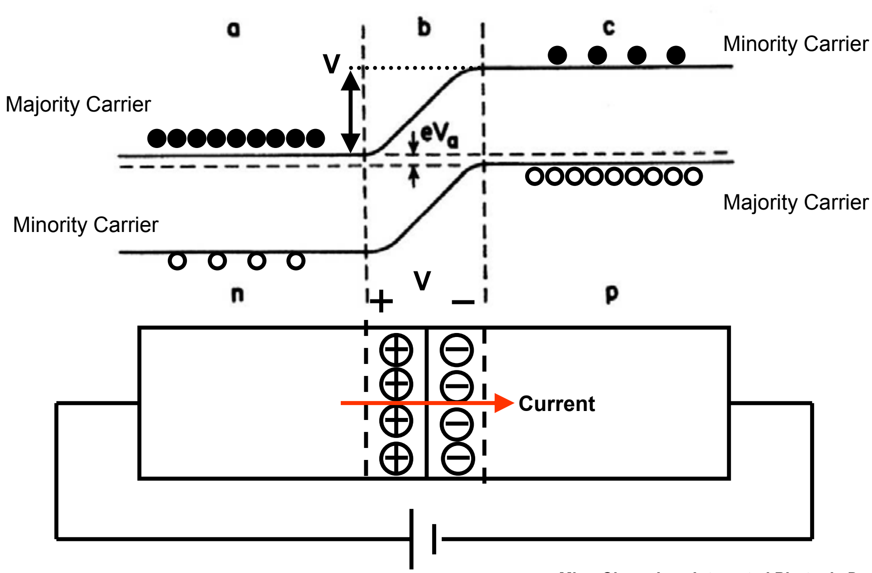
- High Sensitivity
- Short Response Time
- Large Quantum Efficiency
- Low Power Consumption

Photon Electron Interaction



- **Interband absorption → electron and hole pairs (photodetector)** $h\nu > E_g$
- **Intraband absorption → free carrier scattering (metal)** $h\nu < E_g$

Fundamentals of Depletion Layer Photodiodes



P⁺-n (high-low) Junction Diodes

To minimize series resistance and maximum depletion layer, usually one region is low doped.

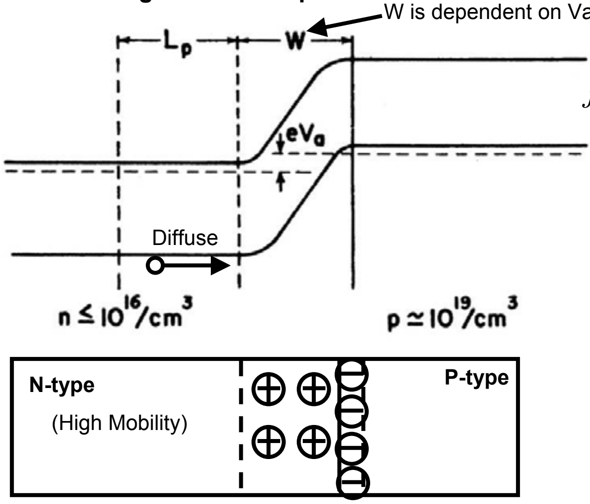


Photo Flux

$$J_{tot} = \underbrace{q\varphi_0\left(1-\frac{e^{-\alpha W}}{(1+\alpha L_p)}\right)}_{\text{Photocurrent}} + \underbrace{q p_{n0}\frac{D_p}{L_p}}_{\text{Dark current}}$$

L_p : diffusion length (hole)

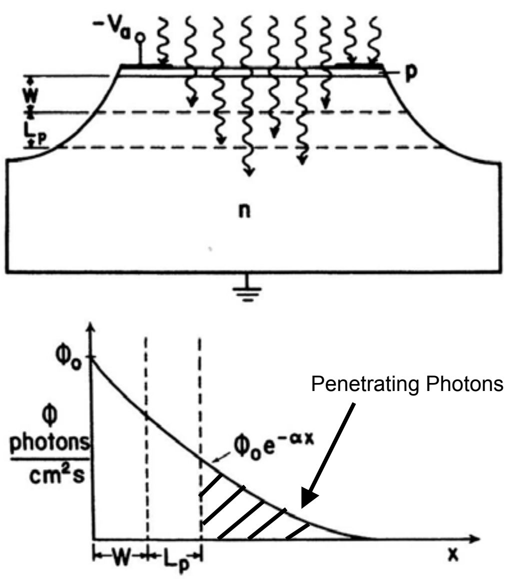
α : interband absorption coeff.

D_p : diffusion constant (hole)

p_{n0} : equilibrium hole density

Quantum Efficiency $\boxed{\eta_q = 1-\frac{e^{-\alpha W}}{(1+\alpha L_p)}}$

Photon Penetration in P⁺-n Photodiodes



To maximize the quantum efficiency, it is desirable to make the product αW and αL_p as large as possible

(1). Drifted Current

Contribution Term $: 1-e^{-\alpha W}$

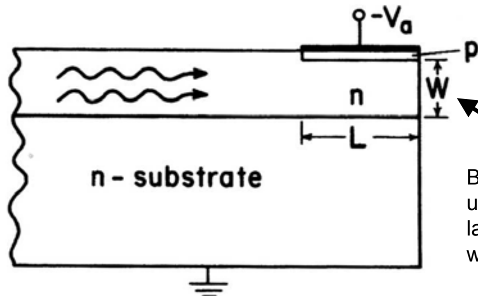
(2). Diffused Current

Contribution Term $: \frac{\alpha L_p}{1+\alpha L_p} e^{-\alpha W}$

However, α is wavelength-dependent

Waveguide Depletion Layer Photodiodes

If the basic depletion layer photodiode is incorporated into a waveguide structure, most of photons are guided in the depletion layer.



Bias at the p-region until the depletion layer is close to the waveguide thickness

Thus, the photocurrent is given by $J = q\varphi_0(1-e^{-\alpha L})$

L can be made as long as possible to have αL >>1. $\longrightarrow$ $\eta_q \sim 100\%$

High speed due to small capacitance and operation in depletion region

Free Carrier Absorption and Scattering Loss

If the free carrier absorption and the scattering loss are comparable to the interband absorption, photons will be annihilated without generating electron-hole pairs.

Consider the photon flux decaying along propagation (x):

$$\varphi(x) = \varphi_0 e^{-\alpha x} \quad \textbf{where} \quad \alpha = \alpha_{IB} + \alpha_{FC} + \alpha_S$$

The hole-electron pair generation rate G(x) is given by

$$G(x) = \alpha_{IB}\varphi_0 e^{-\alpha x}$$

Thus, the photocurrent density is given by

$$J = q\int_0^L G(x)dx \longrightarrow J = q\varphi_0 \frac{\alpha_{IB}}{\alpha_{IB}+\alpha_{FC}+\alpha_S}(1-e^{-(\alpha_{IB}+\alpha_{FC}+\alpha_S)L})$$

- **The effect of additional losses due to scattering and free-carrier absorption reduce the quantum efficiency**

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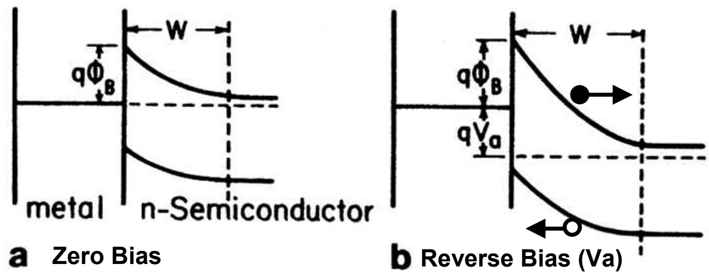
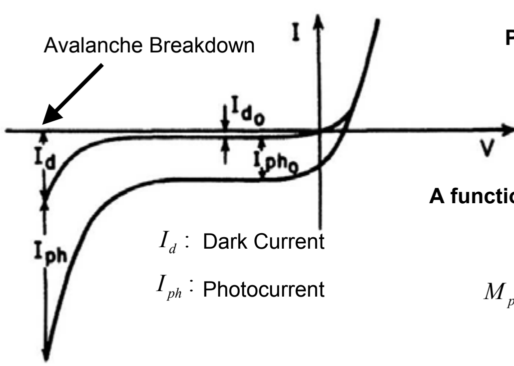
Schottky-Barrier Photodiodes



- The p-n junction is replaced by metal-semiconductor contact.
- The barrier height φ_B depends on the particular metal-semiconductor combination.
- Eliminate strong absorption of high energy photons in the p+ layer (conventional depletion layer photodiodes)
- Easy fabrication

Avalanche Photodiodes

- If the device is biased precisely at the point of avalanche breakdown, carriers are multiplied due to impact ionization.



Photomultiplication Factor: $M_{ph} \equiv \dfrac{I_{ph}}{I_{ph0}}$

Multiplication Factor: $M \equiv \dfrac{I_{ph} + I_d}{I_{ph0} + I_{d0}}$

A functional form of photomultiplication factor

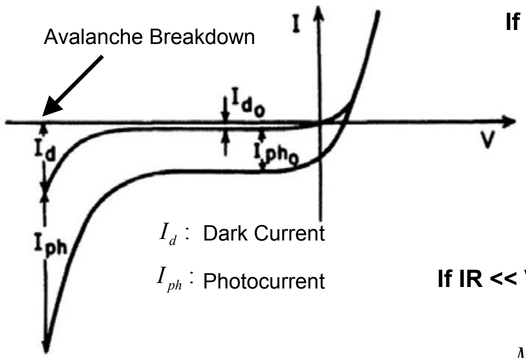
$$M_{ph} = \frac{1}{1-(V_a/V_b)^n}$$

Empirical Value

Biased voltage

Breakdown voltage

Avalanche Photodiodes



If $I_{ph0} >> I_{d0}$, according to Ohm's law

$$M = \frac{1}{1-(\frac{V_a - IR}{V_b})^n}$$

where $I = I_d + I_{ph}$

R : Series Resistance

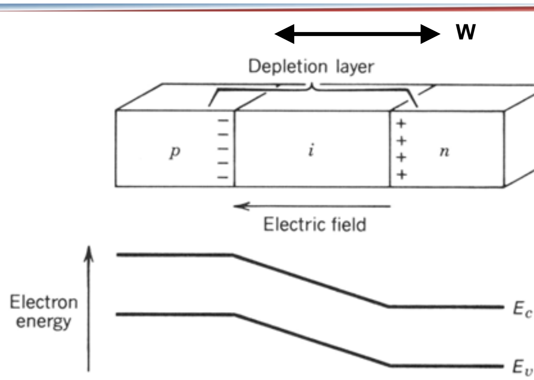
If $IR << V_b$, $V_a \sim V_b$ and $I_{ph}, I_d >> I_{d0}, I_{ph0}$

$$M \cong M_{ph} \cong \sqrt{\frac{V_b}{nI_{ph0}R}}$$

Material Property

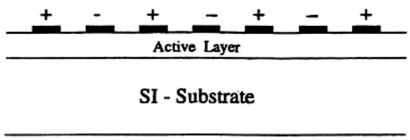
- **High gain (10^4) and high frequency (35GHz)**
- **However, not every p-n junction can be operated in the avalanche multiplication mode →defect sensitive**

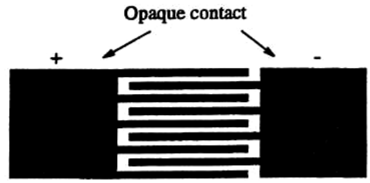
p-i-n Photodiodes



- **The whole intrinsic layer (carrier-balanced) covers the depletion layer**
- **W is large and independent of dopant concentration**
- **Low junction capacitance →reduce the RC time**

Metal-Semiconductor-Metal Photodiodes

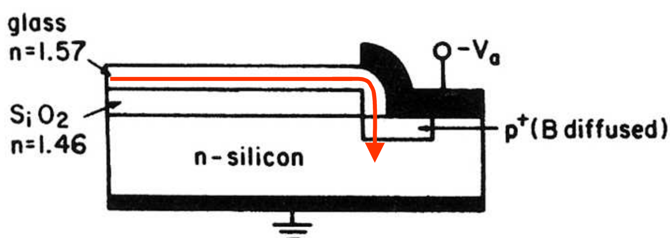




- Electrons and holes are swept to the cathode and anode by fringe field.
- The capacitance is relatively small due to narrow fingers
- Transparent electrodes are preferred (Cadmium Tin Oxide)

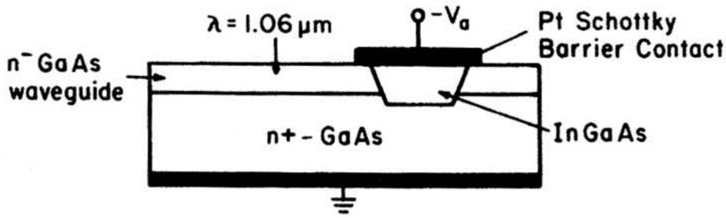
Hybrid Structure

How to monolithically integrate a low-loss waveguide and a high-absorption waveguide detector?



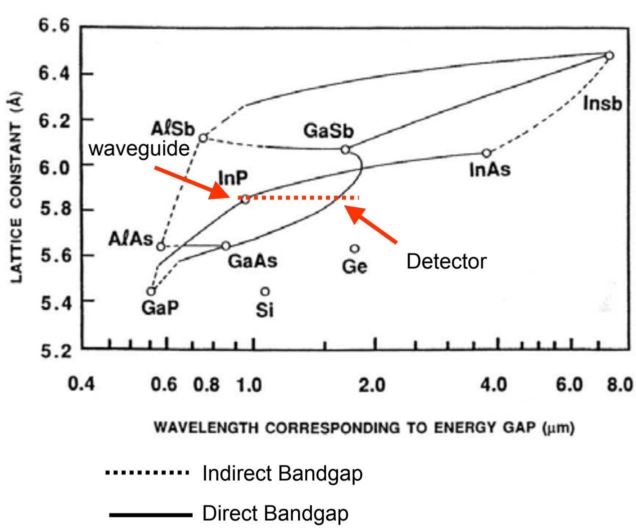
- Hybrid structure
  - Waveguide --- glass
  - Detector --- p+ silicon
- The waveguide loss is 0.8dB/cm (632.8 nm wavelength)
- However, the light enters the diode in the direction normal to junction plane.

Heteroepitaxial Growth

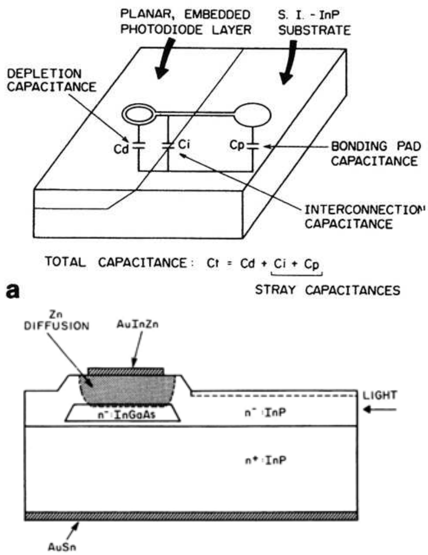


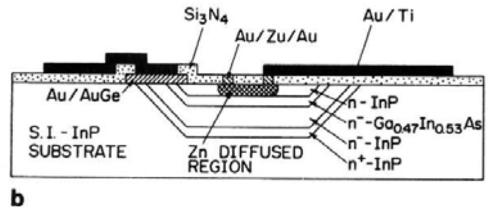
- The most popular method of monolithically integrating a waveguide and a detector is to use heteroepitaxial growth
  - Narrow bandgap --- detector (InGaAs)
  - Wide bandgap --- waveguide (GaAs)
- The absorbed wavelength ranges from 0.9 μm to 3.5 μm by controlling the x $In_xGa_{(1-x)}As$
- A thick oxide layer was pattern as a mask and GaAs was etched. Then InGaAs is epitaxially grown on the etched pits.
- The stress at the interface may play a role in reducing quantum efficiency.

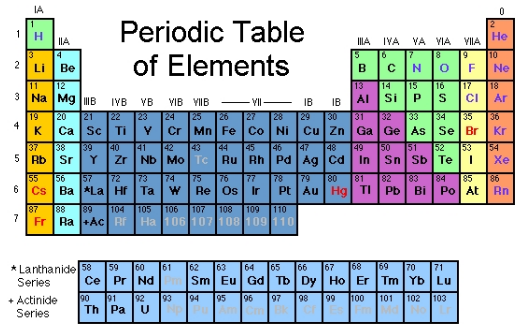
Dependency of absorption edge wavelength and lattice constant



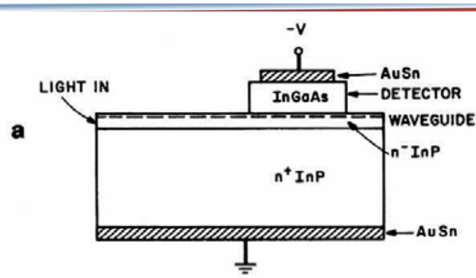
A planar embedded GaInAs p-i-n photodiode

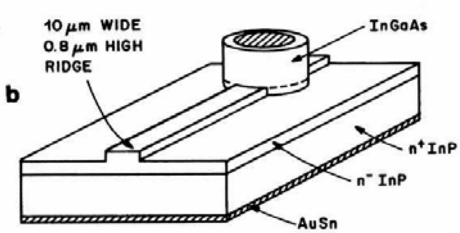






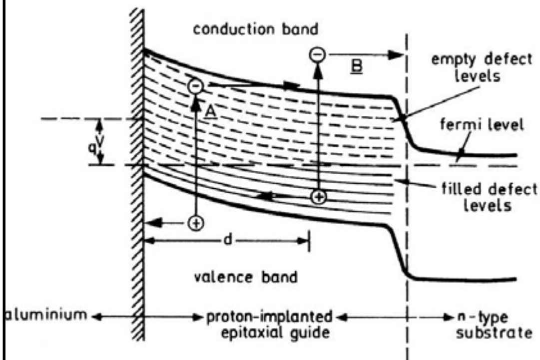
Integrated GaInAs Photodiodes and InP waveguides

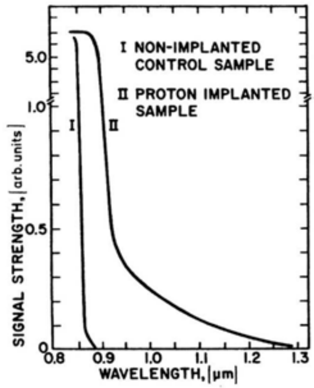




- **An InGaAs detector was grown on top of the waveguide.**
- **Since InGaAs has a larger index of refraction than InP, light is coupled out of waveguide up into the detector.**

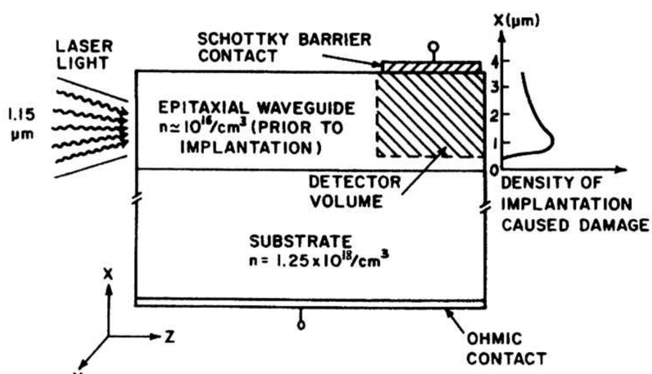
Proton-Bombarded Detectors





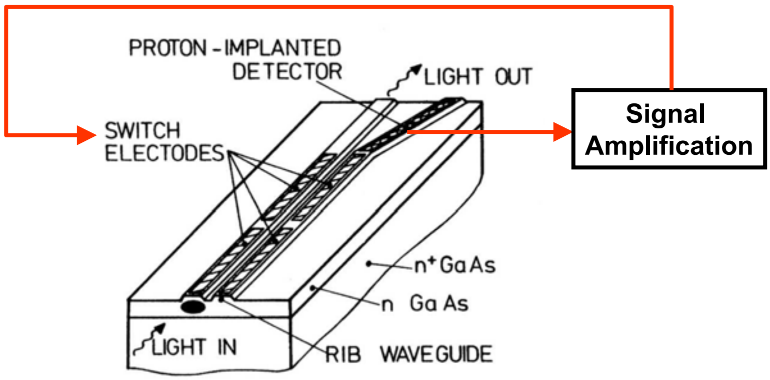
- Proton Bombardment creates traps of carriers. These carriers will be excited out by photon illumination
- The implanted protons also create various defect modes within the bandgap. Therefore, it reduces the absorption edge wavelength

Proton-Bombarded Waveguide Detectors



- **A 3.5 μm thick n-type epitaxial layer ($n \sim 10^{16}/cm^3$) was grown on a degenerately doped n-type substrate ($n \sim 10^{18}/cm^3$).**
- **Proton bombardment in the detector region.**
- **A partial annealing of damage at 500°C for 30 min was performed to reduce the scattering loss (non-interband absorption)**

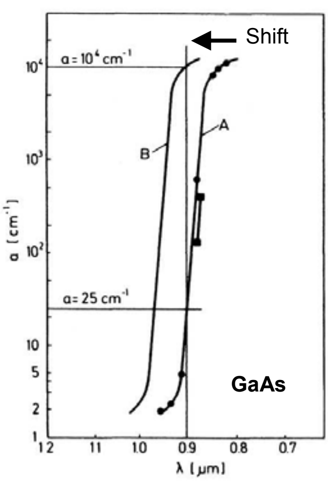
Optical Bistable Devices by Proton-Bombardment Detectors

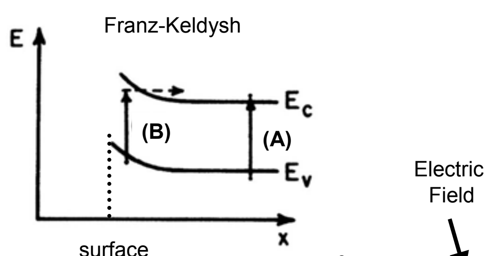


- A directional coupler is controlled by the electrodes.
- The optical detector is employed in one arm of the output waveguides.
- The photocurrent output is amplified by an external circuit and fed back to the control electrodes.

Electro-Absorption

Recall

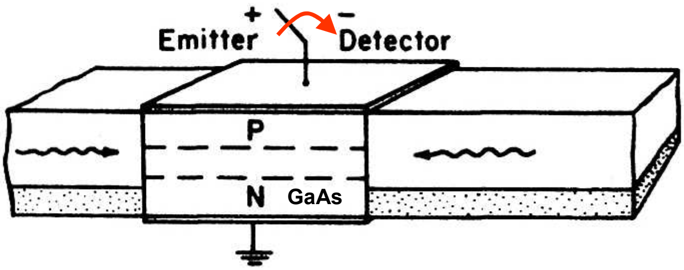




$$\Delta E = \frac{3}{2}(m^*)^{-1/3}(q\hbar\varepsilon)^{2/3}$$

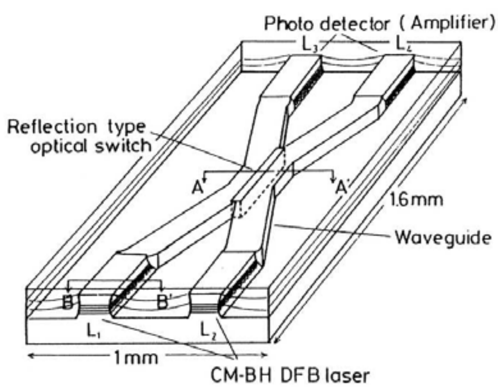
- The band edge shifts to long wavelength with electric bias
- Energy band bends significantly near surface

Integrated-Optic Light Emitting and Detecting Diodes (LEAD)



- By electro-absorption, the absorption edge is shifted to long wavelength.
- The absorption is controlled by reverse bias so that the emitters and detectors can be made in the same semiconductor material.
  – Emitter → forward bias
  – Detector → reverse bias

Distributed Feedback Light Emitting and Detecting Diodes



- Lasers, detectors, amplifiers and switches are integrated monolithically.

Factor Limiting Performance of Integrated Detectors

(1) High Frequency Cutoff

- RC time due to series resistance and junction capacitance --- dramatically reduced in waveguide photodiode
- Carrier drift time across the depletion layer (eg, in GaAs, the scattering limited velocity is 1×10^7 cm/s in electric field greater than 2×10^4 V/cm.)
- Carrier diffusion time (outside the depletion layer)
- Carrier life time and diffusion length
- Carrier trapping and detrapping time
- Capacitance and inductance of the package

(2) Linearity

- At low power levels, the photocurrent is proportional to the input power. However, at high power levels, the electric field is reduced due to space-charge effects, resulting in low drift velocity. The generated carriers are also easily recombined.

Factor Limiting Performance of Integrated Detectors

(3) Noise

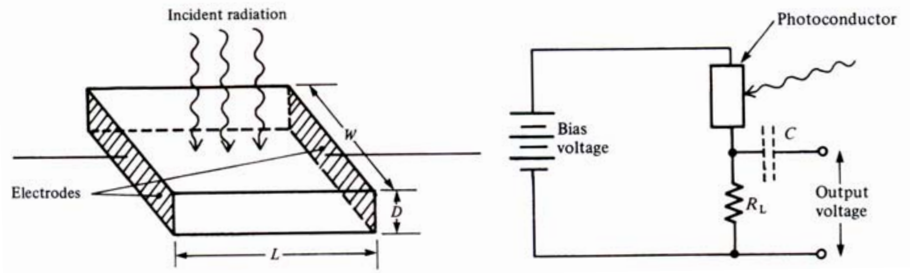
- Thermal Noise
  - Arising in bulk resistances of device
- Shot Noise
  - Non-uniformities of current flow such as carrier generation and recombination
- Background Noise
  - Photons from background (not part of optical signal).

The signal-to-noise ratio in a depletion layer photodiode due to thermal and shot noise is given by

$$\left(\frac{S}{N}\right)_{power} = \frac{\eta_q}{4B} M^2 \varphi_0 A \left(1 + \frac{2KT}{q} \frac{(\omega RC)^2}{RI_s}\right)^{-1}$$

η_q : quantum efficiency
φ_0 : photon flux
R : diode bulk resistance
B : bandwidth
A : input area
I_s : dark current
M : modulation index
K : Boltzmann's constant
C : capacitance

Photoconductive detectors

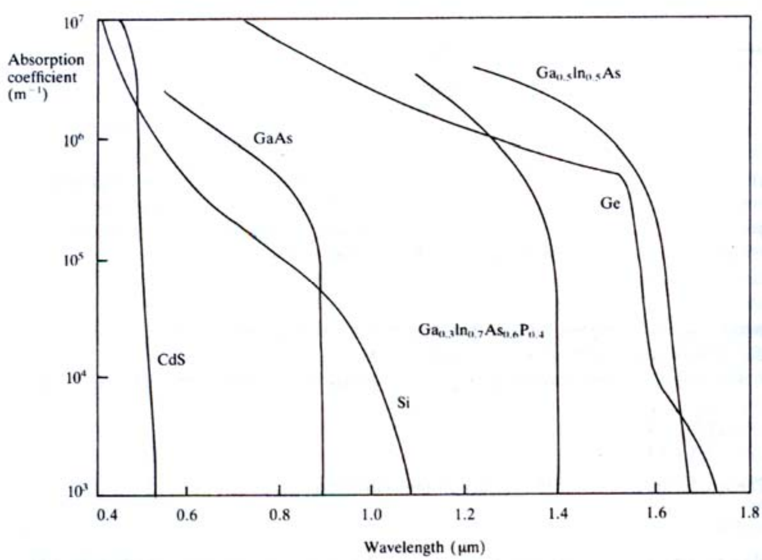


• An electron may be raised from the valence band to the conduction band in a semiconductor by absorbing a photon of frequency ν

$$h\nu > E_g \quad \text{or} \quad \lambda \le \frac{hc}{E_g}$$

• As long as the electron remains in the conduction band, the conductivity of the semiconductor will be increased. This is the phenomenon of photoconductivity.

Absorption Coefficient of Materials



Photoconductive detectors

Not all of this incident energy will be available to generate electrons within the semiconductor: some will be reflected and some will pass trough. The reflection coefficient is given by r

$$r = \left(\frac{n-1}{n+1}\right)^2$$

The irradiance just inside the surface

$$I(0) = I_0(1-r)$$

The irradiance at a point a distance x into the semiconductor

$$I(x) = I(0)\exp(-\alpha x)$$ Where α is absorption coefficient

Photoconductive detectors

The fraction of the incident irradiance which is actually absorbed in the semiconductor can thus be written

$$\eta = (1-r)\cdot\eta_{abs}$$ **where** $$\eta_{abs} = 1-\exp(-\alpha D)$$

The total number of electron-hole pairs generated within the slab per second is

$$r_g = \frac{\eta I_0 WL}{h\nu WLD} = \frac{\eta I_0}{h\nu D}$$

The recombination rate r_r of excess carriers depends on the densities of the excess carrier population $\Delta n, \Delta p$

$$r_r = \Delta n/\tau_c = \Delta p/\tau_c$$ τ_c:minority carrier lifetime

Photoconductive detectors

In equilibrium the recombination rate must equal the generation rate

$$\Delta n = \Delta p = r_g \tau_c$$

The conductivity of a semiconductor material can be written by

$$\sigma = ne\mu_e + pe\mu_h$$

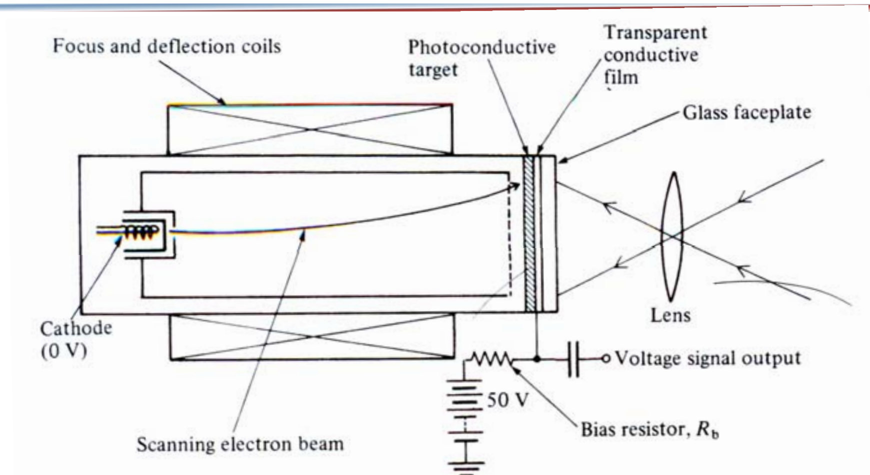
Hence under illumination the dark conductivity will increase by an amount

$$\Delta\sigma = \Delta ne\mu_e + \Delta pe\mu_h = r_g \tau_c e(\mu_e + \mu_h)$$

The application of a voltage V across the electrodes will result in a photoinduced current △i

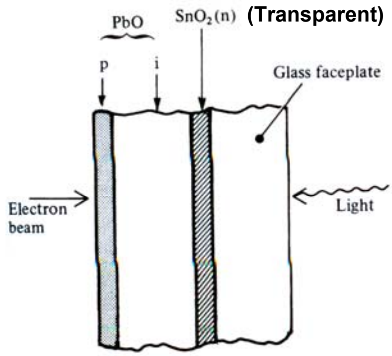
$$\Delta i = \frac{WD}{L}\Delta\sigma V \quad \text{or} \quad \Delta i = \frac{WD}{L} r_g \tau_c e(\mu_e + \mu_h)V$$

Vidicons and plumbicons

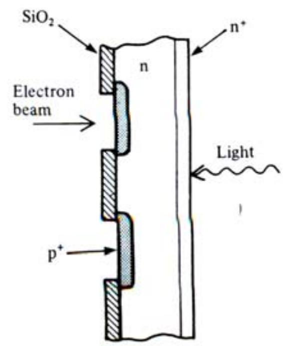


The vidicon is a generic name for a family of devices that relies on the phenomenon of photoconductivity to convert an optical image into an electrical signal.

Principle of Image Conversion (Vidicon)



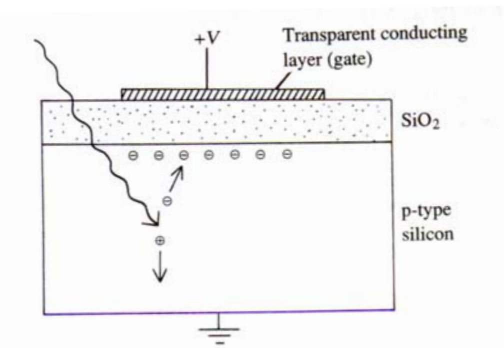
p-i-n Scheme

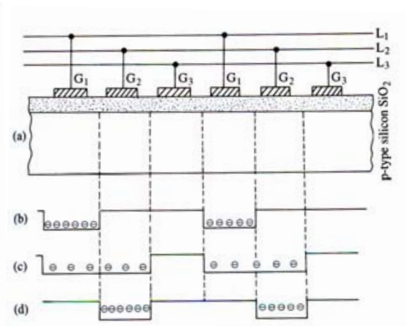


p-n Scheme

- The photoconductive target is like a leaky capacitor
- One of the problems is its relatively high dark current
- A device which exhibits very low dark currents is the plumbicon, consisting of a thin film p-i-n structure

Charge-coupled device (CCD)





Three-phase scheme

- The gate can be made from polysilicon, which is reasonably transparent between 400nm to 1100nm.

Charge-coupled device (CCD)

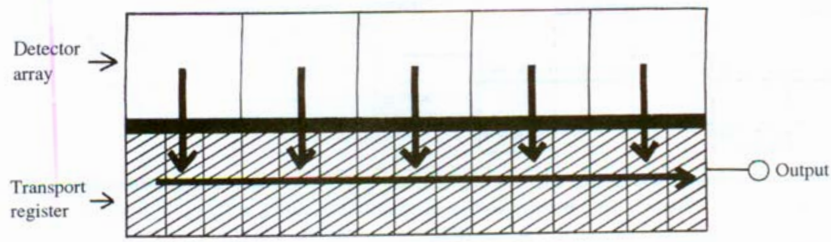


FIG. 7.47 Basic arrangement of the detector array and transport register in a linear CCD optical sensing array. The directions of charge transport are indicated by arrows and shading indicates those areas that are shielded from incident radiation.

- **Little charges may lost on the way of transfer. The fraction of the total charge which is successfully moved in each transfer is called the charge transfer efficiency** η_{ct}

$(\eta_{ct})^m$ **m: transfer times**