OPTI510R: Photonics

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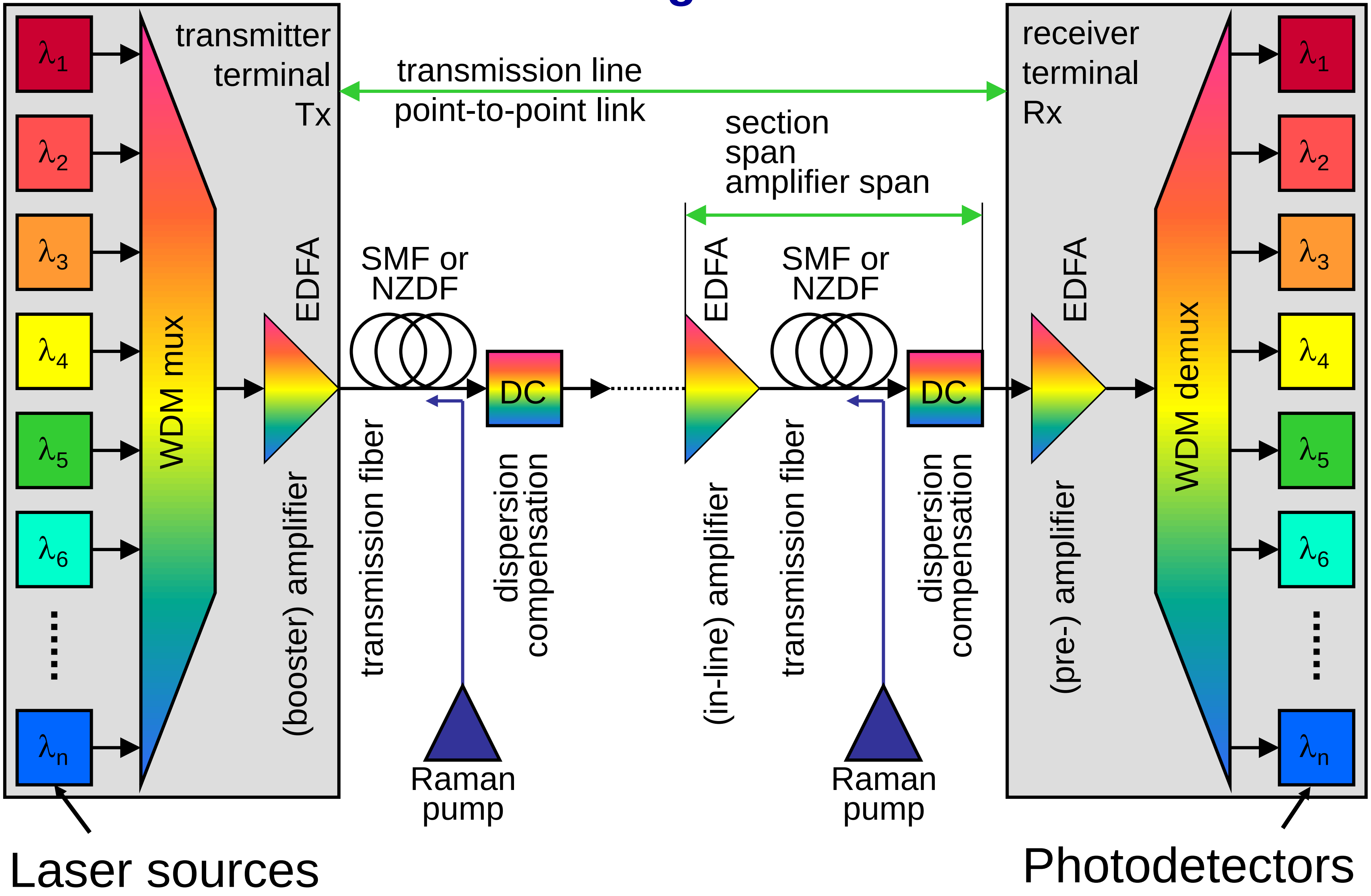
Photodetectors

- ➢ Introduction
- ➢ Most important characteristics
- ➢ Photodetector types
  - Thermal photodetectors
  - Photoelectric effect
  - Semiconductor photodetectors

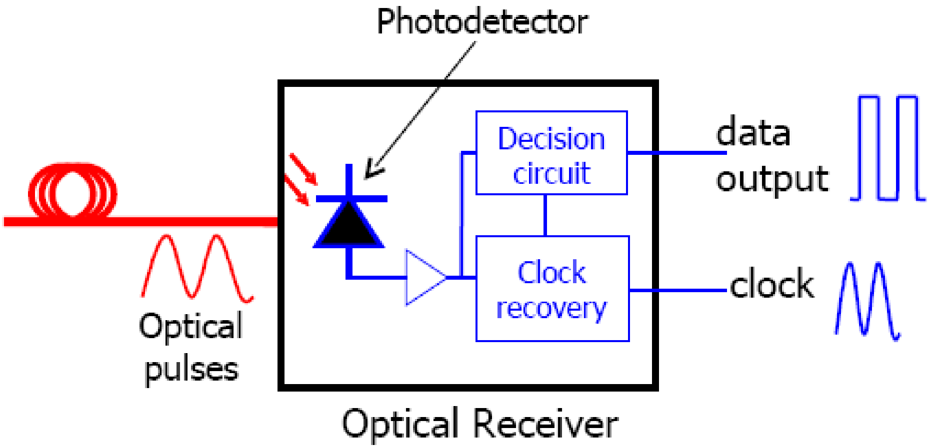
Photodetectors

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

Point-to-point WDM Transmission System
- Building Blocks -



Introduction



Photodetector

Decision circuit

Clock recovery

data output

clock

Optical pulses

Optical Receiver

Convert optical data into electrical data

Laser beam characterization

- Power measurement
- Pulse energy measurement
- Temporal waveform measurement
- Beam profile

Introduction

- ➢ Photodetector converts photon energy to a signal, mostly electric signal such as current (sort of a reverse LED)

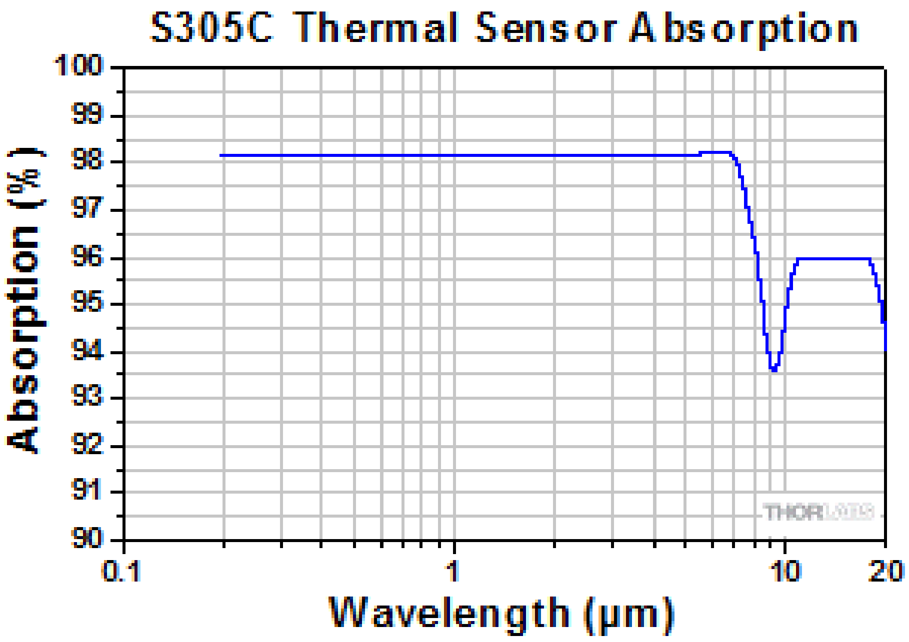
- ➢ Photoelectric detector
  - Carrier generation by incident light
  - Carrier transport and/or multiplication by current gain mechanism
  - Interaction of current with external circuit

- ➢ Thermal detector
  - Conversion of photon to phonon (heat)
  - Propagation of phonon
  - Detection of phonon

Important characteristics

- Wavelength coverage
- Sensitivity
- Bandwidth (response time)
- Noise
- Surface area
- Reliability
- Cost

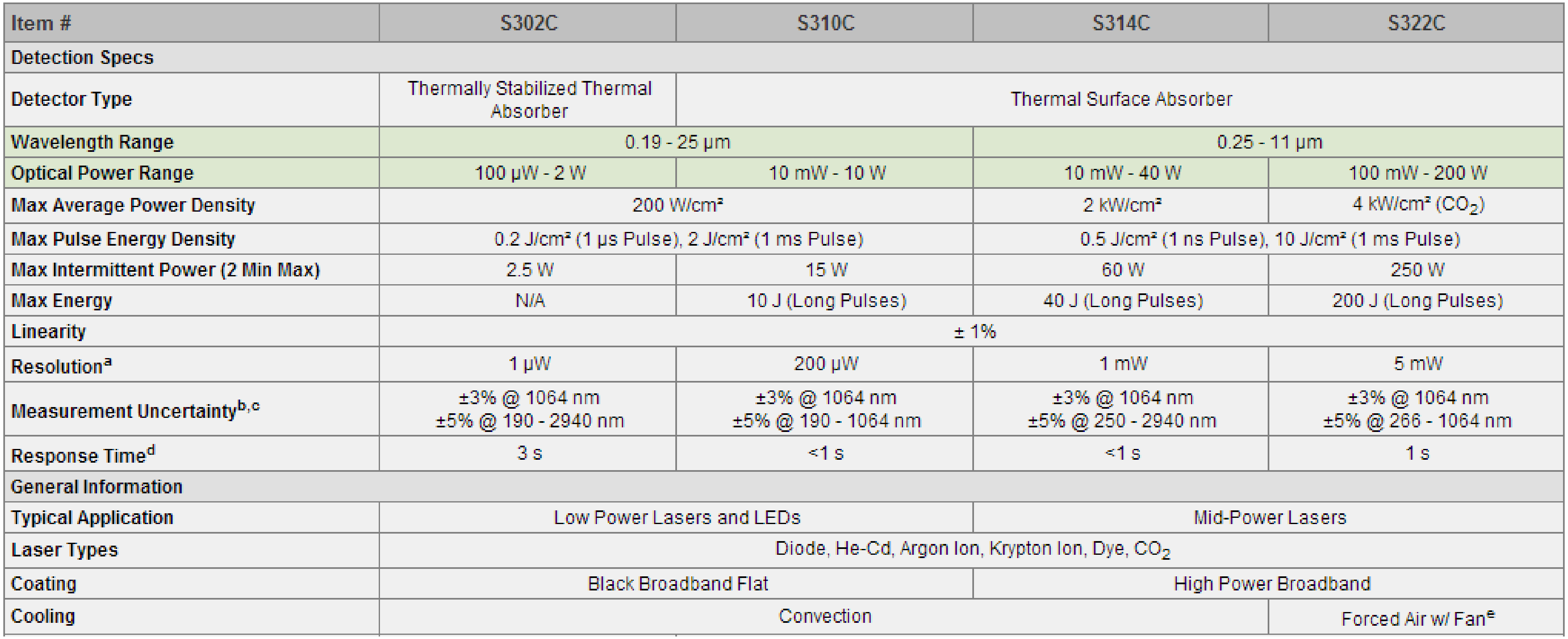
Thermal photodetectors



- ➢ Relatively Flat Spectral Response over a Large Wavelength Range
- ➢ Very small bandwidth (few Hz at most)
- ➢ Low sensitivity

Thermal photodetectors

Standard thermal power meters



Item #	S302C	S310C	S314C	S322C
Detection Specs				
Detector Type	Thermally Stabilized Thermal Absorber	Thermal Surface Absorber		
Wavelength Range	0.19 - 25 µm		0.25 - 11 µm	
Optical Power Range	100 µW - 2 W	10 mW - 10 W	10 mW - 40 W	100 mW - 200 W
Max Average Power Density	200 W/cm²		2 kW/cm²	4 kW/cm² (CO_2)
Max Pulse Energy Density	0.2 J/cm² (1 µs Pulse), 2 J/cm² (1 ms Pulse)		0.5 J/cm² (1 ns Pulse), 10 J/cm² (1 ms Pulse)	
Max Intermittent Power (2 Min Max)	2.5 W	15 W	60 W	250 W
Max Energy	N/A	10 J (Long Pulses)	40 J (Long Pulses)	200 J (Long Pulses)
Linearity	± 1%			
Resolution[a]	1 µW	200 µW	1 mW	5 mW
Measurement Uncertainty[b,c]	±3% @ 1064 nm ±5% @ 190 - 2940 nm	±3% @ 1064 nm ±5% @ 190 - 1064 nm	±3% @ 1064 nm ±5% @ 250 - 2940 nm	±3% @ 1064 nm ±5% @ 266 - 1064 nm
Response Time[d]	3 s	<1 s	<1 s	1 s
General Information				
Typical Application	Low Power Lasers and LEDs		Mid-Power Lasers	
Laser Types	Diode, He-Cd, Argon Ion, Krypton Ion, Dye, CO_2			
Coating	Black Broadband Flat		High Power Broadband	
Cooling	Convection			Forced Air w/ Fan[e]

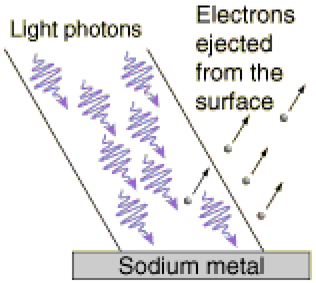
Photoelectric effect

- Absorption of photons creates carriers (electrons)
  - External photoeffect: electron escape from materials as free electrons
  - Internal photoeffect (photoconductivity): excited carriers remain within the material to increase conductivity

- Useful formula:

$$\lambda(\mu m) = \frac{1.24}{E_g(eV)}$$

Photoelectric Effect



Photon energy

$E = h\nu$

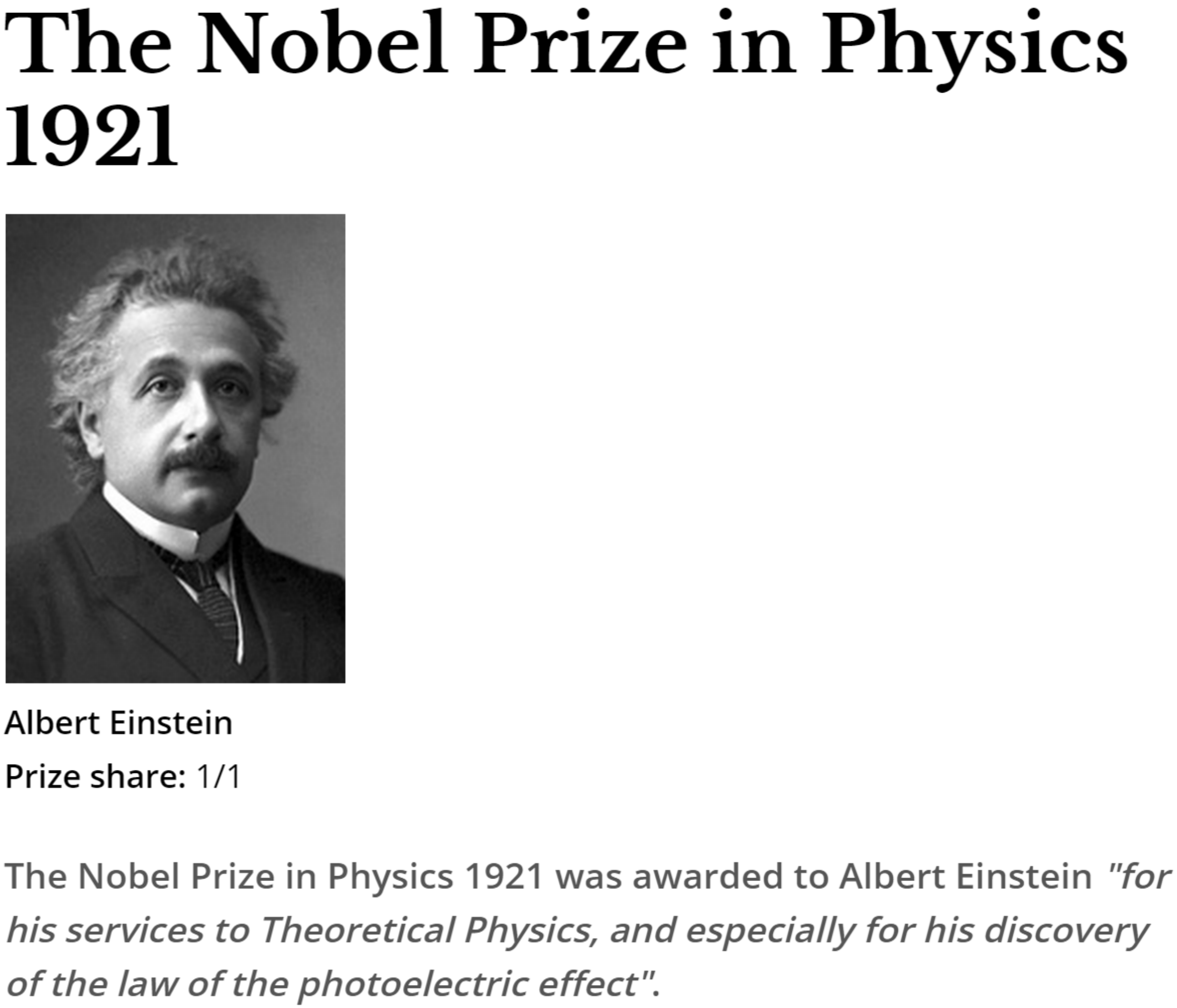
explains the experiment and shows that light behaves like particles.

Photoelectric effect :
a photon with a minimum energy is absorbed to create a free electron

$$h\nu = W + K.E.$$

- Electrons were emitted immediately, no time lag.
- Increasing intensity of light increased number of photoelectrons but not their maximum kinetic energy.
- Red light will not cause ejection of electrons, no matter what the intensity (linear regime).
- A weak violet light will eject only a few electron, but their maximum kinetic energies are greater than those for intense light of longer wavelength.

Photoelectric Effect



The Nobel Prize in Physics 1921

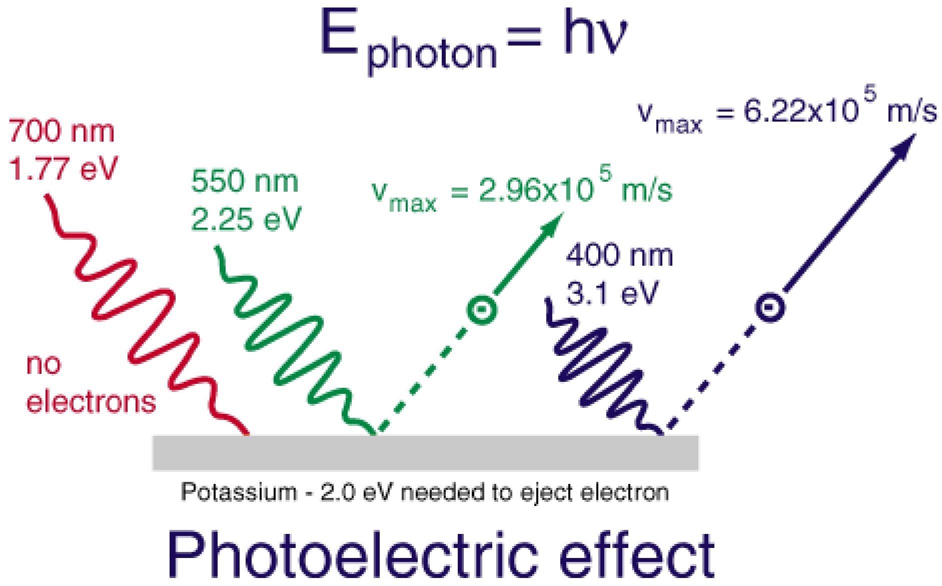
Albert Einstein

Prize share: 1/1

The Nobel Prize in Physics 1921 was awarded to Albert Einstein *"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"*.

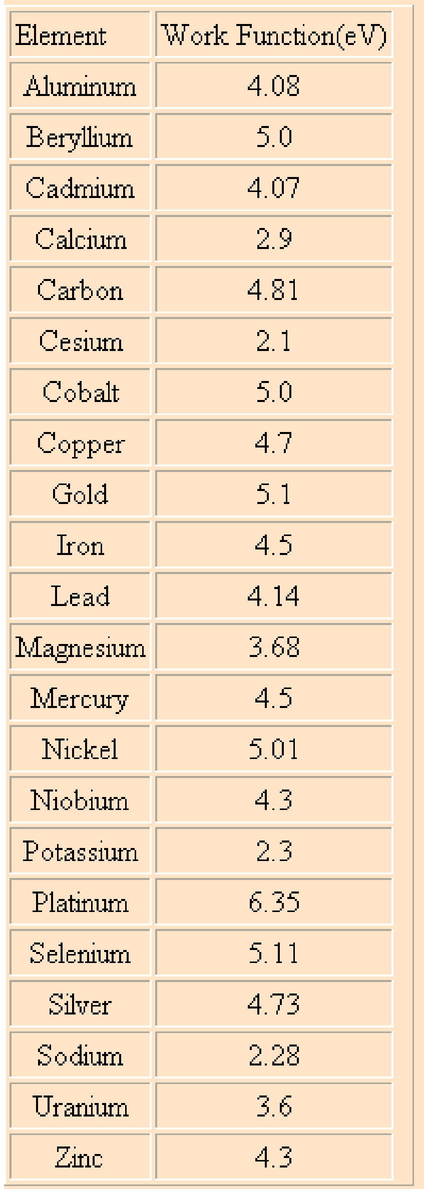
Photoelectric Effect

Work function is the minimum energy needed to remove an electron from a solid to a point immediately outside the solid. It is approximately half the ionization energy of the free atom of the metal and equals to the difference between the vacuum level and Fermi level of the metal.



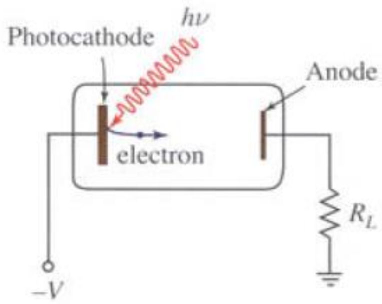
Photoelectric effect

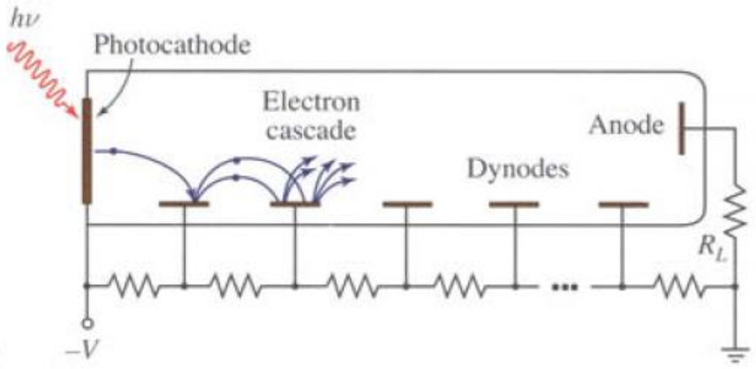
Lowest work function is 2.1eV or ~590nm.



Element	Work Function(eV)
Aluminum	4.08
Beryllium	5.0
Cadmium	4.07
Calcium	2.9
Carbon	4.81
Cesium	2.1
Cobalt	5.0
Copper	4.7
Gold	5.1
Iron	4.5
Lead	4.14
Magnesium	3.68
Mercury	4.5
Nickel	5.01
Niobium	4.3
Potassium	2.3
Platinum	6.35
Selenium	5.11
Silver	4.73
Sodium	2.28
Uranium	3.6
Zinc	4.3

Photo-multiplier tubes (PMT)





- Vacuum photodiode operates when a photon creates a free electron at the photocathode, which travels to the anode, creating a photocurrent.

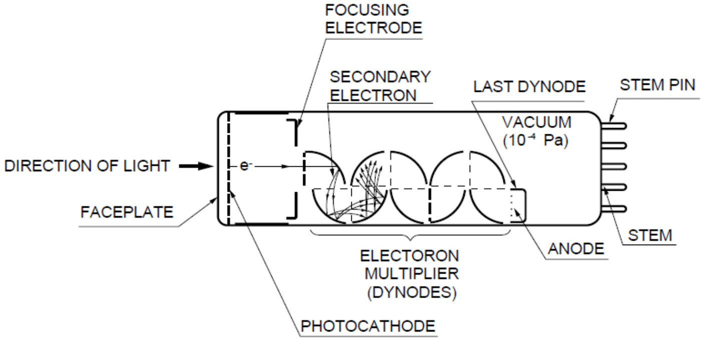
- Photocathode can be opaque (reflection mode) or semitransparent (transmission mode).

- Original electron can create secondary electrons using dynodes, with successive higher potentials, such as a photomultiplier tube, PMT.

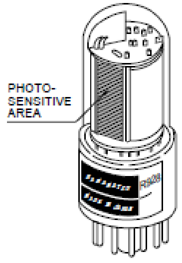
Photo-multiplier tubes (PMT)

Photomultiplier tubes typically require 1000 to 2000 volts for proper operation. The most negative voltage is connected to the cathode, and the most positive voltage is connected to the anode. Voltages are distributed to the dynodes by a resistive voltage divider, though variations such as active designs (with transistors or diodes) are possible.

Cross-Section of Head-On Type PMT



a) Side-On Type



b) Head-On Type

Typical Current Amplification vs. Supply Voltage

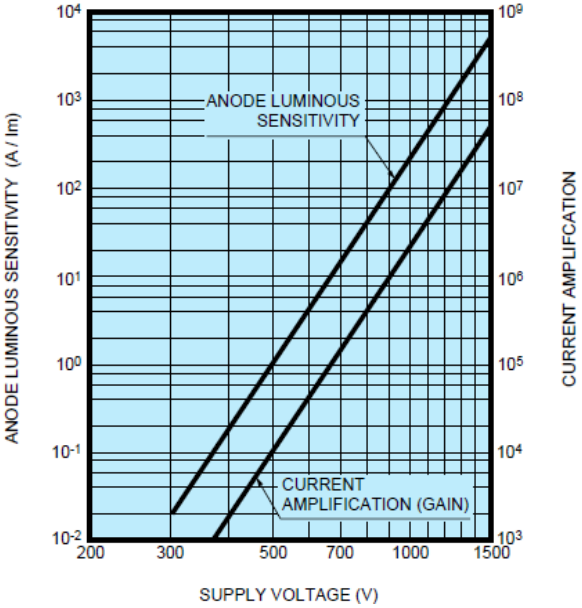


Photo-multiplier tubes (PMT)

- **Ag-O-Cs:** The transmission-mode photocathode using this material is designated S-1 and sensitive from the visible to infrared range (300 to 1200nm). Ag-O-Cs has comparatively high thermionic dark emission.

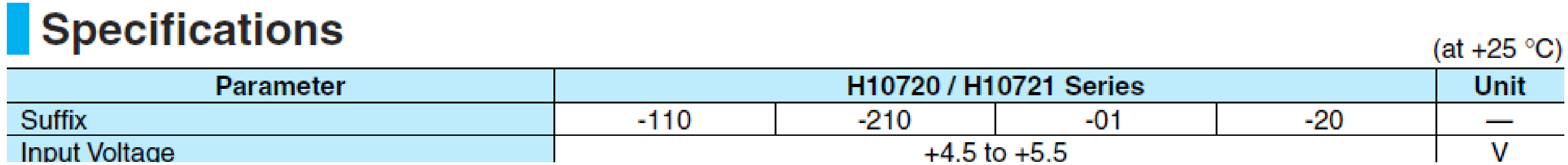
- **GaAs(Cs):** GaAs activated in cesium is also used as a photocathode. The spectral response of this photocathode usually covers a wider spectral response range from ultraviolet to 930nm. GaAsP is very popular for multiphoton microscopy.

- **InGaAs(Cs):** This photocathode has greater extended sensitivity in the infrared range than GaAs. Moreover, in the range between 900 and 1000nm, InGaAs has much higher S/N ratio than Ag-O-Cs.

- **Sb-Cs:** This is a widely used photocathode and has a spectral response in the ultraviolet to visible range. This is not suited for transmission-mode photocathodes and mainly used for reflection-mode photocathodes.

- **Bialkali (Sb-Rb-Cs, Sb-K-Cs):** These have a spectral response range similar to the Sb-Cs photocathode, but have higher sensitivity and lower noise than Sb-Cs.

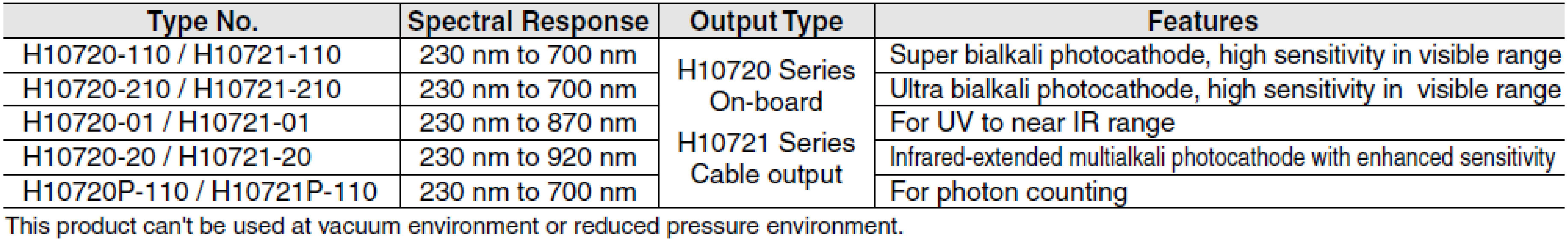
Photo-multiplier tubes (PMT)



Specifications

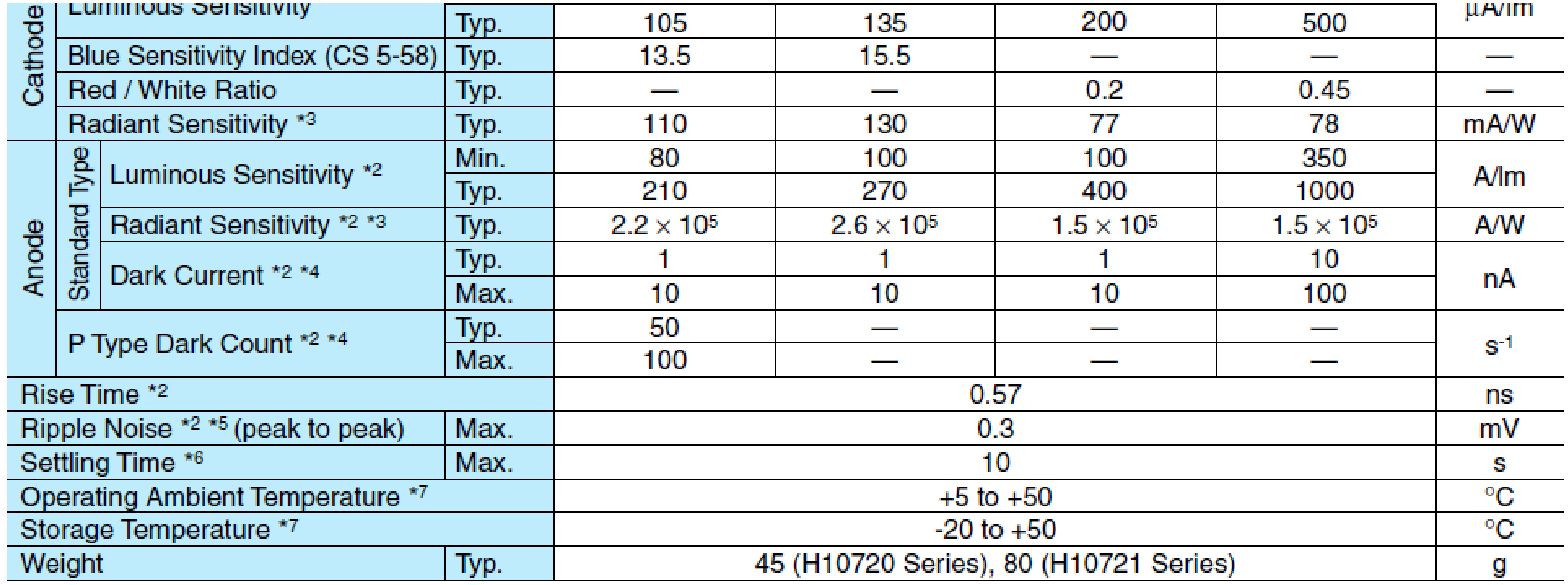
(at +25 °C)

Parameter	H10720 / H10721 Series				Unit
Suffix	-110	-210	-01	-20	—
Input Voltage	+4.5 to +5.5				V



Type No.	Spectral Response	Output Type	Features
H10720-110 / H10721-110	230 nm to 700 nm	H10720 Series On-board H10721 Series Cable output	Super bialkali photocathode, high sensitivity in visible range
H10720-210 / H10721-210	230 nm to 700 nm		Ultra bialkali photocathode, high sensitivity in visible range
H10720-01 / H10721-01	230 nm to 870 nm		For UV to near IR range
H10720-20 / H10721-20	230 nm to 920 nm		Infrared-extended multialkali photocathode with enhanced sensitivity
H10720P-110 / H10721P-110	230 nm to 700 nm		For photon counting

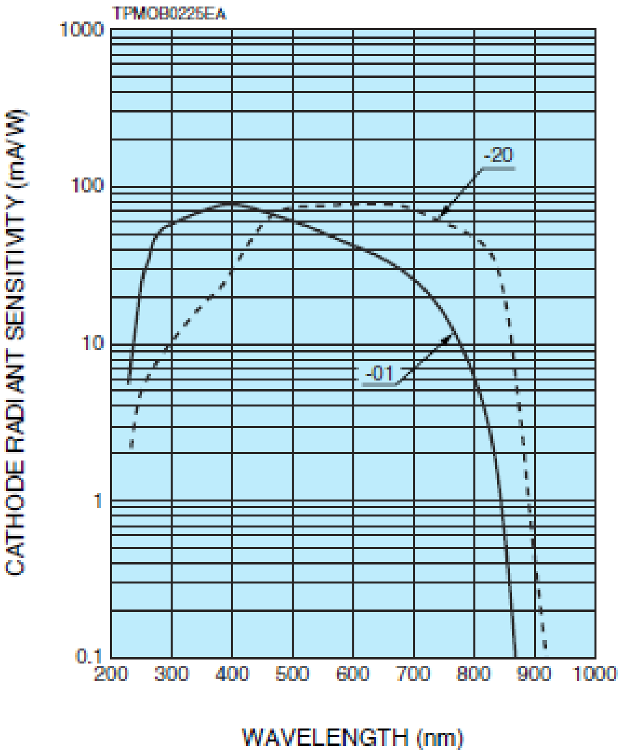
This product can't be used at vacuum environment or reduced pressure environment.



		Parameter		-110	-210	-01	-20	Unit
Cathode		Luminous Sensitivity	Typ.	105	135	200	500	µA/lm
		Blue Sensitivity Index (CS 5-58)	Typ.	13.5	15.5	—	—	—
		Red / White Ratio	Typ.	—	—	0.2	0.45	—
		Radiant Sensitivity *3	Typ.	110	130	77	78	mA/W
Anode	Standard Type	Luminous Sensitivity *2	Min.	80	100	100	350	A/lm
			Typ.	210	270	400	1000	
		Radiant Sensitivity *2 *3	Typ.	2.2×10^5	2.6×10^5	1.5×10^5	1.5×10^5	A/W
		Dark Current *2 *4	Typ.	1	1	1	10	nA
			Max.	10	10	10	100	
		P Type Dark Count *2 *4	Typ.	50	—	—	—	s^{-1}
			Max.	100	—	—	—	
Rise Time *2				0.57				ns
Ripple Noise *2 *5 (peak to peak)			Max.	0.3				mV
Settling Time *6			Max.	10				s
Operating Ambient Temperature *7				+5 to +50				°C
Storage Temperature *7				-20 to +50				°C
Weight			Typ.	45 (H10720 Series), 80 (H10721 Series)				g

Photo-multiplier tubes (PMT)

With internal amplifier



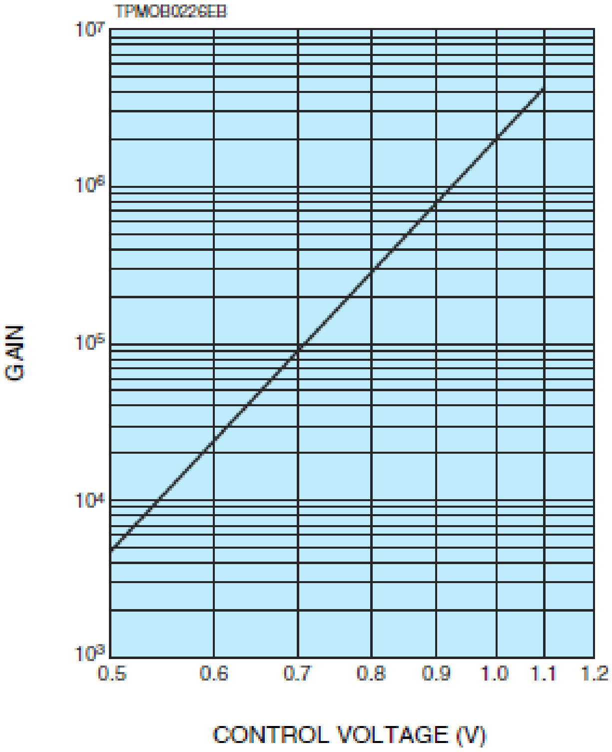
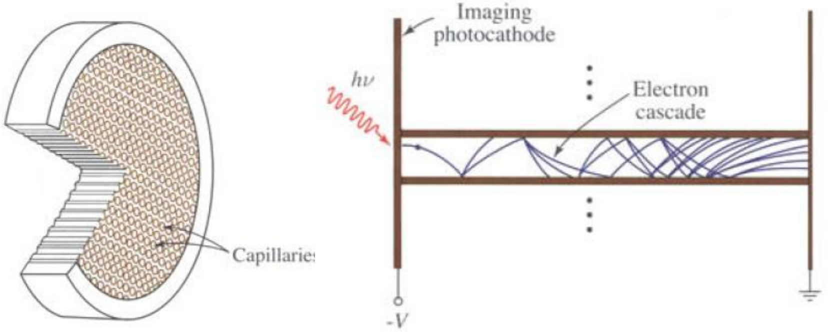


Photo-multiplier tubes (PMT)

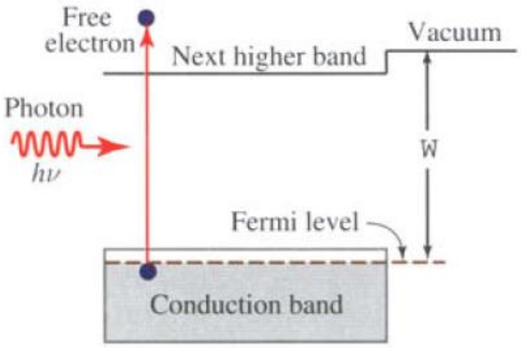
Example of applications:

- Spectroscopy
- Fluorometer
- Medical applications
- Laser radar
- Night vision

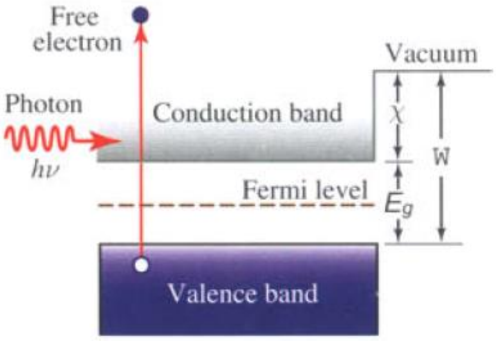


microchannel plate image intensifier

Photoelectric Effect



(*a*) Metal



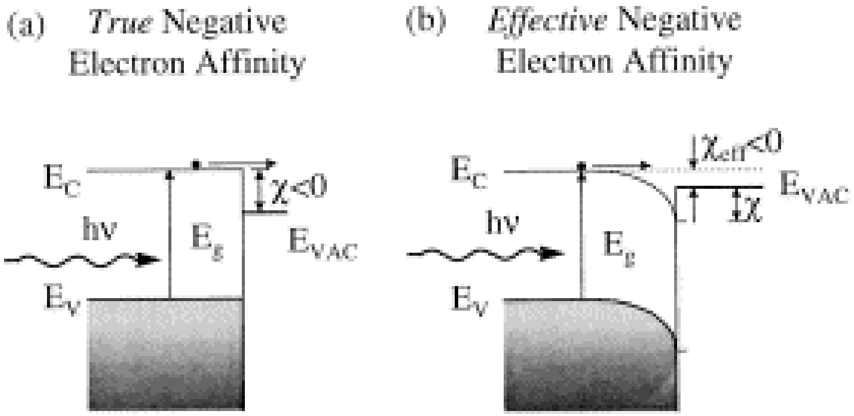
(*b*) Semiconductor

Maximum kinetic energy from a metal: $E_{\max} = h\nu - W$

Maximum kinetic energy from a semiconductor: $E_{\max} = h\nu - (E_g + \chi)$

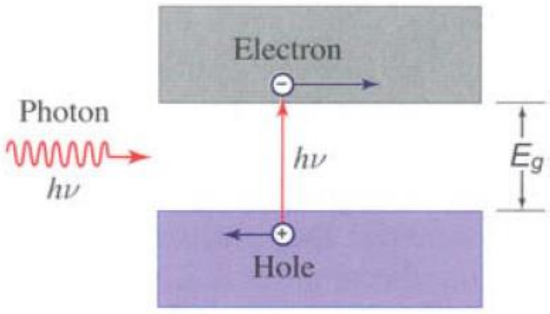
χ = electron affinity, difference between vacuum level and bottom of conduction band

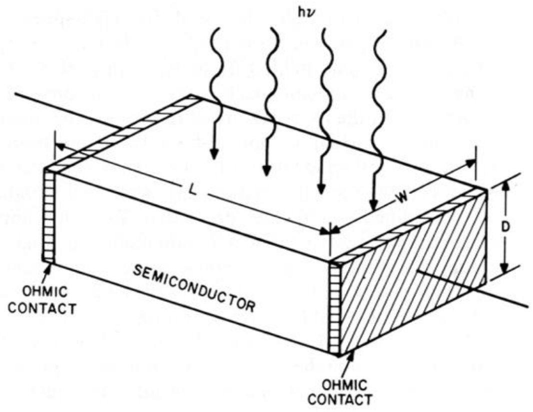
Negative electron affinity



- Semiconductor with conduction band edge above vacuum level
- Photon with E > E_g creates free electrons
- III-V semiconductor (ex. GaAs) can be activated to a state of negative electron affinity by treatment of surface with cesium and oxygen

Internal photoelectric effect

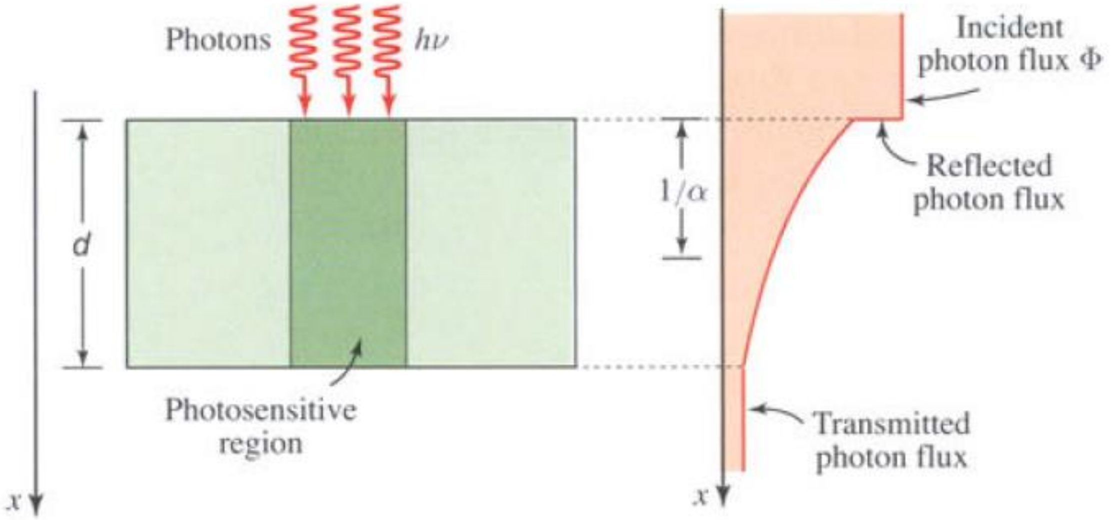




Most photodetectors operate on photoconductivity, where carriers are generated inside the crystal. One example is the photodiode based on a p-n junction. Gain can be achieved through impact ionization by initial electrons. Amplified photoelectric detectors involve three processes:

1) Generation: photons are converted to free carriers
2) Transport: applied E field moves the free carriers
3) Gain: accelerated carriers create more carriers by impact ionizations (in APD, for example)

Quantum efficiency



Quantum efficiency, η, equals to probability of single photon to generate a pair of detectable carriers

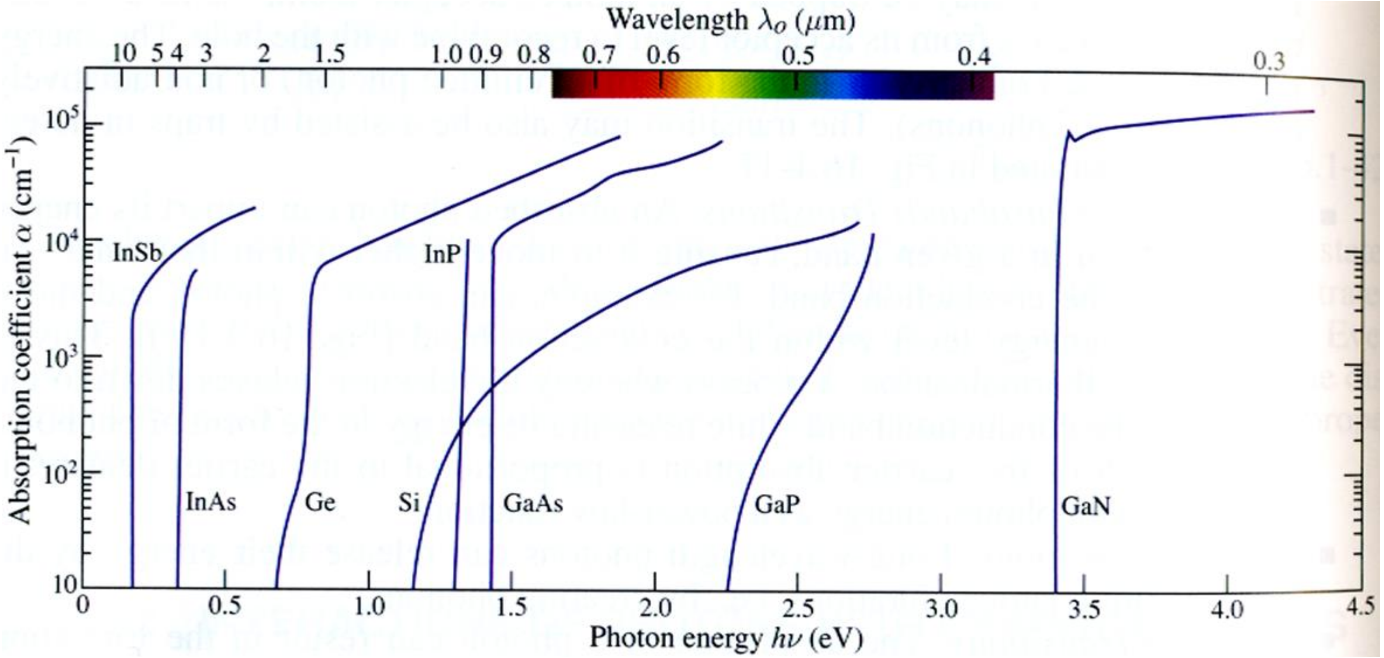
$$\eta = (1 - R)\zeta\left[1 - \exp(-\alpha d)\right]$$

surface reflection

fraction of e-h contribute to current

fraction of absorbed photons

Wavelength coverage



Short wavelength limit is determined by large absorption at surface 1/α, carrier lifetime is short at surface

Long wavelength limit: $\lambda_0 \geq \lambda_g = hc_0 / E_g$

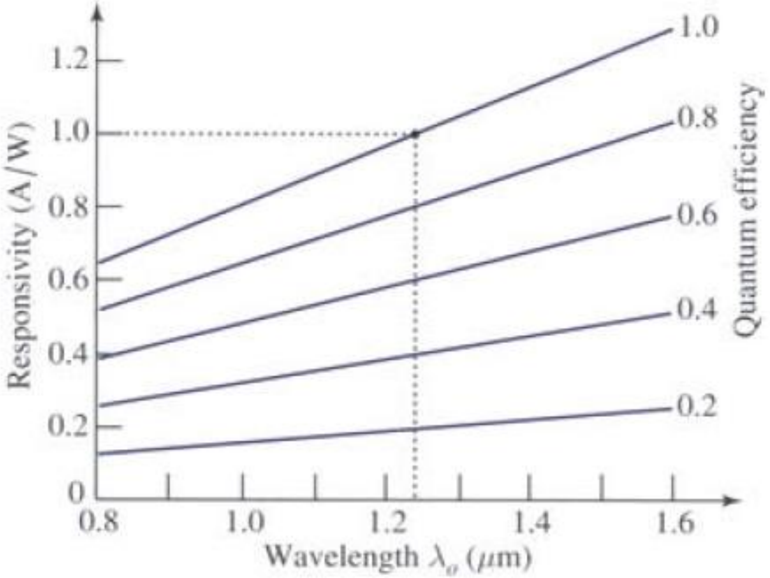
Responsivity

Responsivity, R, relates electric current, i_p, and incident optical power P

$$i_p = \frac{\eta e P}{h\nu} \equiv RP$$

$$R = \frac{\eta e}{h\nu} = \eta \frac{\lambda_0(\mu m)}{1.24} (Amp/Watt)$$

For $\eta=1$, $\lambda=1.24\mu m$, $R=1$ (A/W)



We consider here linear response only. All detectors saturate at high power and have finite dynamic range.

Responsivity

For detector with gain, the photocurrent and responsivity are modified.

Gain $$G = \frac{\#\,\text{of charge generated per carrier pair}}{e}$$

Photo current $$i_p = G\frac{\eta eP}{h\nu}$$

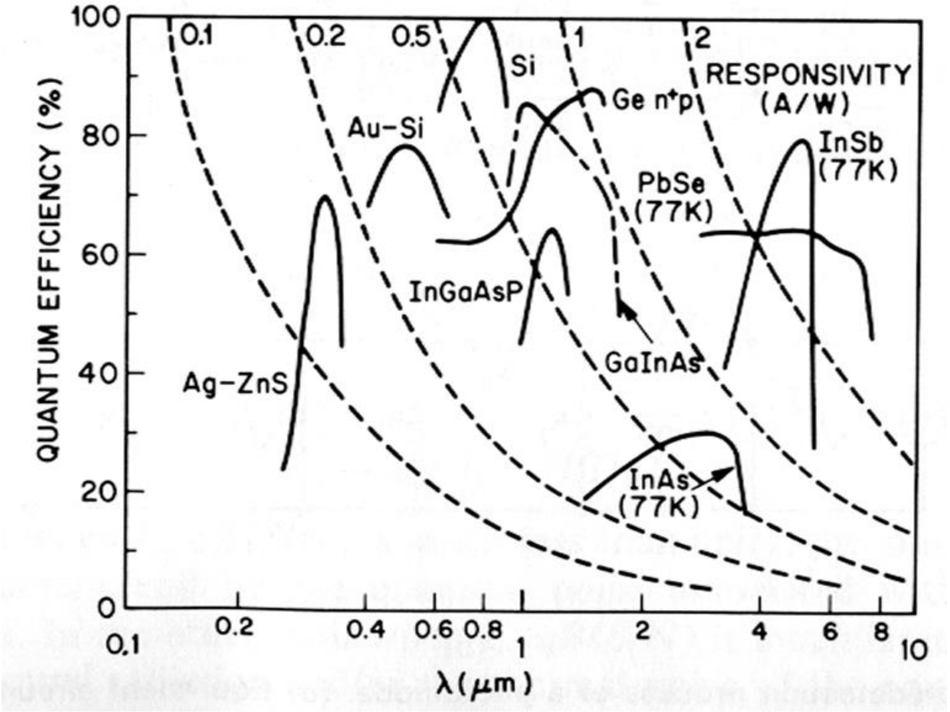
Responsivity $$R = \eta G\frac{\lambda_0}{1.24}$$

Gain can range from 1 to 10^6.

Responsivity

In UV and visible wavelength, metal semiconductor photodiodes show good η. In near-infrared, silicon photodiodes with antireflection coating can reach η=100% near 0.8 to 0.9μm. In 1 to 1.6 μm, Ge photodiodes, III-V ternary photodiodes (InGaAs) and III-V quaternary photodiodes (InGaAsP) have high η. For longer wavelengths, photodiodes are typically cooled (77K).

$$R = \eta \frac{\lambda_0(\mu m)}{1.24}$$



Response time: Ramo's theorem

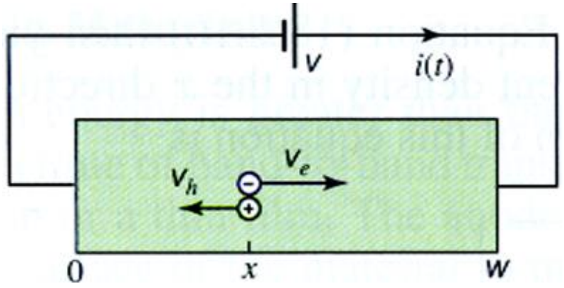
Even if the photon is absorbed instantaneously with the generation of e-h pair, there is a finite time before the carriers emerge as a detectable current.

In a constant electric field, E, inside a semiconductor, charge carriers will (1) accelerate with acceleration, a, (2) collide with imperfection and (3) effectively travel with an average velocity, v.

$$v = a\tau_{col} = \left(\frac{eE}{m}\right)\tau_{col} = \mu E$$

Here τ_{col} is mean time between collision and m is effective mass, μ is mobility.

Consider a carrier with charge Q moves a distance *dx* in time *dt* under a field *E=V/w*



By energy conservation:

$$-QEdx = -Q(\frac{V}{w})dx = i(t)Vdt$$

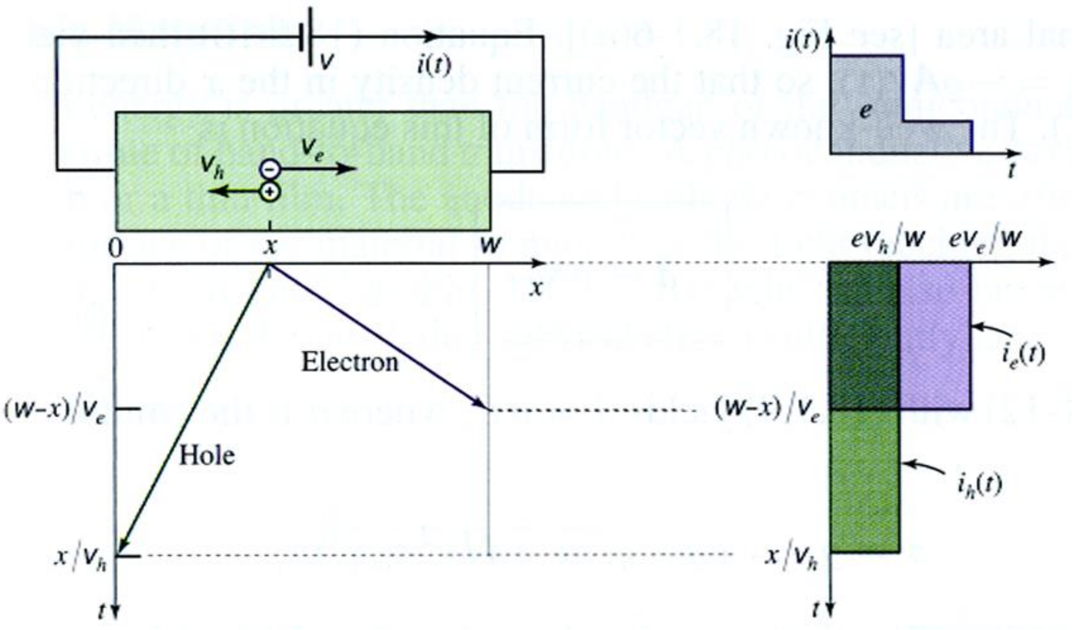
A carrier moving with a drift velocity in x direction creates a current

$$\boxed{i(t) = -\frac{Q}{w}\frac{dx}{dt} = -\frac{Q}{w}v(t)}$$

Response time: Ramo’s theorem

$i_e = -(-e)v_e / w$ electron current

$i_h = -e(-v_h) / w$ hole current



total charge induced in external circuit

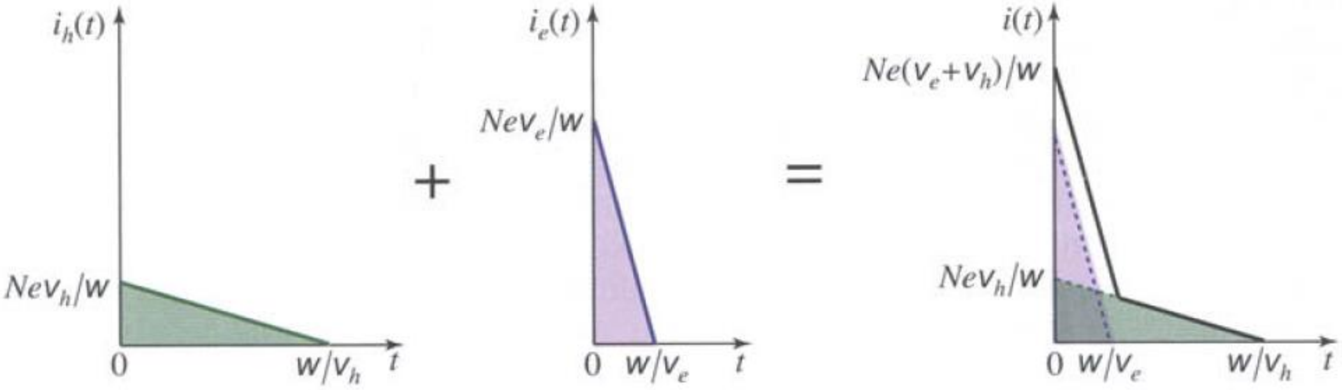
$$q = e\frac{v_h}{w}\frac{x}{v_h} + e\frac{v_e}{w}\frac{w-x}{v_e} = e\left(\frac{x}{w} + \frac{w-x}{w}\right) = e$$

(not 2e!)

Response time: Ramo's theorem

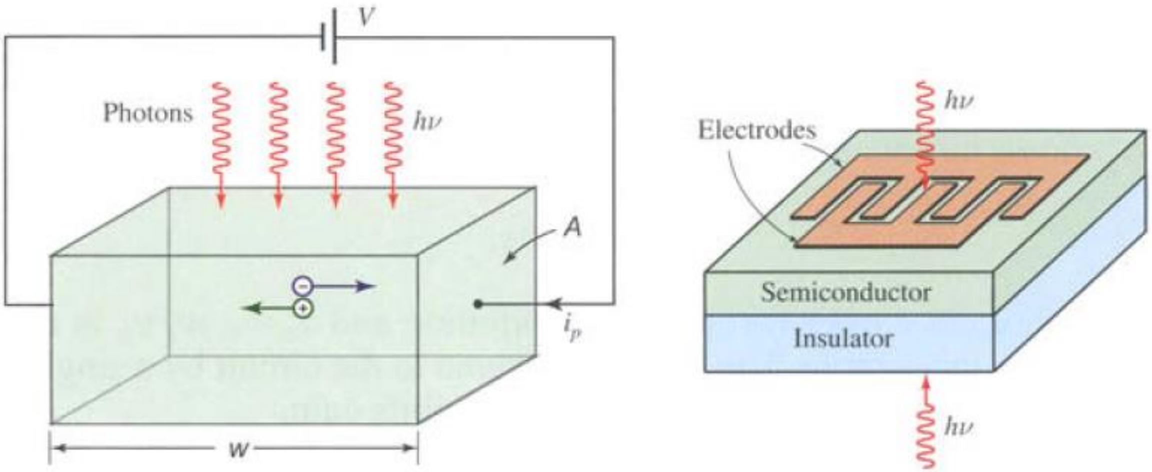
Current induced by N photons uniformly distributed between 0 and w. i(t) can be viewed as the impulse response function for a uniformly illuminated detector subject to transit time spread.

$$i_h(t) = \begin{cases} -\dfrac{Nev_h^2}{w^2}t + \dfrac{Nev_h}{w}, & 0 \le t \le \dfrac{w}{v_h} \\ 0 & \text{elsewhere} \end{cases}$$



Current for each type of carrier is linear with time. Charge delivered to external circuit is not instantaneous and has a finite spread determined by drift velocities.

Photoconductors



(a) (b)

Photoconductive detectors can be classified as intrinsic or extrinsic. In intrinsic photoconductor, mobile charge carriers are generated by incident photon flux Φ (photon per second). The generated photo-current is proportional to the photon flux:

$$i_p \approx \eta(\tau/\tau_e)e\Phi$$

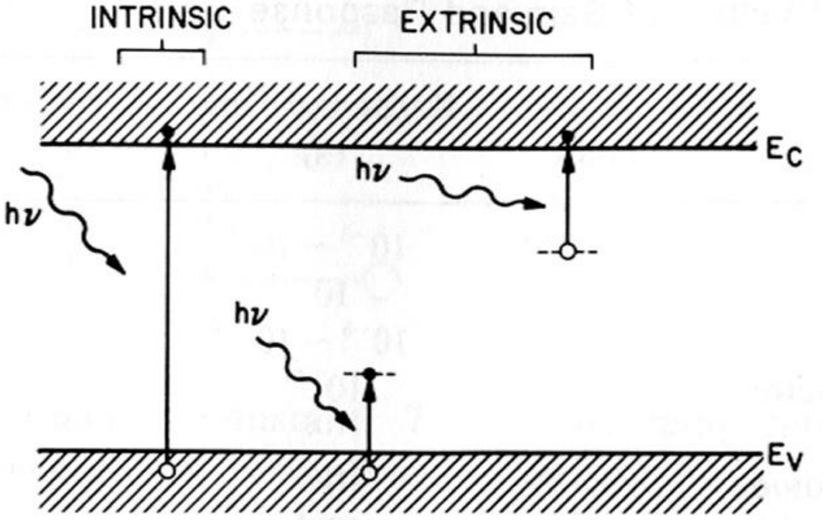
τ is the excess carrier recombination lifetime
τ_e is the electron transit time

(interdigitated electrodes to maximize light collection and minimize transit time)

Photoconductors

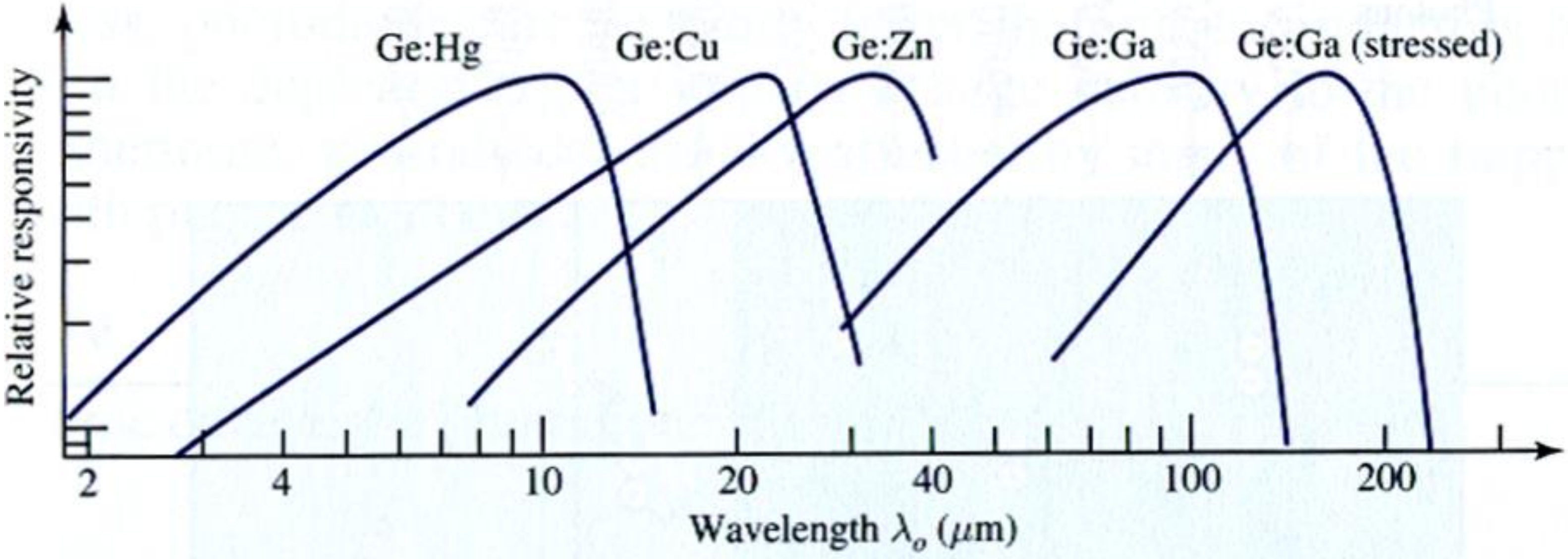
Photoconducivity can be achieved in longer wavelengths by using dopant. Incident photons can interact with electron at a donor site, creating a free electron or with a bound hole at an acceptor site, creating a free hole. Donor and acceptor levels are characterized by the activation energy (E_A) and wavelength (λ_A).

$$\lambda_A = \frac{hc_0}{E_A}$$



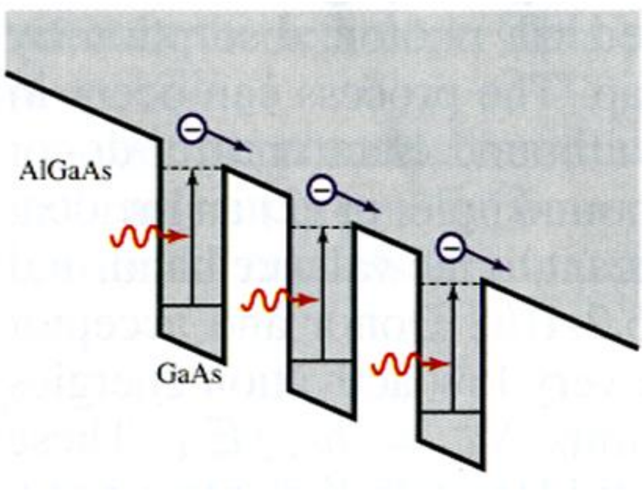
Photoconductors

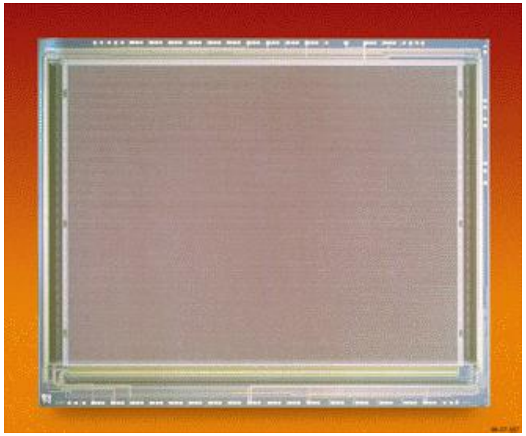
Semiconductor:Dopant	E_A (eV)	λ_A (μm)
Ge:Hg	0.088	14
Ge:Cu	0.041	30
Ge:Zn	0.033	38
Ge:Ga	0.010	115
Si:B	0.044	23



Quantum well photodetectors

640 x 512 pixels focal plane array

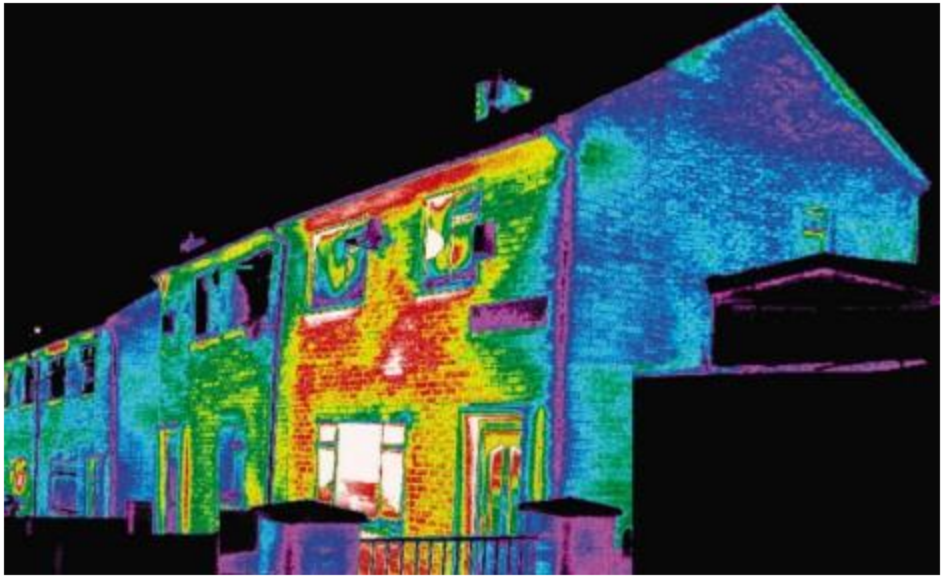




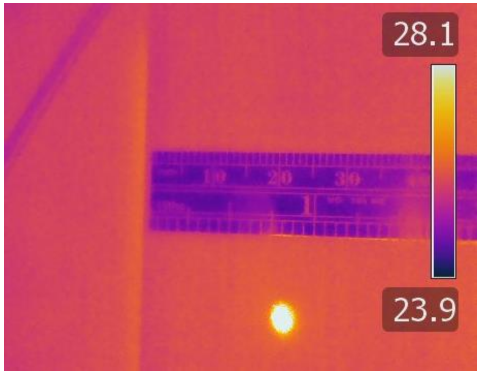
Photoconductive detectors can be constructed using multiple quantum wells. In a quantum well infrared photodetector (QWIP), an incident infrared photon releases an electron occupying a bound energy level in a quantum well, creating a free carrier.

Quantum well photodetectors

Detector is at 75K with f2.3 optics. Sensitivity is at 8-10 microns. Applications include thermal imaging and night vision.



Thermal image with a uncooled detector



Mid-IR laser beam