The University Of Sheffield.

EEE 6212
Semiconductor Materials

Lecture 23: photo-detectors

The University Of Sheffield.

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- principle of light detection by semiconductors
- photoconductor
- photo-diode
- avalanche photo-diode
- photo-transistor
- charge-coupled device (CCD) vs. complimentary metal-oxide-semiconductor (CMOS) detector

principle of light detection by semiconductors

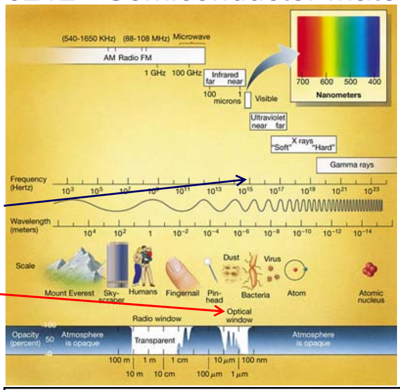
principle:

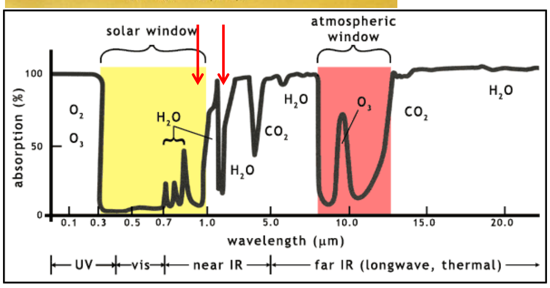
- most cases use **intrinsic** semiconductor: generation of electron-hole pairs by band-to-band transition if photon energy is at least as large as the band-gap: $hc/\lambda = E_\gamma \geq E_g = eV$

- for IR applications also **extrinsic** semiconductors are used: electron-hole pair generation from impurity band to band edge (electron from valence to acceptor level or from donor level to conduction band): $E_\gamma \geq E_A - E_V$ or $\geq E_C - E_D$

semiconductors do not see ‘colours’, hence need to use colour filters or diffraction gratings or tailor the thickness of absorption region for 2D detectors (more towards the end of this lecture)

semiconductors:
$E_g \approx 0.6\text{-}6\text{eV} = hf$
->
$f = 1.45 \times 10^{14}\text{-}10^{15}$ Hz
->
$\lambda = c/f = 0.2\text{-}2\mu$m
covers the range UV-vis-NIR





common wavelength bands for detectors

Band 1	UV-vis-NIR	0.19-1.0μm (reflected sunlight)
Band 2	short wave IR (SWIR)	1.0-2.6μm (some reflected sunlight and some emitted radiation)
Band 3	mid wave IR (MWIR)	3-5μm (emitted thermal radiation)
Band 4	long wave IR (LWIR)	8-14μm
Band 5	far IR (FIR)	>15μm

common wavelength windows for telecommunications are centred around the H_2O absorption minima of red/IR spectrum

1^{st} window	red	800-900nm	**Si**, GaAs
2^{nd} window	SWIR I	~1300nm	**InGaAs**, Ge
3^{rd} window	SWIR II	~1550nm	**InGaAs**, Ge, HgCdTe,..

detector types

photo-conductor: doped semiconductor with metal contacts
–> cheap

photo-diode: p-i-n diode with metal contacts
–> unity gain (1), high quantum efficiency, fast (10^{-9}-10^{-11}s)

avalanche photo-diode: diode operated near reverse breakdown voltage
–> high gain (10^2-10^4), fast (10^{-10}s), potentially noisy
for detailed description: see EEE337, lecture 4

photo-transistor
–> medium high gain (10^2-10^3), slower (10^{-6}s)

quantum efficiency

definition of (external) quantum efficiency:
electron-hole pairs generated per incident photon

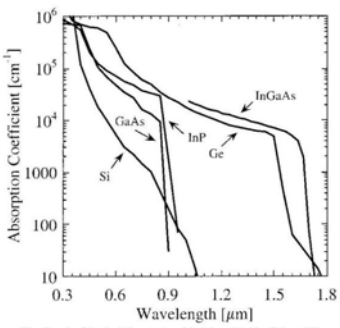
$\eta=(I_{photo}/e)\,/\,[P_{opt}/(hf)]=I_{photo}\,hf\,/\,(eP_{opt})$

where I_{photo} is measured photocurrent and P_{opt} the incident optical power. The photon energy is hf.

- To maximise efficiency, carrier loss due to recombination within the semiconductor must be minimised. This is achieved in a p-i-n diode by confining illumination and absorption to the depleted i-region, and by separating this from carrier multiplication region (in APDs).
- Carrier loss through recombination must be minimised by surface passivation, and wide band-gap p and n layers can be used to reduce dark current.

photon absorption & quantum efficiency

When light falls onto the semiconductor, its intensity falls exponentially with depth, z:
$I(z)=I_0\exp(-\alpha z)$
with an absorption coefficient of
$\alpha=2\kappa k=4\pi\kappa/\lambda\sim10^6\text{-}10^8\ \mathrm{m}^{-1}$
above the band edge.



Handbook of Optical Constants of Solids, edited by Edward D. Palik, (1985), Academic Press NY.

Within the depletion region of area A and total depth d, and for reflectivity R at the semiconductor surface, the generation rate for electron-hole pairs is
$g(z)=(1-R)P_{opt}/(Ahf)\exp(-\alpha z)$

photon absorption & quantum efficiency

Assuming light is absorbed in the intrinsic region only, the generated photo-current in the depletion region is

$$I_{photo} = eA \int_0^d g(z)\,dz$$
$$= e\,(1-R)\,P_{opt}/(hf) \int_0^d \exp(-\alpha z)$$
$$= e\,(1-R)\,P_{opt}/(hf)\,[1-\exp(-\alpha d)]$$

Insert this into the expression for the quantum efficiency:

$$\eta = I_{photo}\,hf\,/\,(eP_{opt})$$
$$= (1-R)\,[1-\exp(-\alpha d)] \in [0,1)$$

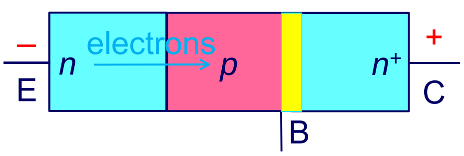
This shows that

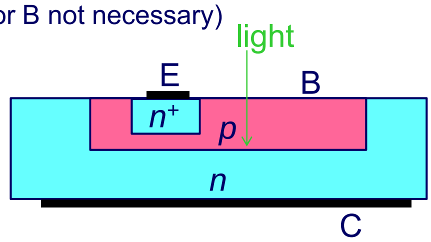
- reflection at the interface to air must be minimised (R->0)
- the depth of the depletion region, d, must be made large. However, the latter can be costly for epitaxy, so typically $d \sim 1/\alpha \sim$ several μm is chosen. Further increase would reduce the response speed, given by the time it takes the carriers to transit the depletion region (which is $\propto 1/d$).

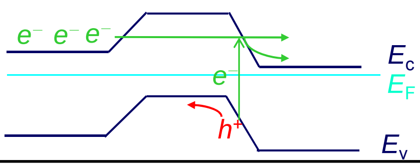
photo-transistor

principle fabrication steps for a lateral BJT:

- start with n-type substrate for npn [p substrate for pnp]
- create base region by p [n] doping a wider sub-region several μm deep
- form emitter by n^+ [p^+] doping a small part of that sub-region
- deposit metal contacts for E and C (for B not necessary)



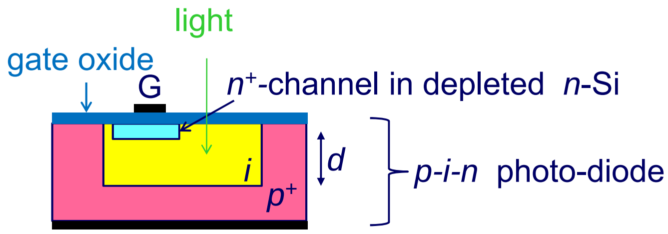


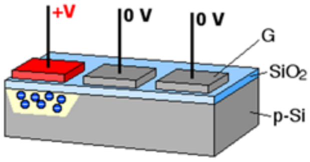


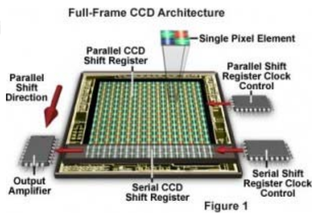
holes (h^+) generated predominantly at the lower part of the base accumulate in the base. Electrons (e^-) can move to the collector. If they reach it, a high photo current can flow from E to C, due to carrier injection at E, giving gain>>1.

charge-coupled devices (CCDs)

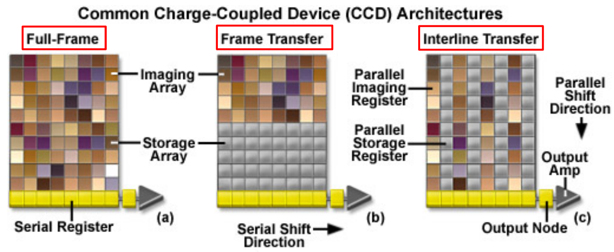
principle: up to 10^5 electrons accumulate in n-type channel under gate on top of photo-diode and are read out serially by charge transfer along the surface from one pixel/row to the next (‚shift register'). The last capacitor in the array dumps it charge into an op-amp. As charge collected is proportional to incoming light intensity, the response is linear over a large range. The quantum efficiency can be very high, commonly η=0.7-0.95.

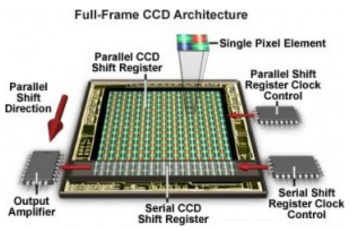


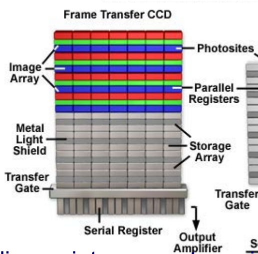


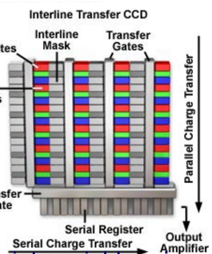


CCD: different architectures









charge transfer method	from one pixel to next, line-by-line, column-by column	into separate storage array	into neighbouring column
shutter	mechanical (slow)	electronic	mechanical (fast)

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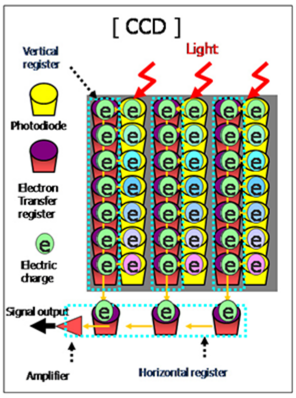
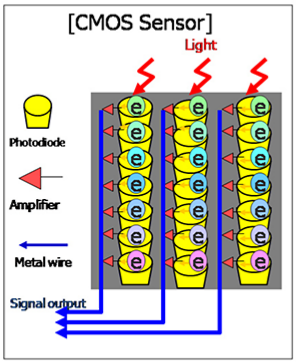
CCD vs CMOS detectors





pixel	photodiode with capacitor	photo-diode with transistor
read-out	successive by shift register	direct for each pixel
speed	slow	fast
price	expensive	cheap (since late 90's)
signal cross-talk	vertical smear ('blooming')	weak blooming
noise level	low	higher

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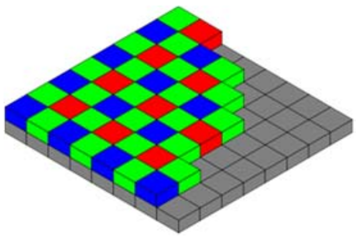
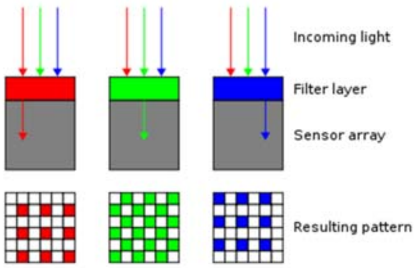
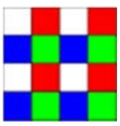
colour filters for 2D detectors



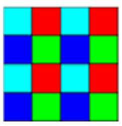
standard Bayer filter (G-RGB), needs additional anti-moiré filter



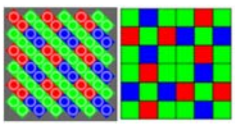
other colour filter schemes



RGB-W filter by Kodak



RGB-E filter by Sony



EXR and X-Trans filter by Fuji

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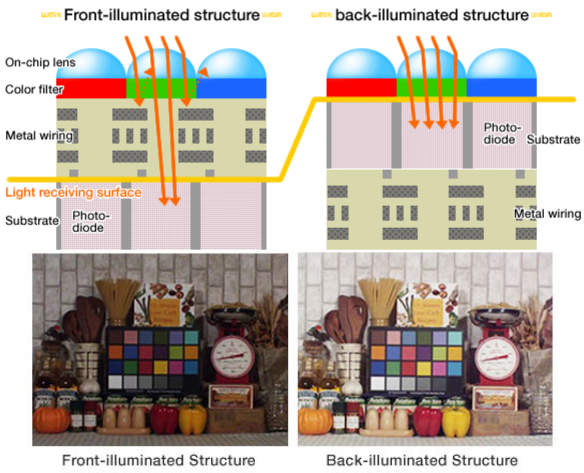
front vs back-illumination

front vs back-illumination in CCD/CMOS design



Flipping the processed wafer over places the photo-diodes directly under the colour filter. More light reaches them, giving more intensity and less noise.

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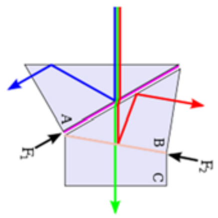
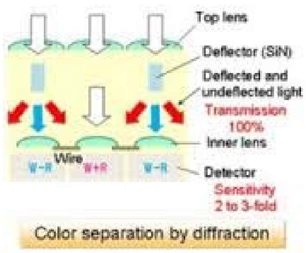
alternative approaches for colour, I

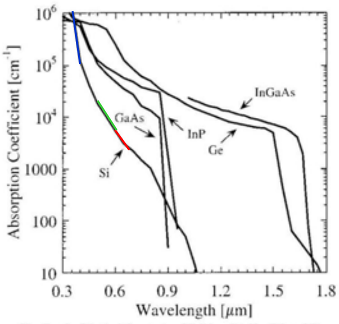
double dichroic (trichroic) colour separation by double prisms as beam splitters



colour separation by diffraction grating as deflector whose angular separation is proportional to wavelength



alternative approaches for colour, II



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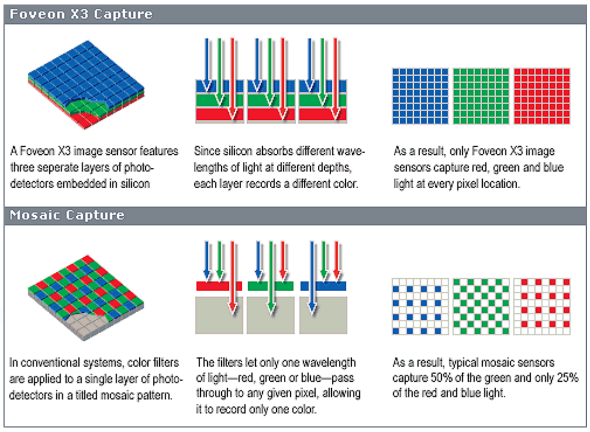

optimisation of depth dependent absorption in 3 individual layers of CMOS sensors stacked on top of each other