Detection of Light

See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

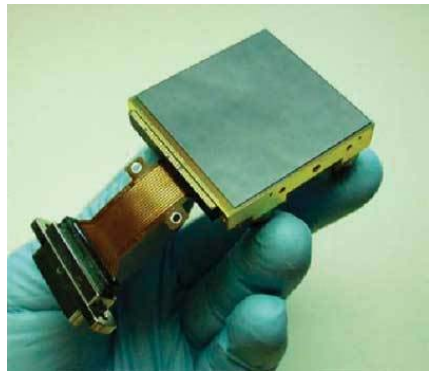
Side note:

The HAWAII-2 Detector

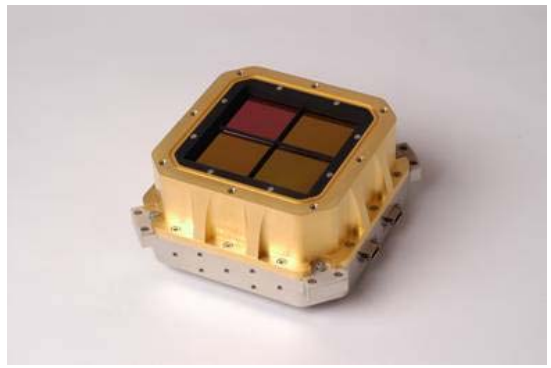
The Teledyne (formerly Rockwell) 2k x 2k Hawaii-2RG detector

See http://www.rsc.rockwell.com/imaging/hawaii2rg.html for more info

Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 µm
Fill factor	≥ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3µm
Operating temperature	≥ 30K
Quantum efficiency (array mean)	≥ 65%
Charge storage capacity	≥ 100,000e^-
Pixel operability	≥ 95%
Dark current (array mean)	≤ 0.1 e^-/sec (77K, 2.5 µm)
Read noise (array mean)	≤ 15 e^- CDS @ 100 kHz
Power dissipation	≤ 4 mW @ 100 kHz



Can also be combined to a 2x2 mosaic



Following Measurements taken from …

SPIE Vol. 5499, pp. 47-58 (2004)

Performance of large format 2Kx2K MBE grown HgCdTe Hawaii-2RG arrays for low flux applications.

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European Southern Observatory, Karl Schwarzschildstrasse 2 D-85748 Garching, Germany.

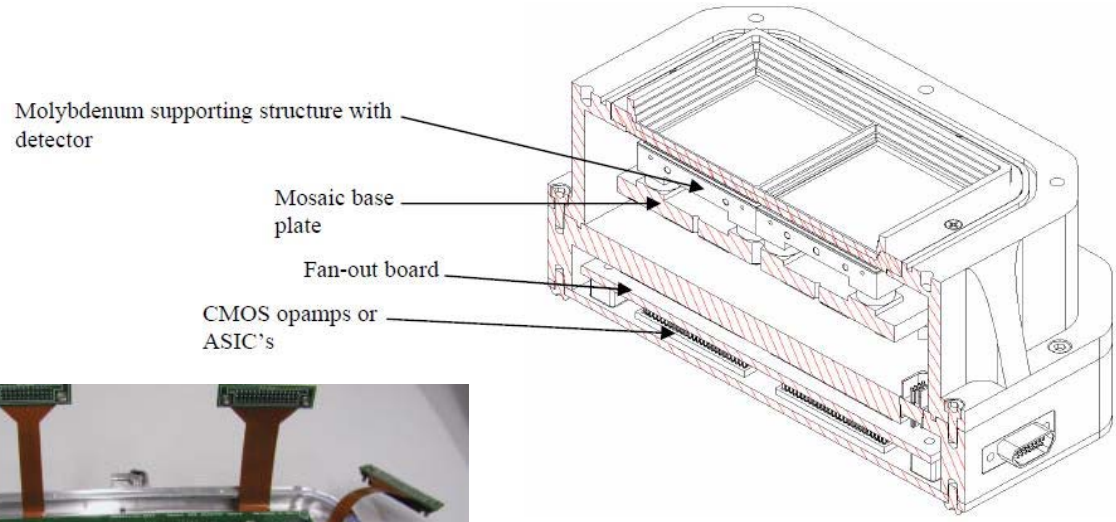
ABSTRACT

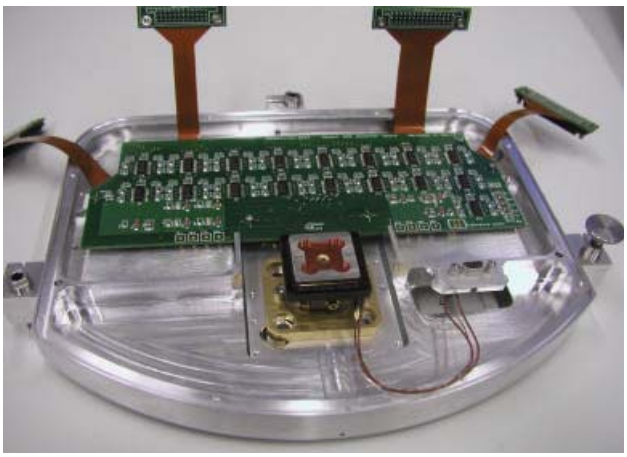
VLT instruments increasingly require high sensitivity large format focal planes. Adaptive optics combined with multiple integral field units feeding high resolution spectrographs drive the pixel performance as well as the array format. Three VLT instruments, the wide field imager Hawk-I [1]and the integral field spectrographs SINFONI [2] and KMOS [3] will be equipped with MBE-grown HgCdTe Hawaii-2RG arrays, which have a cut-off wavelength of 2.5 micron. The Hawaii-2RG array was originally developed for the near infrared camera of JWST having a cut-off wavelength of 5 micron [4].

The Hawaii-2RG multiplexer is one of the most advanced readout architectures offering a large variety of operating modes. A special 32 channel package has been developed which allows reading out all 32 output channels of the detector in parallel [7]. Symmetric cryogenic CMOS operational amplifiers are placed next to the focal plane instead of using ASIC's which are not yet available. The internal bus of the detector is accessed directly, bypassing the on-chip buffer amplifier. Noise performance employing different techniques of using reference pixels is discussed. Basic performance characteristics of the Hawaii-2RG arrays will be presented. Unlike LPE arrays, which lose quantum efficiency at lower temperatures, MBE arrays with λ_c=2.5 µm do not show this effect. However, the MBE arrays under test still suffer from persistence.

Keywords: infrared detector, Hawaii-2RG, HgCdTe, readout noise, dark current, quantum efficiency, persistence

HAWAII-2: Mounting the Detector(s)

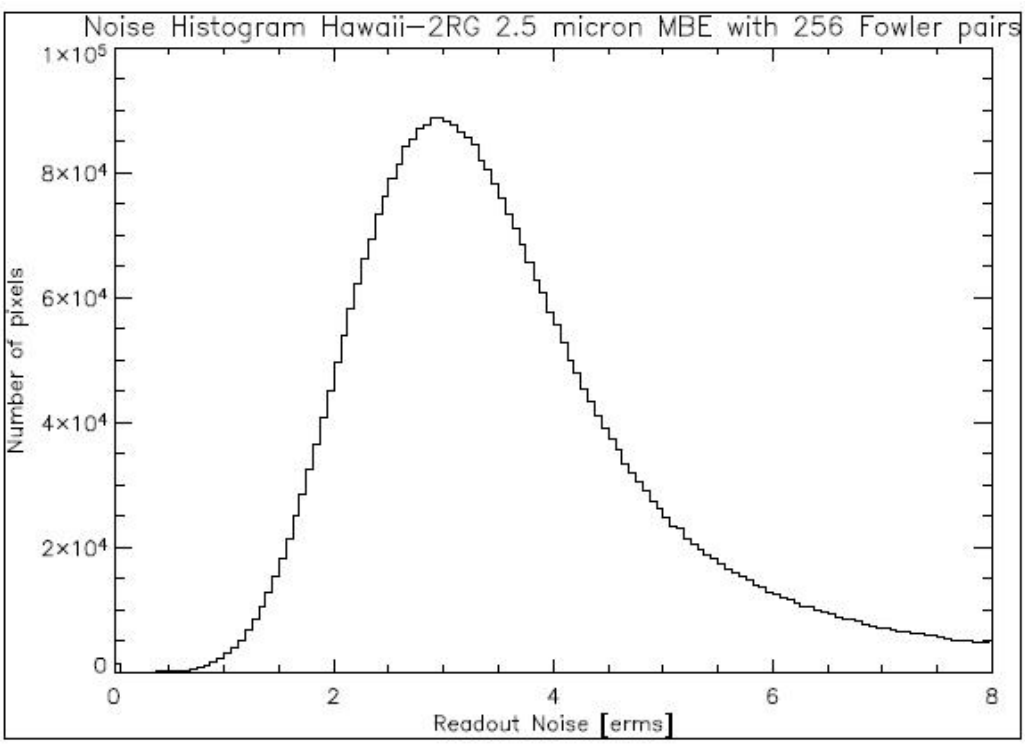




Above: GL Scientific HAWAII-2RG mosaic module

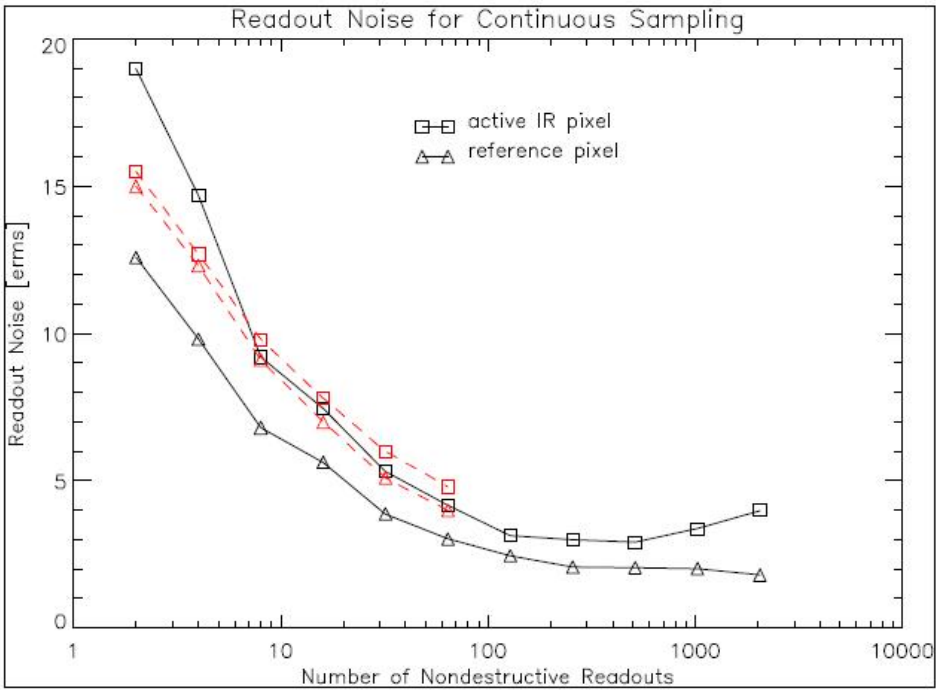
Left: Detector mount for SPIFFI with cryogenic preamplifiers for 32 (+2) video channels

HAWAII-2: Distribution of Readout Noise



Histogram of readout noise on infrared active pixels of Hawaii-2RG array with 256 Fowler pairs. Readout Noise is 3 electrons rms.

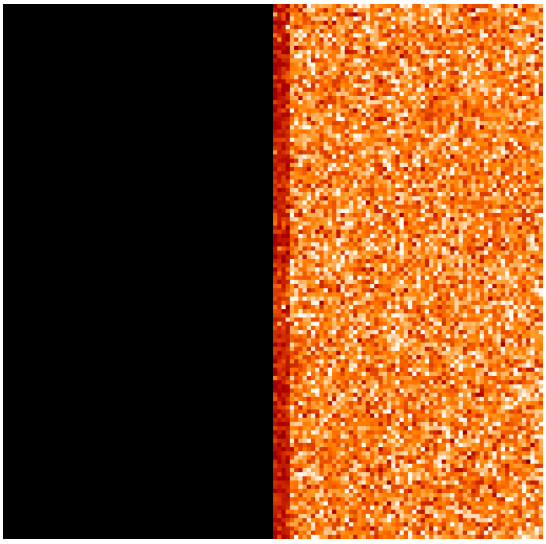
HAWAII-2: Readout Noise = $f(n_{reads})$



Readout noise versus number of non-destructive readouts (825ms each). Squares: active infrared pixels. Triangles: reference pixels. Solid line: ESO data. Dashed line: STScI data for comparison.

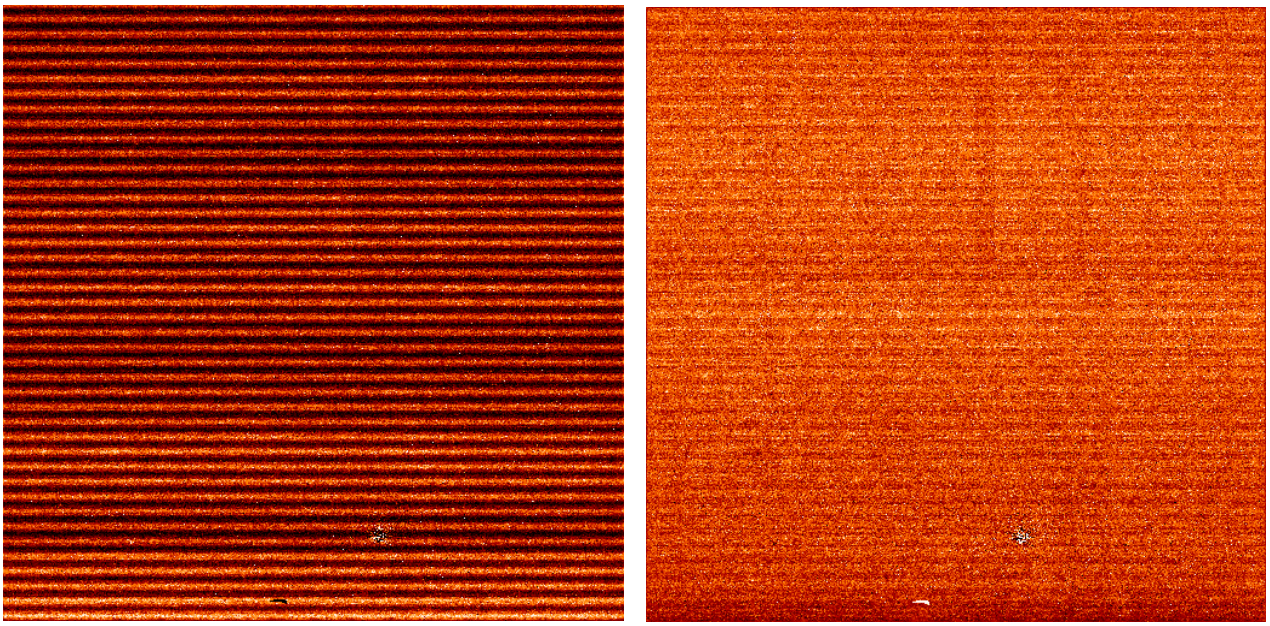
HAWAII-2: "Reference Pixels"

- IR active pixels are surrounded by 4 rows and columns of reference pixels at the edges of the array.
- Reference pixels are not connected to detector photodiodes.
- Their signal is embedded in the regular signal of 2048 x 2048 pixels.
- Reference pixels can be used to track low frequency noise pickup.



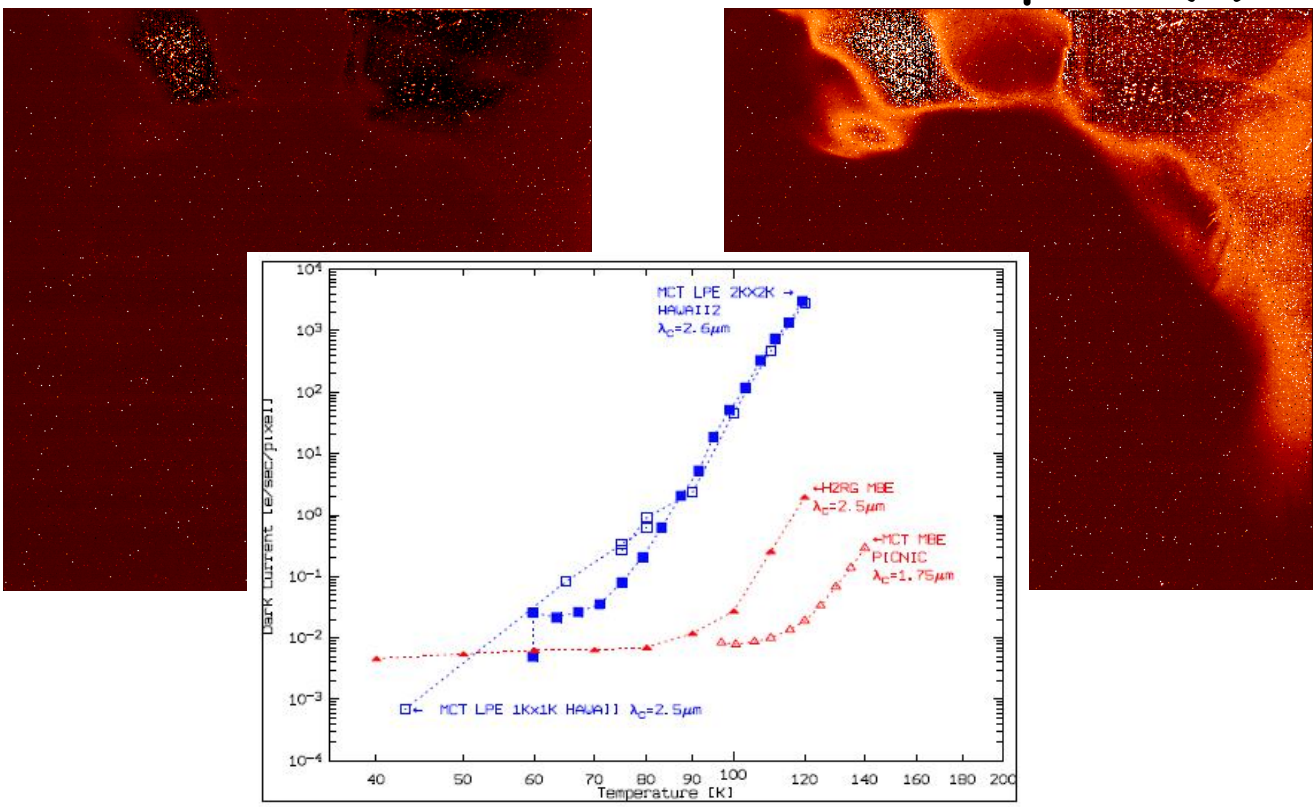
Noise map with reference pixels at the left edge. Readout noise on active pixels: 17 e- rms. Readout noise on reference pixels at left edge: 8 e- rms.

HAWAII-2: The Need for Reference Pixels



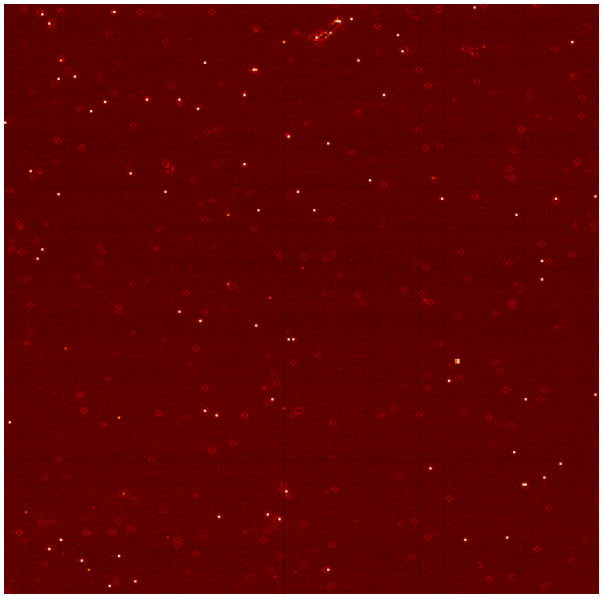
Difference images of double correlated reads
Left: Uncorrected showing 50Hz pick-up.
Right: corrected with mean of reference pixels subtracted.

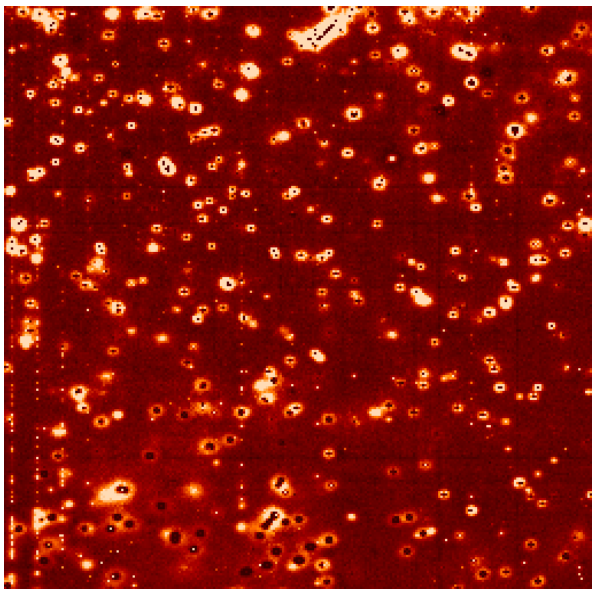
HAWAII-2: Global Dark Current Maps = f(T)



Dark current maps for T=40K (left) and T=80K (right); t_{int} = 11´

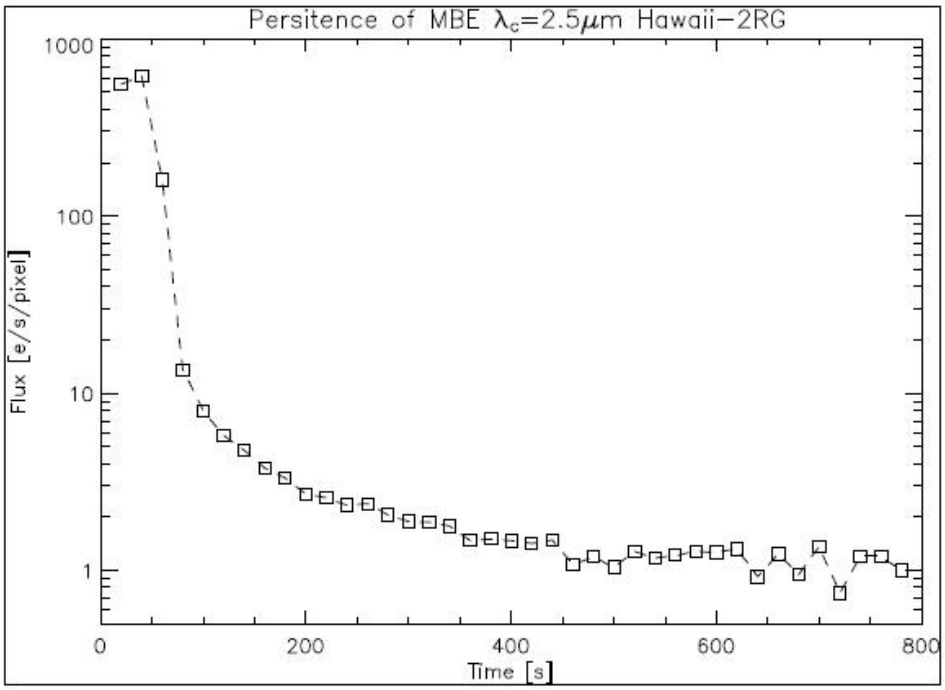
HAWAII-2: Cosmetic Quality = f(T)





Comparison of cosmetic quality in high dark current region.
Left:40 K. Right: 80K.Cut levels: -250 /2000 e. Integration time: 900 sec

HAWAII-2: Persistent Images = f(t)

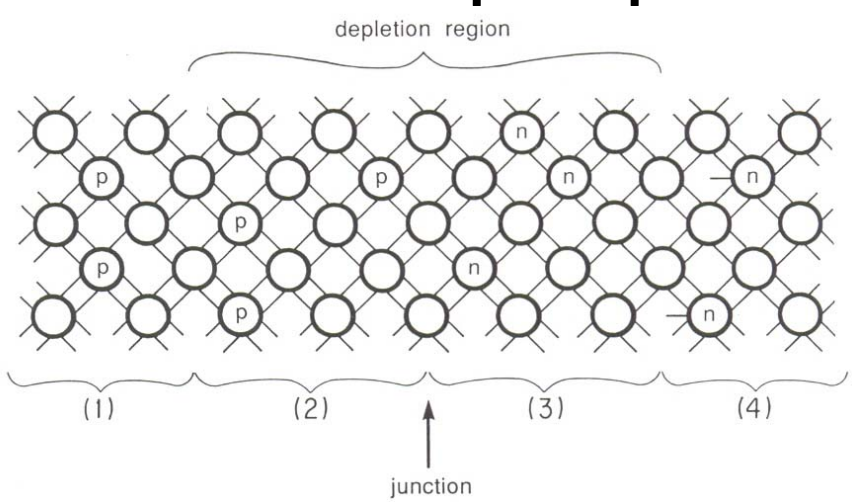


Persistence of Hawaii-2RG MBE array in J band. Detector integration time 20 s.

Back to:

Performance of Photodiodes

Remember: Basic Principle: p-n Junction

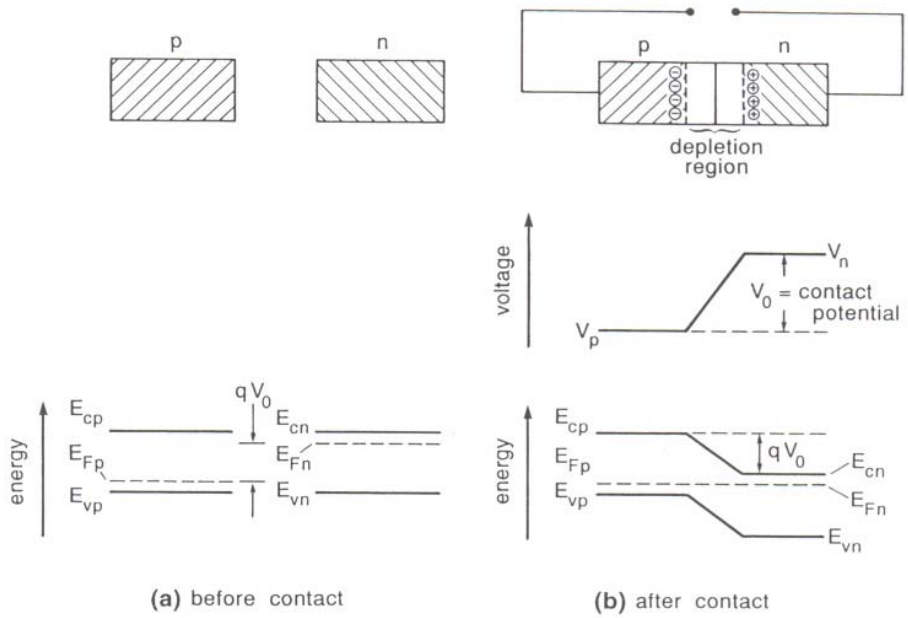


n-type: surplus of e^- p-type: lack of e^-
Thermal excitation → e^- diffuse into p-type region → space charge region → depletion of charge carriers → high resistance.

Diffusion process results in a voltage difference across the junction : contact potential V_0.

Outside the depletion region (due to high doping levels): R and $\bar{E}$ are low

Remember: Contact Potential



The contact potential V_0 is determined by the difference in the Fermi levels:

$$\Delta E_F = q V_0$$

The NEP of Photodiodes

Remember, the NEP is the signal power that yields an RMS signal-to-noise of unity in a system that has an electronic bandpass of 1 Hz

Photodiodes show *efficient* diffusion of the photo-excited charge carriers into the junction.

→ Every absorbed photon will contribute to the photocurrent, and the photo-conductive gain of photodiodes is $G = 1$.

$$\Rightarrow I_{ph} = \varphi q \eta$$

Hence we get for the responsivity: $S = \frac{I_{ph}}{P_{ph}} = \frac{\varphi q \eta}{\varphi h \nu} = \frac{\eta \lambda q}{hc}$

which increases linearly with wavelength (up to hc/E_g).

Since there is no recombination noise, $\langle I^2_{G-R} \rangle$ is reduced by a factor $(\sqrt{2})^2$ to $\left\langle I^2_{shot} \right\rangle = 2q^2 \varphi \eta \Delta f$

The NEP of a photodiode is $NEP = \frac{I_{G-R}}{S} = \frac{\left(2q^2 \varphi \eta \Delta f\right)^{1/2} hc}{\eta \lambda q} = \frac{hc}{\lambda}\left(\frac{2\varphi}{\eta}\right)^{1/2}$

Diffusion

Diffusion = statistical process, mainly the outcome of random motion.
Here: thermal motions of charge carriers.

Diffusion is described by the diffusion coefficient D [cm^2s^{-1}]

Applying $\bar{E}$ field → effective motion is the sum of thermal motion + $\bar{E}$ field induced motion.

The connection between the diffusion coefficient D and the mobility μ of charged particles in an electric field is described by the Einstein-Smoluchowski equation:

$$D_n = \frac{\mu_n kT}{q}$$

The diffusion length is defined as: $L_n = \left(D_n \tau_n\right)^{1/2}$

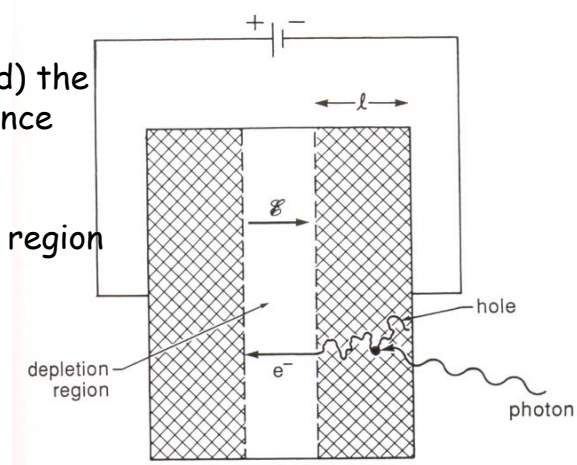
(τ_n is the mean lifetime of the electron before recombination).

Quantum Efficiency of Photodiodes

To cause a photocurrent (i.e., to be detected) the charge carriers must reach the high-resistance region of the detector.

→Must diffuse across the neutral depletion region

➔ τ_n requires that the width of the neutral layer in the junction must be smaller than one diffusion length $L_n \sim \sqrt{\tau_n}$.

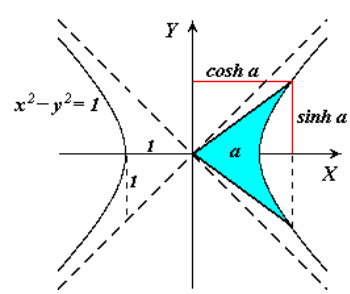


Continuity equation for charge diffusion:
(see Rieke book, page 87/88 for derivation)

$$\frac{d^2n}{dx^2} - \frac{n}{L^2} + \frac{g}{D} = 0$$

Which has the general solution:

$$n(x) = A\cosh\left(\frac{x}{L}\right) + B\sinh\left(\frac{x}{L}\right) + \frac{gL^2}{D}$$

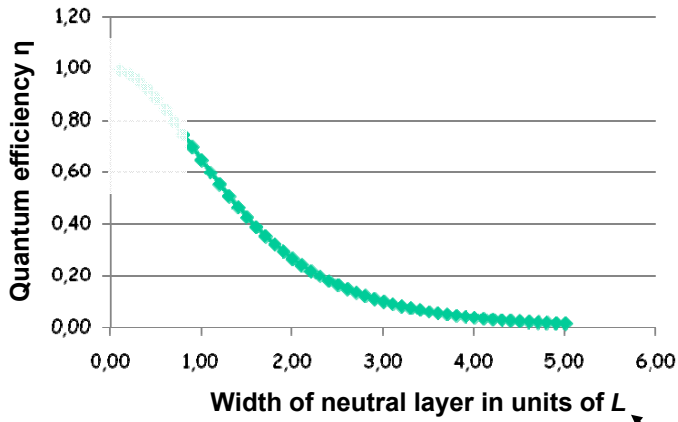


Quantum Efficiency (2)

We (re)define the quantum efficiency as the flux of charge carriers into the junction divided by the flux of input photons:

$$\eta = \frac{D(dn/dx)_{(x=0)}}{\varphi} = b\,\mathrm{sech}\left(\frac{c}{L}\right) = \boxed{\frac{2b}{e^{c/L}+e^{-c/L}}}$$

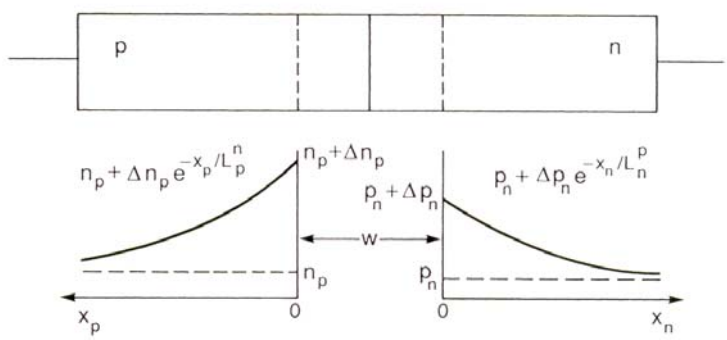
Where *c* is the thickness of neutral layer and *b* is the fraction of incident photos available for absorption and producing charge carriers.



diffusion length

The Diode Equation

The carrier densities in a diode are schematically:

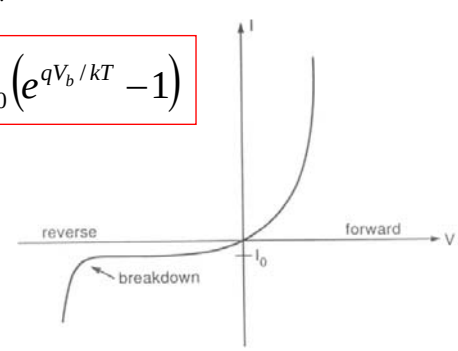


where p_p and p_n are the majority and minority charge carriers, respectively.

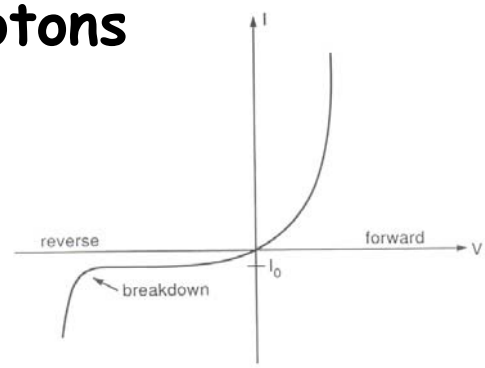
The diode equation can be written as (see Rieke book p. 89/90 for derivation):

$$I = \left[qA\left(\frac{D_n^p}{L_n^p}p_n + \frac{D_p^n}{L_p^n}n_p\right)\right]\left(e^{qV_b/kT}-1\right) = \boxed{I_0\left(e^{qV_b/kT}-1\right)}$$

I_0 is called the saturation current



Response to Photons

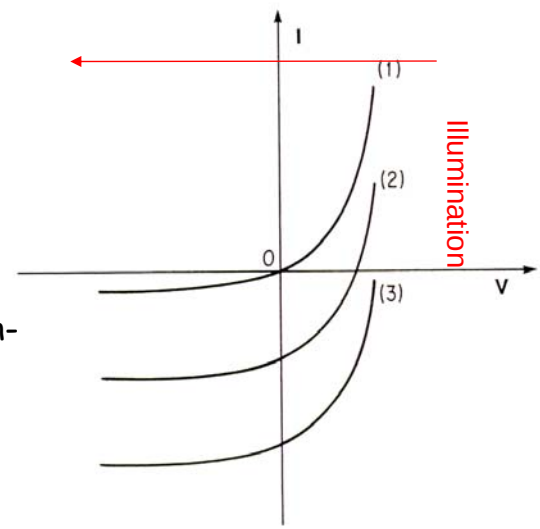


So far, response of an ideal diode in the absence of light.

Now: illumination → charge carriers → current across the depletion region

Photocurrent: $I_{ph} = -\varphi q\eta = -P/(h\nu)\cdot q\eta$

"Dark" current: $I = I_0(e^{qV/kT}-1)$



➔ Total current $$I = -\frac{\eta q P}{h\nu} + I_0\left(e^{qV_b/kT} - 1\right)$$

Two operating modes:

1. Fix current and measure voltage (highly non-linear)
2. Keep voltage constant and measure current (photoconductive mode)

Capacitance

A photodiode has a high capacitance because the charge distribution across the junction is similar to a parallel plate capacitor.

The space charge on either side of the junction must be equal: $N_A l_p = N_D l_n$

The overall width of the depletion region is: $$w = l_p + l_n = \left[\frac{2\varepsilon_0 (N_A + N_D)(V_0 - V_b)}{q N_A N_D}\right]^{1/2}$$

and the junction capacity: $$C_j = \kappa_0 \varepsilon_0 \frac{A}{w}$$

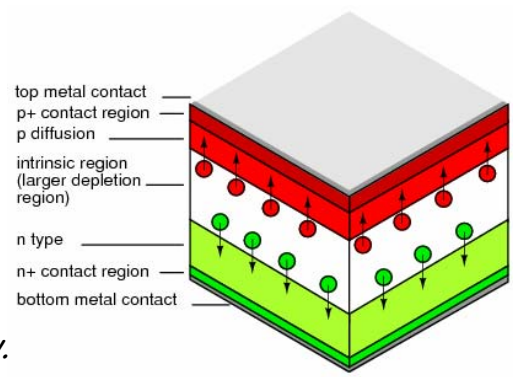
where A is the junction area, κ_0 is the dielectric constant, and ε_0 the permittivity of free space.

Variants of Photodiodes

PIN, Avalanche, Schottky, QWIP, STJ

PIN Diodes

p-type intrinsic n-type



Remember: photodiode have the structure of a capacitor, with $C_j = \kappa_0 \varepsilon_0 \frac{A}{w}$

→ The capacitance can be reduced by enlarging *w*.

→ For large *w* the photon absorption will (most likely) occur there and the charges will quickly drift ($\bar{E}$-field) rather than diffuse = better frequency response.

➔Increase the width of the depletion region by: $w = l_p + l_n = \left[\frac{2\varepsilon (N_A + N_D)(V_0 - V_b)}{q N_A N_D} \right]^{1/2}$

- reduced doping (but then R drops and noise increases)
- interpose an intrinsic layer between n-type and p-type material

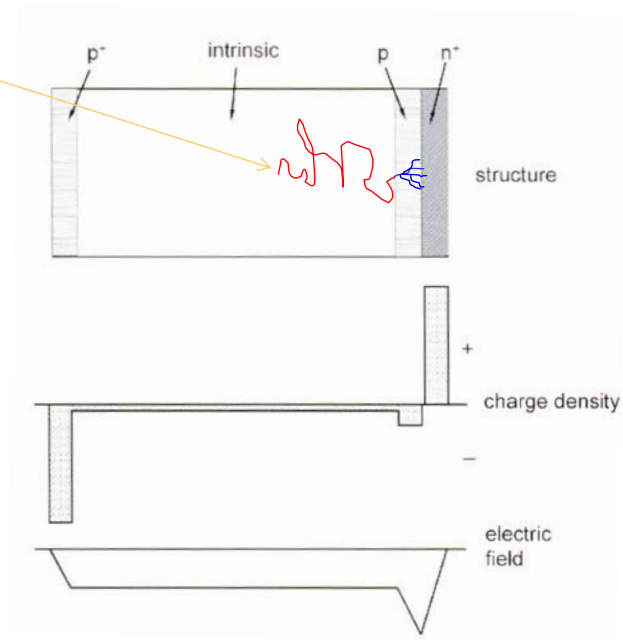
Note the improved time response $\tau_{PIN} = \frac{l^2}{\mu (V_0 + V_b)}$, where bias voltages can be up to V_b ~ 100V → fast!

Avalanche Diodes

Principle: increase reverse bias voltage close to breakdown → strong acceleration in the depletion region → avalanching

In principle that would work for PIN diodes as well, but gain and noise would vary depending on where the photon was absorbed.

Device with two functional regions:
- one region where the charges are produced (~ one absorption length L).
- one region where the avalanching occurs (larger field).



Best for:

- simple, compact, inexpensive detectors
- low light levels
- fast response

Schottky Diodes

Schottky diodes are used both as direct photon detectors and as millimeter wave receivers.

Basic principle:

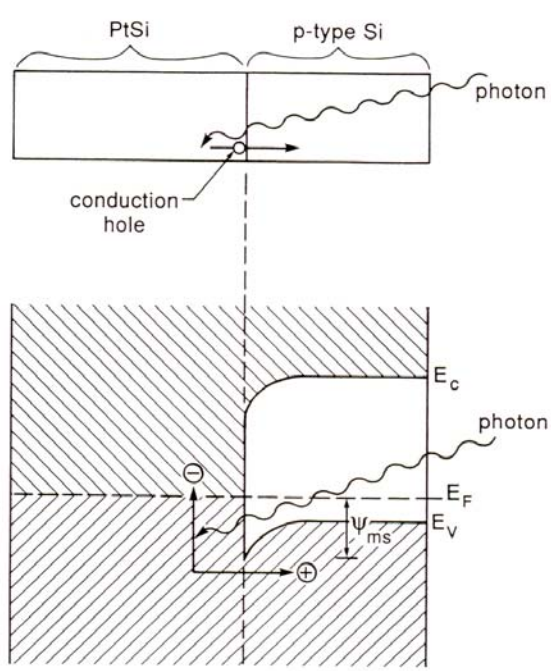
1. Junction between a metal (PtSi) and a semiconductor (p-type Si).

2. e^- flow from metal to semiconductor (E_F).

3. Conduction holes must surmount a low potential barrier ψ_{ms} to reach the valence band of the metal.

4. ψ_{ms} is determined by the contact potential and can be << E_g in a semiconductor:

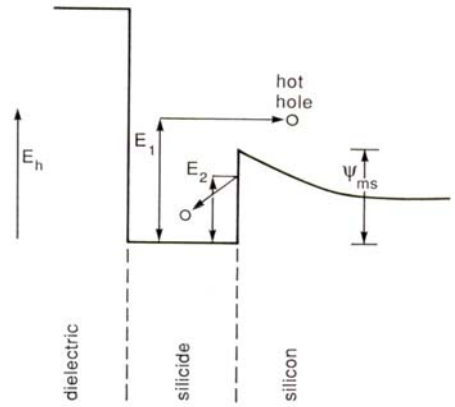
Pd2Si: ψ_{ms} = 0.35eV, λ_c = 3.5μm
PtSi: ψ_{ms} = 0.22eV, λ_c = 5.6μm
IrSi: ψ_{ms} = 0.15eV, λ_c = 8μm



Quantum Efficiency of Schottky Diodes

Emission of a "hot hole" over the Schottky barrier (the hole with E_1 has sufficient energy to cross the Schottky barrier, E_2 is too low).

Escape probability: $P(E) = \frac{1-(\Psi_{ms}/E)^{1/2}}{2}$



Quantum efficiency of a Schottky diode is:

Probability that a photon gets absorbed η_{ext}

×

Probability to produce a hole that can escape η_{int}

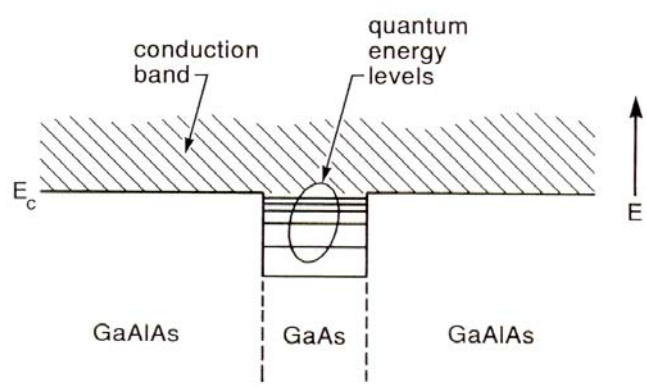
$$\eta = \eta_{\text{int}}\eta_{ext} = \frac{\eta_{ext}}{2}\left[1-\left(\frac{\Psi_{ms}}{h\nu}\right)^{1/2}\right]^2$$

General characteristics:

- barrier width >> 10^{-3}μm (to keep tunnel currents low)
- simple to construct
- high degree of uniformity
- built on silicon → readout transistors can be integrated → large format arrays

Quantum Well Detectors

Quantum well detectors make use of a heterojunction (bandgap itself changes across junction). E.g., a junction between GaAs and $Al_xGa_{1-x}As$ has a discontinuity of the conduction band edge of about x eV, and of the valence band edge of ~0.15x eV.



Conduction e- from the GaAlAs loose energy, wander to the GaAs and get trapped in the potential well. The e- occupy the energy levels: $E_n = \left(\frac{\hbar^2\pi^2}{2m_e^* w^2}\right)n^2$

where w is the width of the well, and n an integer number.

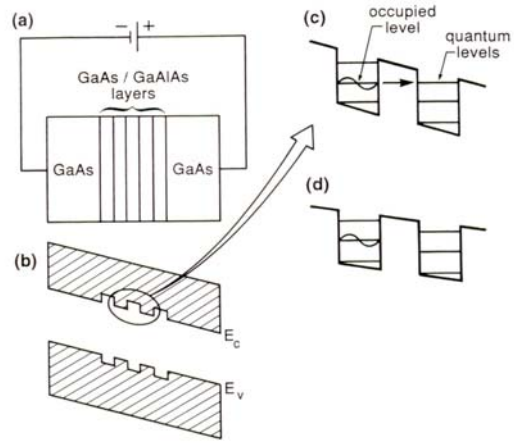
Quantum Well Detectors (2)

If the walls of the wells (the GaAlAs layers) are made sufficiently thin, electrons can tunnel from one well to another. High tunnelling probabilities occur for small barrier width of ~10^{-8}m.

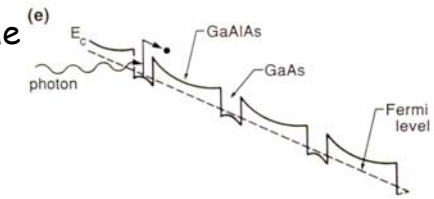
If the energy levels are "aligned" the tunnelling electrons carry an electrical current through the device.

This is the principle of quantum well infrared photodetectors (QWIPs).

Problems:
- narrow bandwidth (~1/4th of λ)
- ground state e- tunnel as well → dark current
- relatively low quantum efficiency



Solution: lift e- out of the quantum well into the conduction band ("bound-to-continuum" mode):



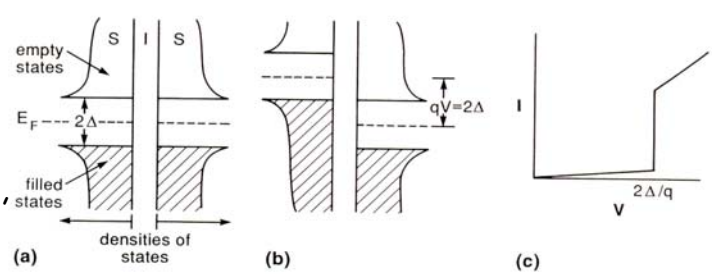
… and many more variants of this scheme …

Superconducing Tunnel Junctions (STJs)

Photoconductors: $E_\gamma \sim E_{gap}$ → few charge carriers
Superconductors: $E_\gamma \sim 1000 \times E_{gap}$ → thousands of charge carriers ~ photon energy

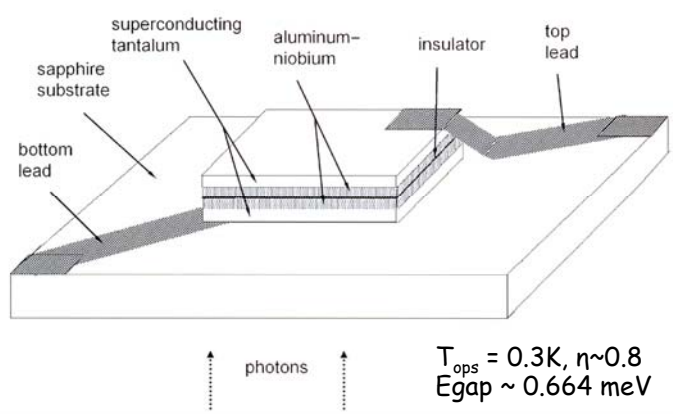
Principle: sandwich of two layers of superconductor, separated by this insulating layer (SIS junction)

At low T: all charges as Cooper pairs, can carry small currents (Josephson effect*)



A larger bias voltage causes single electron tunnelling

Photocurrent =
= f{number of quasiparticles**} =
= f{photon energy}



T_{ops} = 0.3K, η~0.8
Egap ~ 0.664 meV

* = dark current – could be suppressed applying a magnetic field
** = broken Cooper pairs