OBSERVATIONAL ASTROPHYSICS AND DATA ANALYSIS

Lecture 9

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Next Generation Detectors

Better spectral resolution, Higher QE,
Wider operational wavelength range

Transition Edge Sensor Bolometers / Quantum Calorimeters

Superconducting Tunnel Junction Detectors

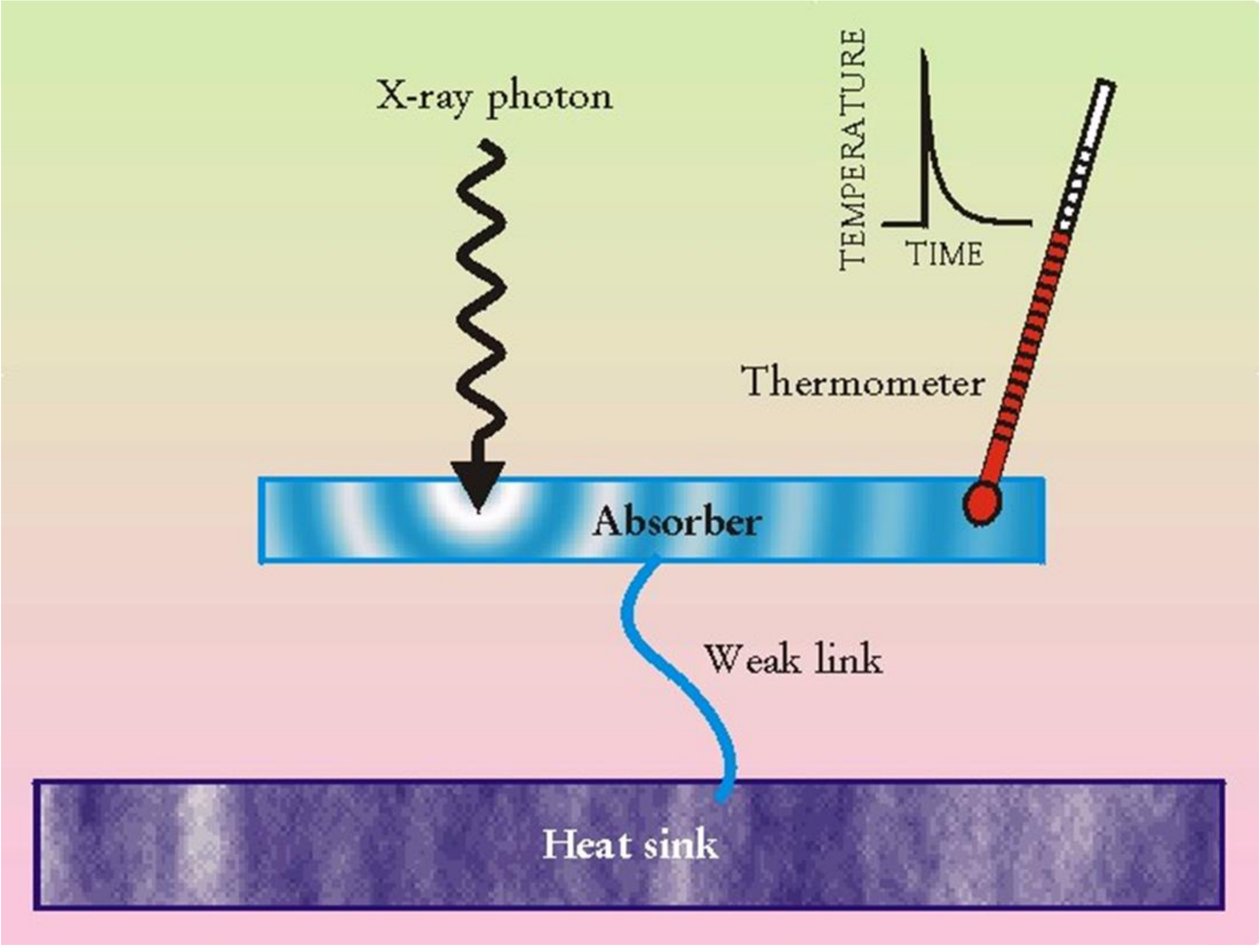
Transition Edge Sensor Bolometers (TES) / Quantum Calorimeters

- A Quantum calorimeter is a bolometer which is so sensitive, and has such good energy resolution, that it is able to measure the energy deposited in an absorber by an individual photon.
- This is rather easier of course for higher energy photons.
- Transition Edge Sensors have been used successfully as Quantum Calorimeters at X-ray, and recently optical and IR wavelengths.

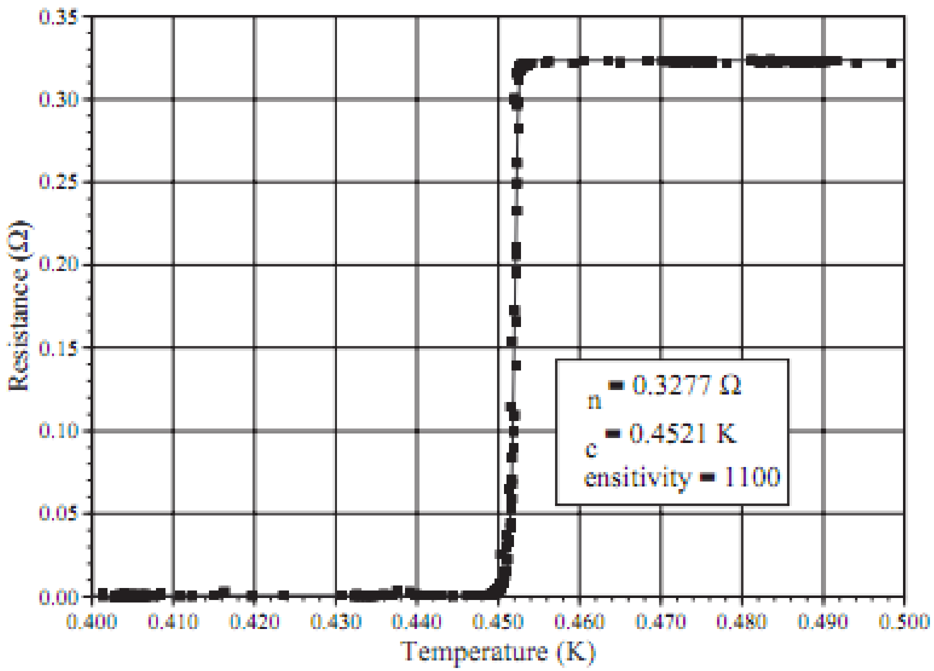
Transition Edge Sensors (TES)

- A superconducting material in the region of transition between its superconducting and normal states has a very steep dependence of resistance upon temperature.
- Typically thin film metal bilayers are used, for instance the Scuba II detectors are a Molybdenum-Copper bilayer.
- Such detectors are called Transition Edge Sensors (TES).

Transition Edge Sensors (TES)



Transition Edge Sensors (TES)

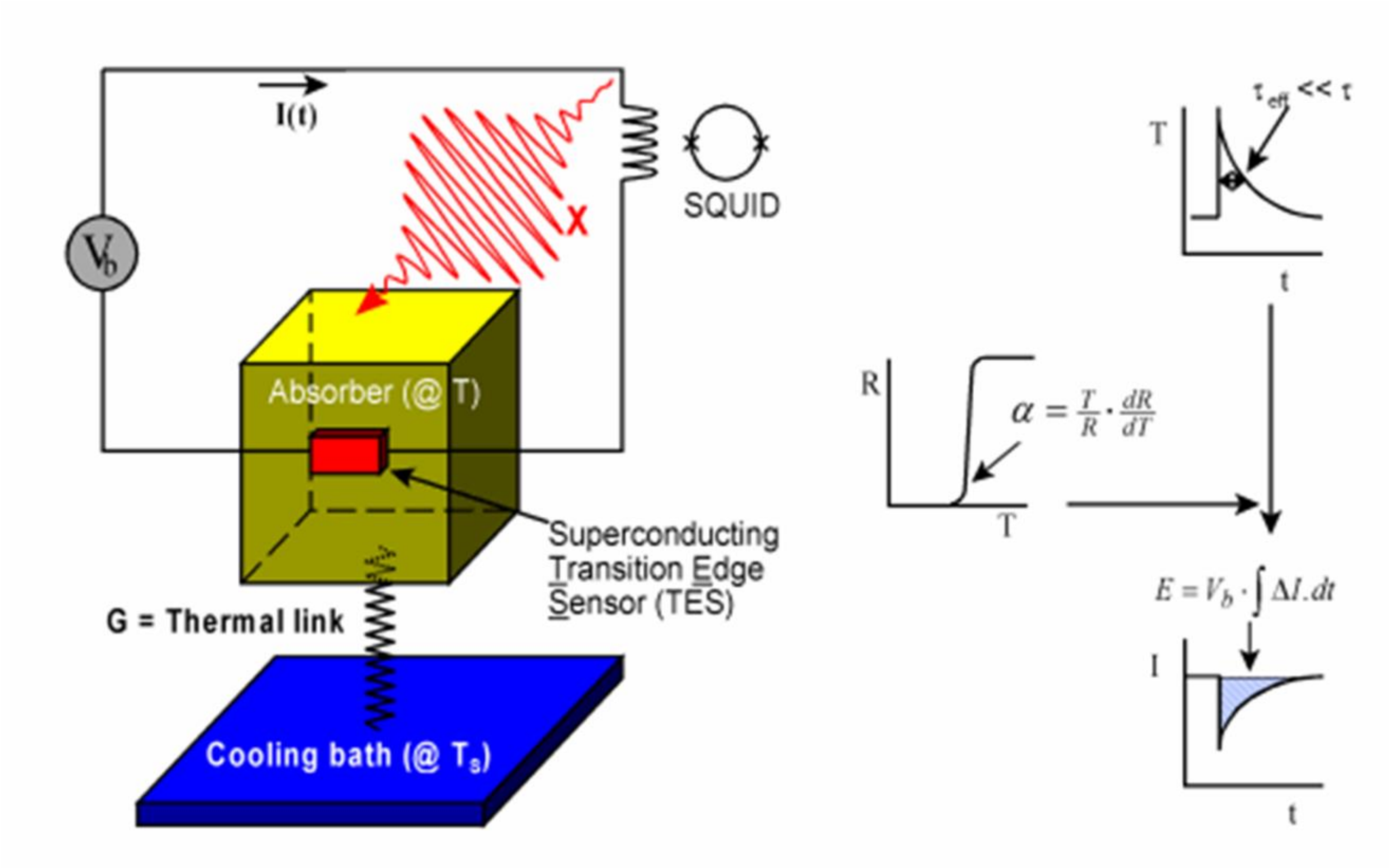


- A TES is in the transition region between normal and semiconductor states, and the resistance changes really sharply, so the temperature coefficient of resistance, and therefore the responsively, is very high.

Transition Edge Sensors (TES)

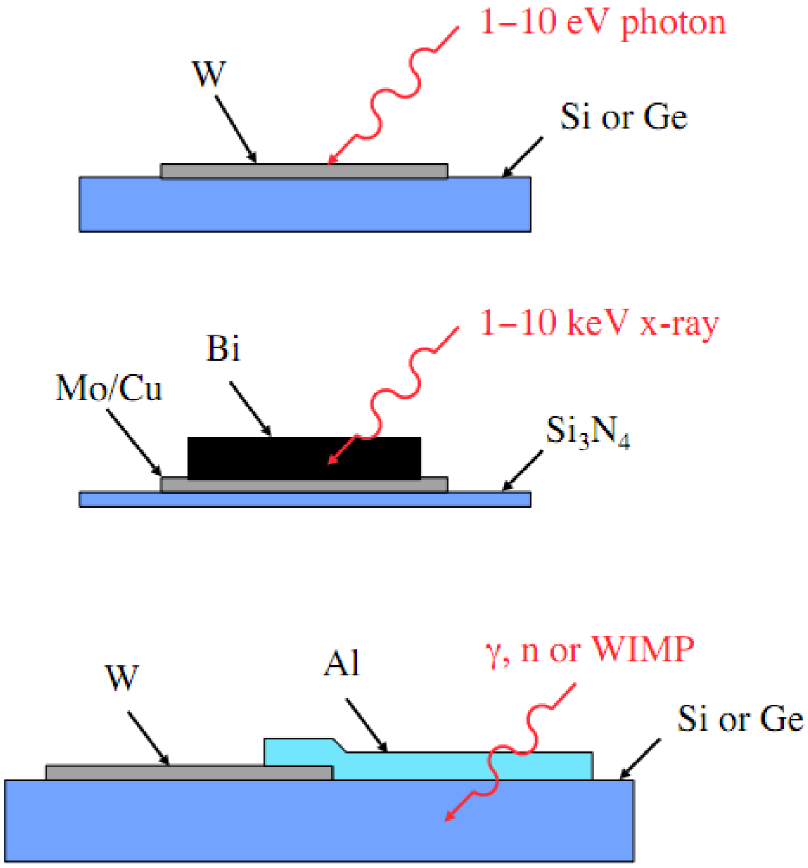
- A TES has a large temperature coefficient of resistance – $\alpha \approx 50 - 2000$.
- TES devices have low impedance, so are stabilized with a constant bias voltage rather than constant current.
- Change in resistance results in a change in current through the thin film, which is read out using a Superconducting Quantum Interference device (SQUID) amplifier.

Transition Edge Sensors (TES)



Transition Edge Sensors (TES)

- Three types of detectors:
  - Direct absorption of photon in TES (e. g., IR-optical-UV photons)
  - Photon absorber in electical contact with TES (e. g., x-ray detectors)
  - Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES



Transition Edge Sensors (TES)

- Energy resolution of a TES is given by:

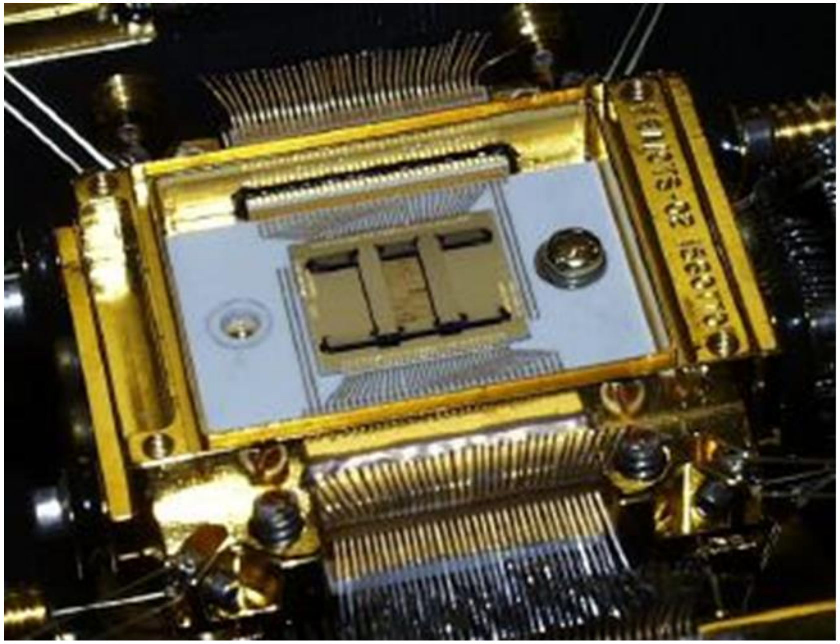
$$\Delta E_{FWHM} = 5.92\sqrt{\frac{k_B T_B{}^2 C}{\alpha}}$$

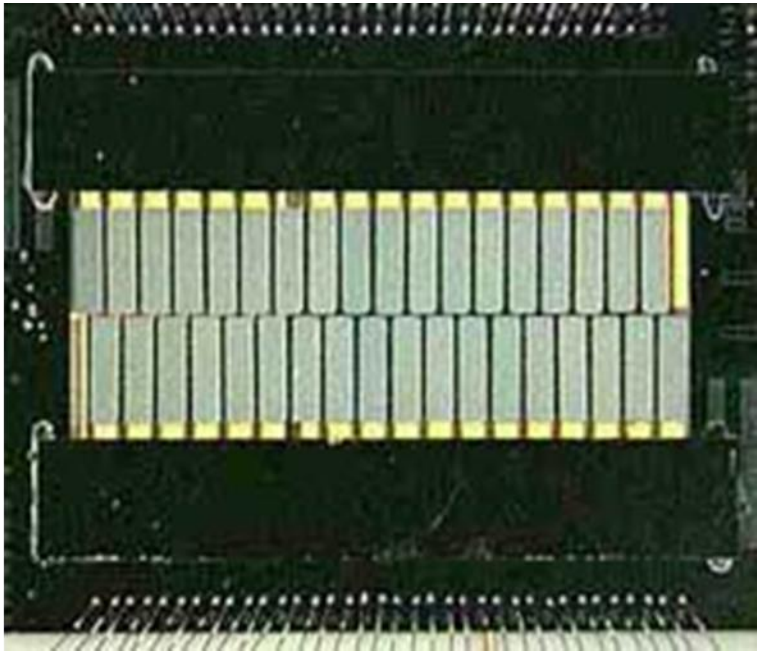
where T_B is the temperature of the heat sink, and C is the heat capacity of the absorber at that temperature, a is the temperature coefficient of resistance.

Quantum Calorimeters

- For a Quantum Calorimeter operating at optical wavelengths, we make C and T_b as low as possible, and α as large as possible. The time constant must be short enough that the array pixel recovers from one photon event before the next arrives. Electrothermal feedback in TES sensors makes the time constant short.

X-ray Quantum Calorimeters

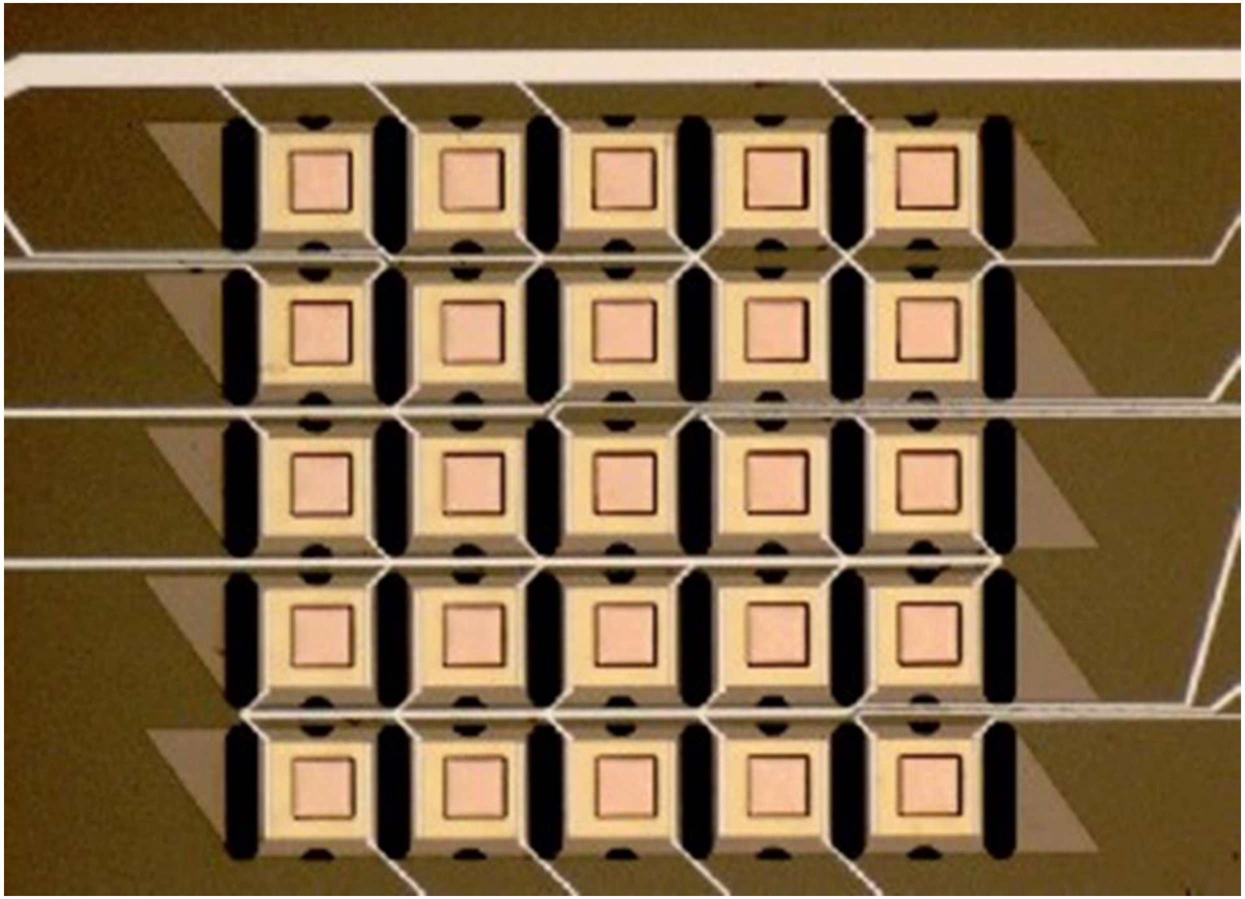




Two Quantum Calorimeter array detectors for X-ray missions

TES sensor array

This prototype TES array is being developed for X-ray missions in the next decade.



Superconducting Tunnel Junction (STJ) Detectors

- A possible replacement for the CCD in a few years
- Can operate across a wide spectrum from ultraviolet to infrared, and also in x-rays
- Can detect individual photons
- Has a very rapid response
- Provides intrinsic spectral resolution ($E/\Delta E$) of 500 – 1000 (in the visible region)

Superconducting Tunnel Junction (STJ) Detectors

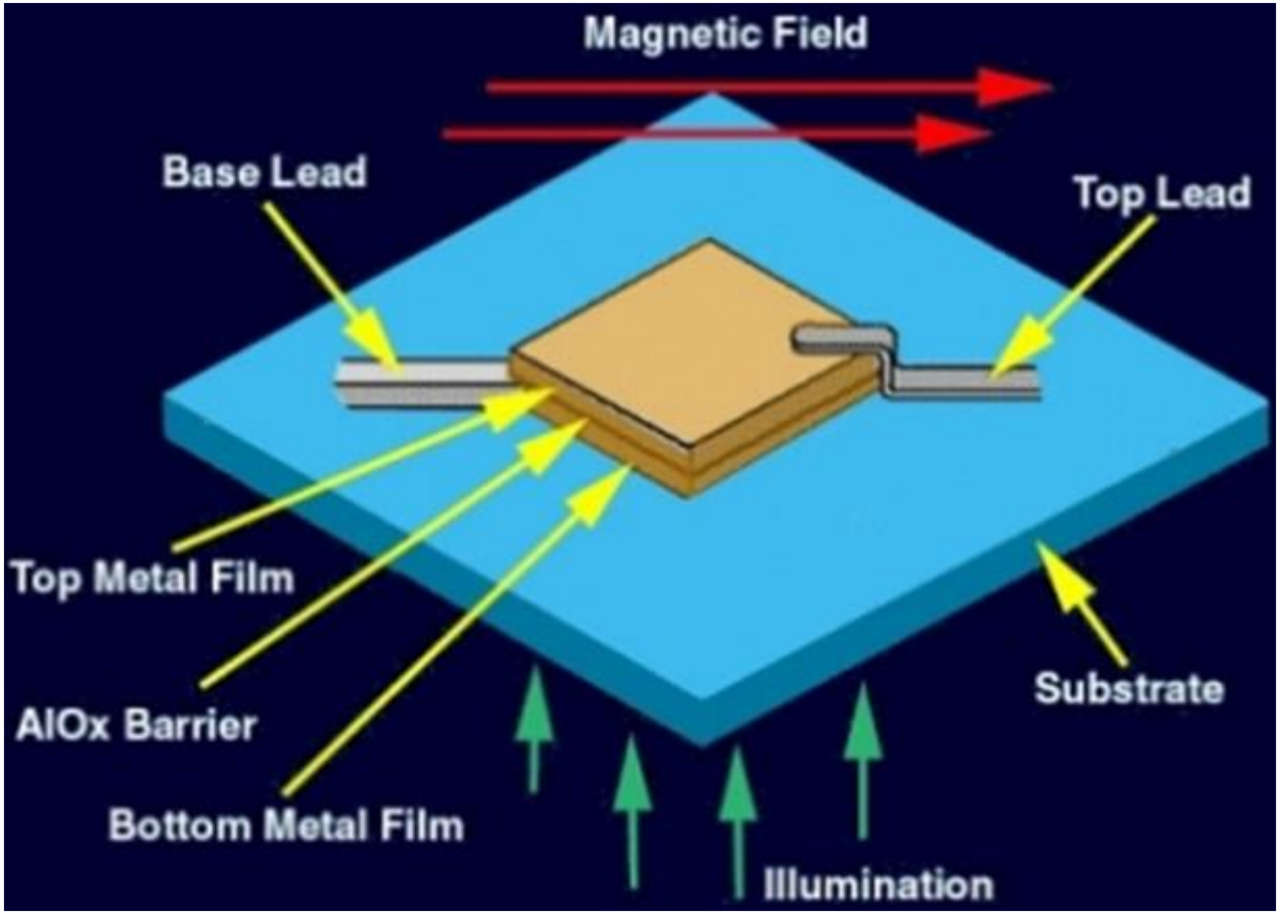
- STJ detectors are cryogenic detectors operating on a principal more similar to the semiconductor detectors we discussed earlier.
- Consist of two thin films of a superconducting metal (such as niobium or tantalum) separated by a thin insulator.
- Detectors work using the superconducting tunnel (Josephson) effect.

STJ basics

- Within the superconductor, the lowest energy state for the electrons occurs when they link together to form Cooper pairs.
- Cooper Pairs can tunnel across the junction despite the presence of the insulating layer, because they have a wave-like behaviour as well as a particle-like behaviour.
- The current flowing across the junction can be suppressed by a magnetic field.

STJ Detectors

Schematic of a single STJ pixel.



STJ basics

- Photons strike the superconducting film and break up electron Cooper Pairs.
- The energy required to break up these pairs, called the band-gap, is as small as 1milli-eV (1meV).
- A single optical photon can produce of order 1000 carriers (compare with a silicon detectors where the band gap is 1.1 eV).
- Carriers then tunnel through the barrier to the other electrode, and produce an increased current which can be measured.

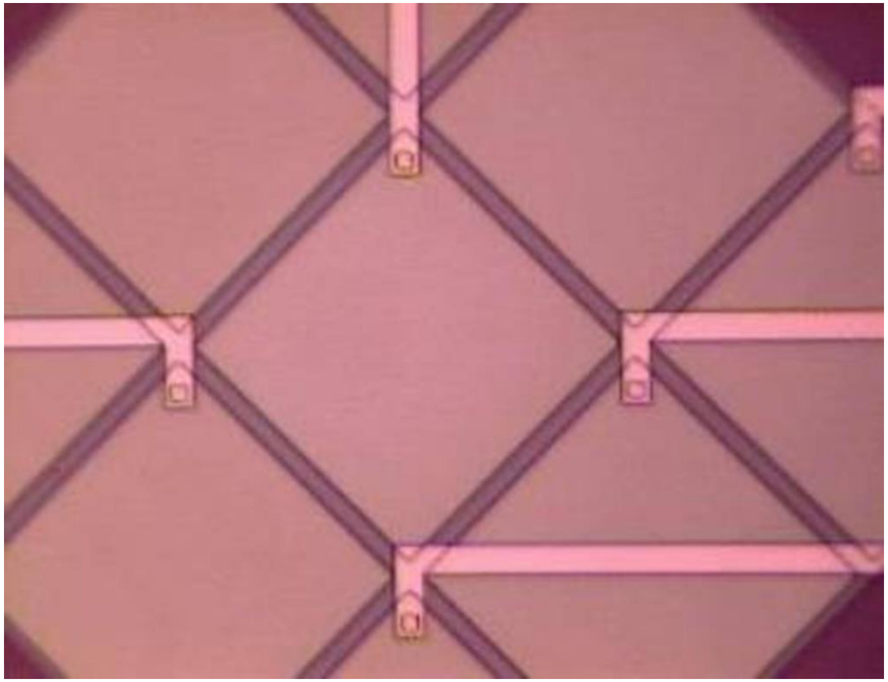
STJ Detectors

- The amplitude of this current is directly proportional to the energy of the incident photon over a wide range of photon energies.
- The STJ is theoretically capable of detecting single photons with micro-second time resolutions and energy resolution of 10 ev or better.
- Energy resolution of an STJ is limited by an equivalent of Fano noise, and in general is not as good as TES Quantum Calorimeters.
- Time resolution is limited by the recombination time of the quasi-particle states, which is of order 2-10 μs, which is better than TES Quantum Calorimeters.
- RQE of both kinds of detector is in the range 50-70%.

STJ Detectors: Applications

- A 6 x 6 STJ array has been used on the William Hershel Telescope for a number of test observations.

Successfully observed the light curve of the Crab pulsar and colour changes in the rapidly variable binary UZ For.



STJ & TES Advantages

- TES

$$\Delta E_{FWHM} \approx 15\ \text{meV} \left(\frac{E_{sat}}{1\ \text{eV}}\right)^{1/2} \left(\frac{T_c}{70\ \text{mK}}\right)^{1/2}$$

- STJ

$$\Delta E_{FWHM} \approx 45\ \text{meV} \left(\frac{E}{1\ \text{eV}}\right)^{1/2} \left(\frac{T_c}{1\ \text{K}}\right)^{1/2}$$

Single photon counting
- Time-stamping (better than 0.1 μs is possible)
- Low resolution spectroscopy (R ~ 100 $(\lambda/100\text{nm})^{1/2}$)

Broadband from near IR to far UV on up to X-rays
- Same technologies scale through large dynamic range

High efficiency
- QE is greater than 50% in optical and UV
- With coatings nearing 100% is possible

STJ & TES Arrays

- Demonstrated:
  - 8×2 STJ imaging array by ESA
  - 2×2 TES array by Stanford/NIST
- Under construction
  - 10×10 STJ imaging array by ESA
  - 8×4 TES imaging array by Stanford
- In five to ten years
  - 32×32 pixels TES or STJ