Detectors for Laser Measurements (introduction for practitioners)

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Outline

Motivation

Past
Present
- Organization
- Limitations
- Types of detectors
- Amplifiers
- Terms
  - Metrology related
  - Noise related

Future
Practical matters
- Cleaning
- Quiz

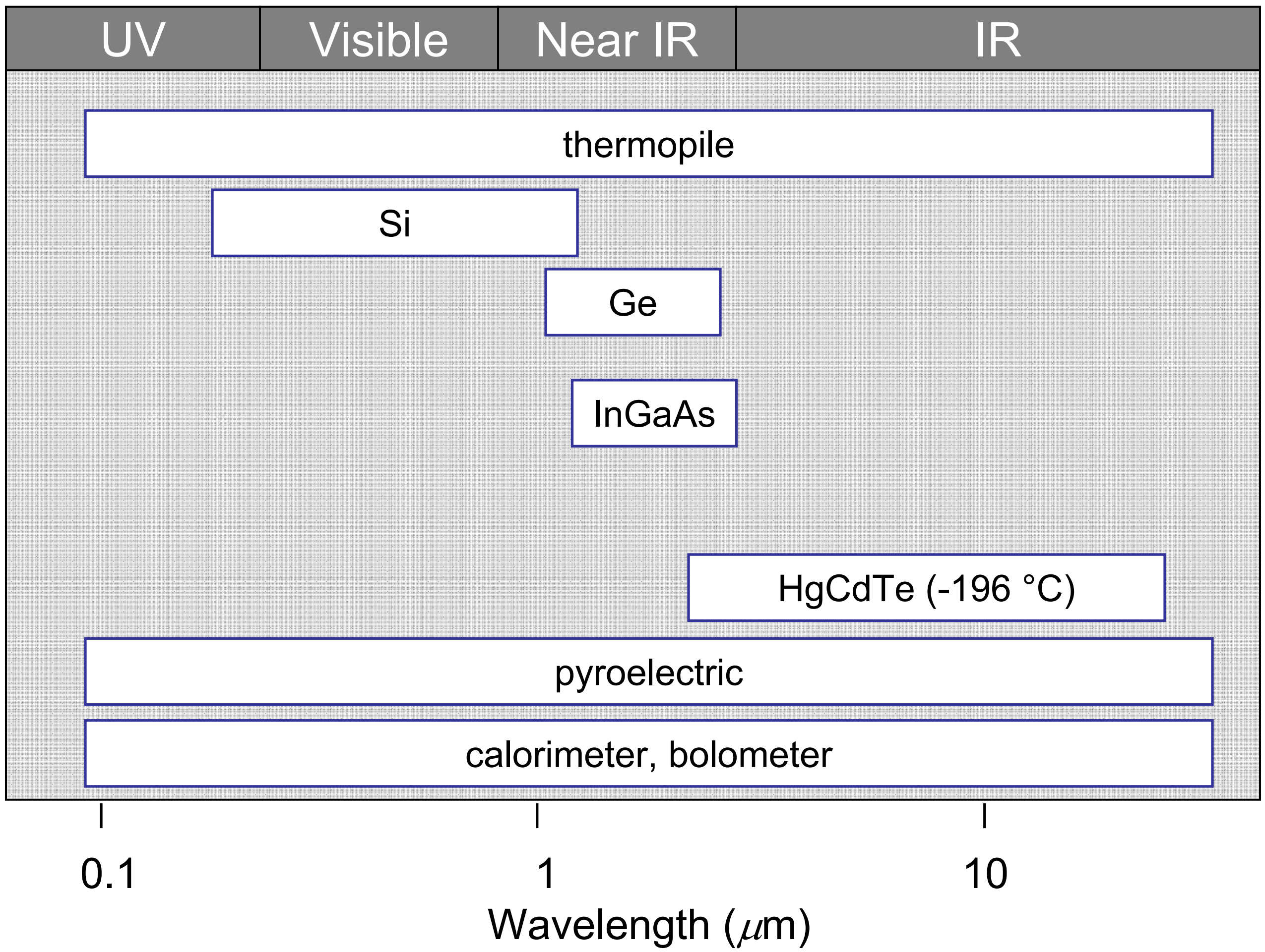
Motivation

For Laser Measurements:
Optical detectors capable of measurements having low uncertainty

- wavelength range 0.157μm to 10μm and beyond
  (high spectral uniformity preferred)
- spatial uniformity variations ~ 0.1 %
- angular (directional) uniformity
  variations (no polarization sensitivity) ~ 0.1 %
- noise equivalent power (NEP) ~ 1 to 10 nW $Hz^{-1/2}$ cm^{-1}
- high damage threshold > 250 mJ/cm^2

- size ~ 1 cm diameter
- temperature dependence ~ negligible
- temporal response 1:1
- no window
- robust and convenient

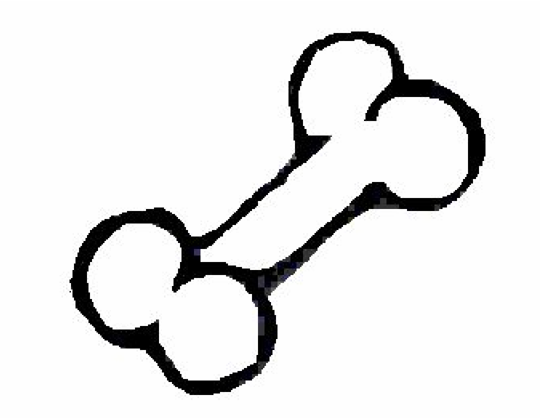
Detectors for laser power and energy measurements



Past

History

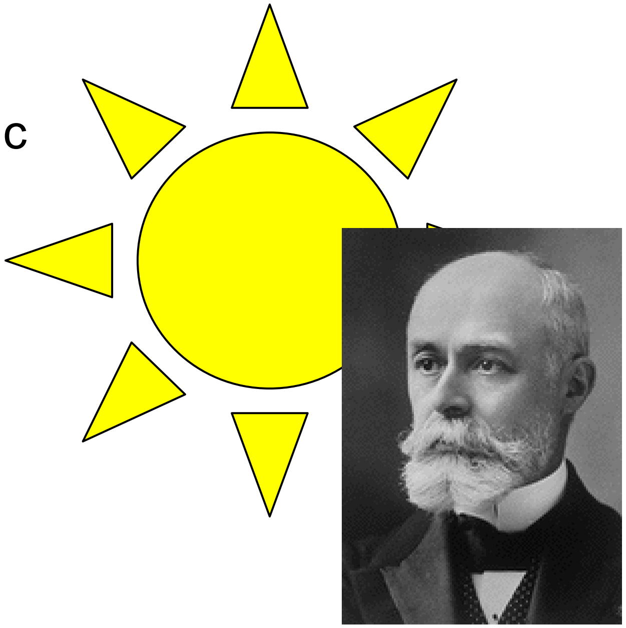
The earliest written description of pyroelectricity was in 315 B.C. by a Greek named Theophrastus. “Rediscovered” in 1703.



S. B. Lang, *Sourcebook of Pyroelectricity*, (Gordon and Breach, New York, 1974), pp. 167-375.

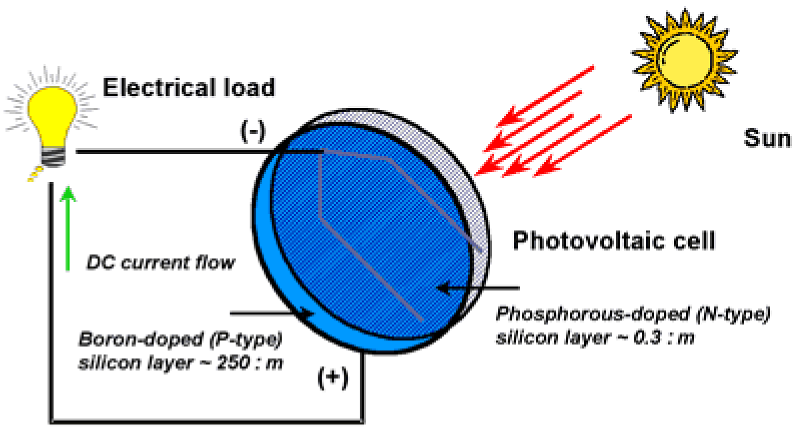
History

Photovoltaic



The photovoltaic effect, which is the transformation of solar energy (photon) into electricity (Volt) was discovered in 1839, by the French physicist Antoine Henri Becquerel

1827 Joseph Nicephore; Photography



http://www.nobel.se/physics/laureates/1903/becquerel-bio.html

http://www.fsec.ucf.edu/pvt/pvbasics/

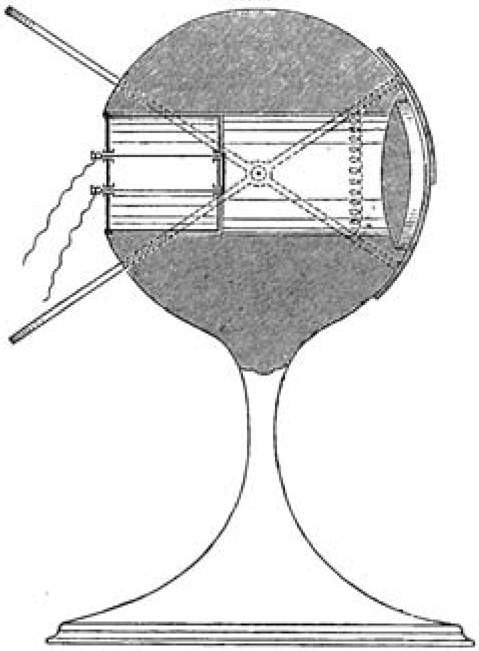
History

William Siemen’s “electric eye,” 1876

Selenium photoconductor

SIEMENS, C.W., "The Action of Light on Selenium" Evening Disclosures in Physical Sciences - Royal Institution, *Proc. Roy. Inst. Gt. Brit.*, 18 February 1876, VIII, 68. C. (Reproduit in *Physical Sciences*, Vol 2, pp 466-477 Applied Science Publisher Ltd, London 1970)
"Artificial Eyes Made Sensitive to Light", *Scientific American*, 6 May 1876.
"Siemens' Sensitive Artificial Eye", *Scientific American,* 8 December 1876.

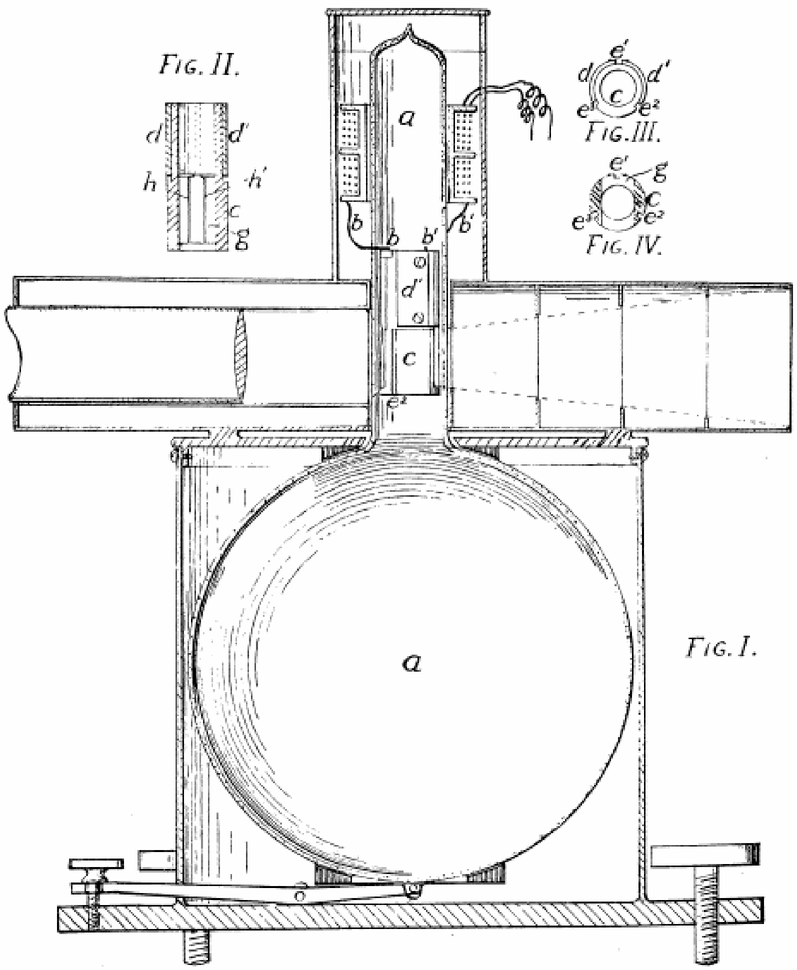
Fig. 5.



~ 1878, Alexander Bell, During these years of the Volta Laboratory he invented the photophone, an apparatus for transmitting speech over a ray of light (the sun!) by means of the variable electric resistance of selenium to light and shade.

History

ANNALS OF THE ASTROPHYSICAL OBSERVATORY vol. 6 1881



1. THE MAKE-UP OF THE BOLOMETER

Sensitive strips h, h' mounted on the copper blocks c, d' form two arms of a Wheatstone's bridge, completed by the two coils b, b'. Solar spectral rays are admitted by a vestibule with diaphragms, and may be adjusted by the eyepiece. The vessel, a, is highly evacuated.

http://www.hao.ucar.edu/public/education/sp/images/langley.html

Samuel Langley's bolometer, 1881

Langley's chief scientific interest was the sun and its effect on the weather, and believed that all life and activity on the Earth were made possible by the sun's radiation. In 1878 he invented the bolometer, a radiant-heat detector that is sensitive to differences in temperature of one hundred-thousandth of a degree Celsius (0.00001 C) . Composed of two thin strips of metal, a Wheatstone bridge, a battery, and a galvanometer (an electrical current measuring device), this instrument enabled him to study solar irradiance (light rays from the sun) far into its infrared region and to measure the intensity of solar radiation at various wavelengths.

"Langley's bolometer was so sensitive that it could detect thermal radiation from a cow a quarter of a mile away."

Present

Detector confusion

Optical detectors are often written about and explained with jargon that obstructs a comprehensive understanding of the many and varied detector types.

For example, a detector is often informally referred to by the material from which it is made, such as a "germanium detector," or the principle upon which it operates, such as a "photodiode," or the primary use, such as an "IR detector" or "fast pulse detector." Despite the obviously different meanings of each of these detector types, the names may simply refer to the same physical device.

Optical detectors constantly evolve with the implementation of new materials and fabrication techniques that are intended to enhance the performance and reduce the cost of existing detector types.

http://schools.sd68.bc.ca/ruth/Classes/mrtaylor/class20022003/idioms/idioms2003/idioms3/mix%20you%20up.jpg

Detector organization by subject, principle of operation, type, and example.

Principle	Detector Type	Examples
Thermal: Signal is proportional to the power or energy in the optical beam. Optical power is converted to heat, causing a temperature rise in the material. Certain types can be calibrated with electrical heaters.		
Quantum: Signal is proportional to incidence rate of photons (photons/s).Photons generate events in material, which are detected electrically.		

Detector organization by subject, principle of operation, type, and example.

Principle	Detector Type	Examples
Thermal: Signal is proportional to the power or energy in the optical beam. Optical power is converted to heat, causing a temperature rise in the material. Certain types can be calibrated with electrical heaters.	Thermopile: Temperature change is sensed with one or more thermocouples. Pyroelectric: Temperature change generates a charge which produces an electrical current. Bolometers: Temperature change is sensed with a resistance thermometer.	
Quantum: Signal is proportional to incidence rate of photons (photons/s).Photons generate events in material, which are detected electrically.	Photovoltaic: Photons generate electron-hole pairs which are separated by internal electric fields which generate current and voltage. Photoconductor: Photons generate electron/hole pairs, increasing electrical conductivity. Photoemitter: Photons excite electrons which escape from the material surface into vacuum (photoelectric effect) and are collected by an electrode.	

Detector organization by subject, principle of operation, type, and example.

Principle	Detector Type	Examples
Thermal: Signal is proportional to the power or energy in the optical beam. Optical power is converted to heat, causing a temperature rise in the material. Certain types can be calibrated with electrical heaters.	Thermopile: Temperature change is sensed with one or more thermocouples.	Cu-K, Bi-Sb, or Bi-Te; thin film thermopiles, cavity thermopiles, calorimeters.
	Pyroelectric: Temperature change generates a charge which produces an electrical current.	$LiTaO_3$, TGS, and Plastic materials.
	Bolometer: Temperature change is sensed with a resistance thermometer.	Mn, Ni, Co oxides, low temperature Ge or Si resistance thermometers, thermistors, Pt resistance thermometers
Quantum: Signal is proportional to incidence rate of photons (photons/s).Photons generate events in material, which are detected electrically.	Photovoltaic: Photons generate electron-hole pairs which are separated by internal electric fields which generate current and voltage.	Photodiodes such as Si, Ge, InGaAs, InSb, InAs, HgCdTe; Avalanche photodiodes.
	Photoconductor: Photons generate electron/hole pairs, increasing electrical conductivity.	GaN, CdS, CdSe, HgCdTe, and PbS photoconductors, extrinsic Si and Ge for far IR detection.
	Photoemitter: Photons excite electrons which escape from the material surface into vacuum (photoelectric effect) and are collected by an electrode.	Photomultipliers with metal or semiconductor photocathodes (such as Ce2Te, Ce3Sb, GaAs, S-1, S-4)

Detectors and detector capability ranges for continuous laser input conditions.

(Adapted from W. Budde, the OSA handbook, and vendor literature.)

Detector	Wavelength (μm) Range	Noise Equivalent Power [∅ 1 cm, 1 Hz]* (W)	Max Input (W/cm^2)	Response time (s)	Max Area (mm^2)	Uniformity (% spatial response variation)
Avalanche diode	0.25 to 1.9	1×10^{-12}	2×10^{-4}	8×10^{-11} to 5×10^{-9}	0.007 to 7	5
Germanium photodiode	0.4 to 1.9	1×10^{-11}	2×10^{-3} to 0.3	5×10^{-10} to 2×10^{-7}	0.01 to 80	5
Silicon photodiode, biased	0.25 to 1.1	1×10^{-12}	5×10^{-3} to 1×10^{-2}	3×10^{-11} to 2×10^{-7}	0.01 to 800	2
Silicon photodiode, unbiased	0.25 to 1.1	1×10^{-14}	5×10^{-3} to 1×10^{-2}	8×10^{-9} to 2×10^{-6}	0.85 to 800	2
Photoconductor for shorter or "near" infrared wavelengths (InSb, PbS, PbSe)	0.35 to 6	1×10^{-9} -1×10^{-11}	2×10^{-3}	1×10^{-6} to 1×10^{-4}	3 to 100	5
Photoconductor for longer infrared wavelengths cooled (HgCdTe)	5 to 20	1×10^{-11}	1×10^{-3}	1×10^{-8} to 1×10^{-7}	0.1 to 10	10
Photomultiplier: S-4	0.18 to 0.95	1×10^{-15}	1×10^{-10}	5×10^{-10} to 2×10^{-8}	14 to 12000	20 to 50
Photomultiplier: S-1	0.3 to 1.1	1×10^{-13}	1×10^{-7}	1.5×10^{-9} to 3.5×10^{-9}	80 to 280	20 to 50
Vacuum phototube, high bias voltage	0.2 to 1.1		2×10^{-4} to 2×10^{-8}	1×10^{-10} to 1×10^{-9}	78 to 18000	20 to 50
Vacuum phototube, low bias voltage	0.2 to 1.1	1×10^{-8}	1×10^{-3}	5×10^{-10} to 1×10^{-8}	25 to 7000	20 to 50
Pyroelectric detectors	0.2 to 25	1×10^{-9}	1×10^{-1} to 2×10^{-1}	1×10^{-9} – 1×10^{-7}	1 to 1000	5
Bolometers and Thermistors	0.2 to 25	1×10^{-10}	2×10^{2} to 1×10^{3}	1×10^{-3}	0.01 to 100	10
Thermopile-based	0.2 to 20	1×10^{-10}	5×10^{1} to 5×10^{3}	1×10^{-3} to 1	100 to 2000	5 to 10

* 1 cm diameter specification is for purposes of comparison and is not practically achievable for all types of detectors.
Noise equivalent power varies as a function of wavelength; the values given are an approximate minimum.

Detectors and detector capability ranges for pulsed laser input conditions.

(Adapted from W. Budde, the OSA handbook, and vendor literature.)

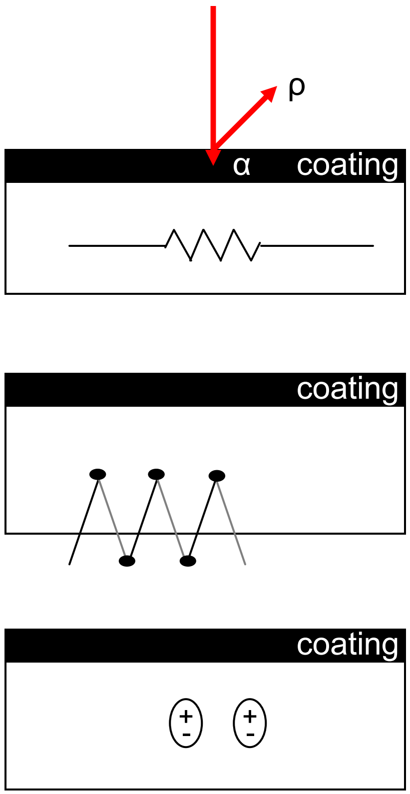
Detector type	Wavelength range (μm)	Max Input range (J/cm^2) (duration < 1 s)	Max Single Pulse Energy (J)	Max Area (mm^2)*
Germanium photodiode	0.8 to 1.8	5×10^{-5} to 5×10^{-4}	5×10^{-5} to 5×10^{-4}	0.01 to 100
Indium Gallium Arsenide	0.75 to 1.8	5×10^{-5} to 5×10^{-4}	5×10^{-5} to 5×10^{-4}	0.01 to 80
Silicon photodiode	0.25 to 1.1	1×10^{-3} to 5×10^{-5}	1×10^{-3} to 5×10^{-5}	0.01 to 800
Pyroelectric detector	0.2 to 25	8 to 80	1×10^{-6} to 1×10^{-3}	1 to 1000
Thermopile, surface	0.2 to 20	0.1 to 100	1×10^{-3} to 0.15	0.8 to 70
Thermopile, volume	0.2 to 20	0.5 to 1×10^{3}	1×10^{-4} to 1×10^{2}	100 to 2000

* Larger detectors are relatively slower

Detector operation

Detector operation

Thermal type



bolometer
calorimeter

thermopile

pyroelectric

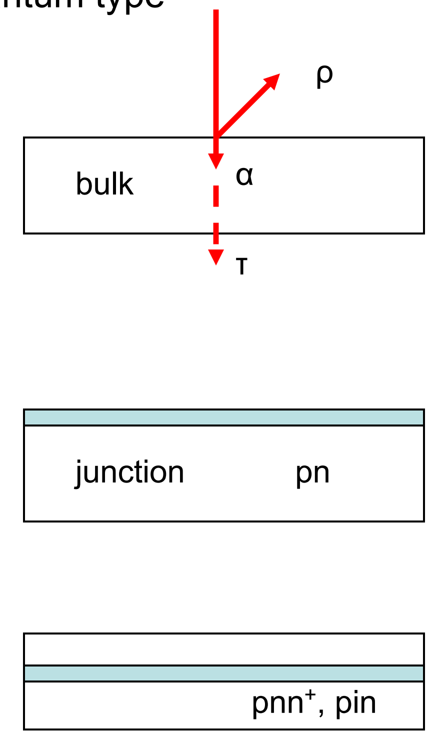
low thermal mass for max sensitivity

Quantum type

photoconductor

photoconductor
or photovoltaic

photoconductor
or photovoltaic



max sensitivity
Photon energy vs. bandgap energy

Photovoltaics and photoconductors

Different ways of thinking about them

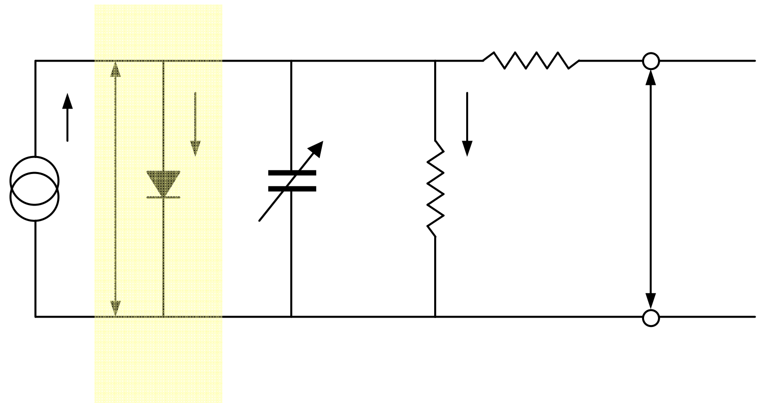
(by way of introduction)

photovoltaic or photoconductive

junction or bulk

Are also known as photodiodes

Are semiconductors

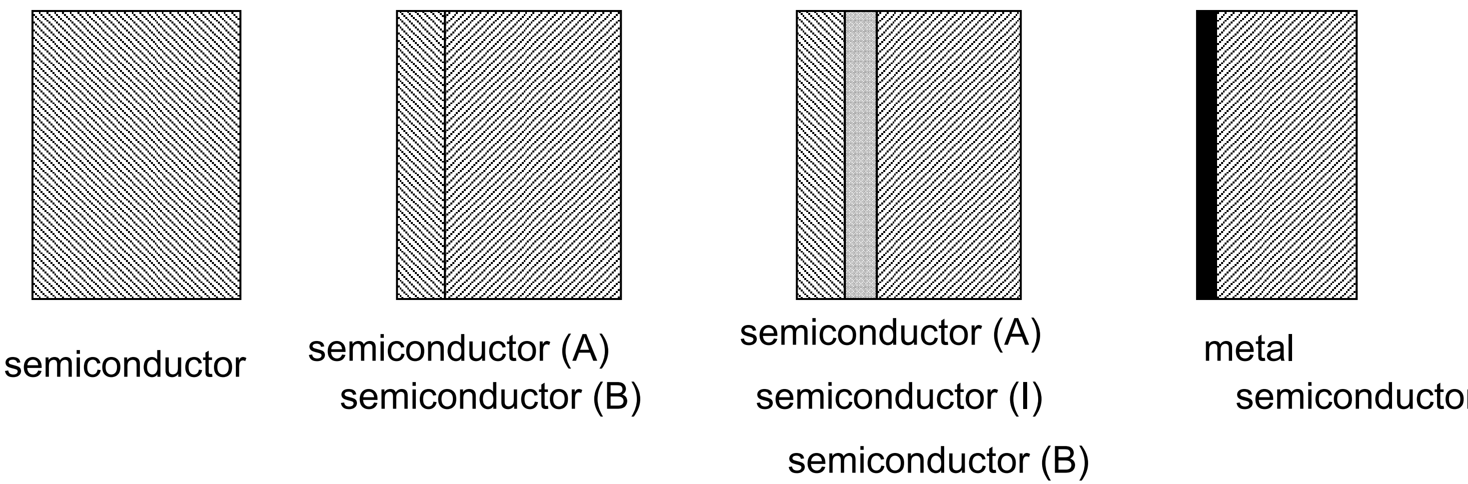


Photovoltaics and photoconductors

www.Hamamatsu.com

Photovoltaic: Photons generate charge (electron-hole pairs which are separated by internal electric fields which generate current and voltage).

Photoconductor: Photons increase electrical conductivity (generate electron-hole pairs).

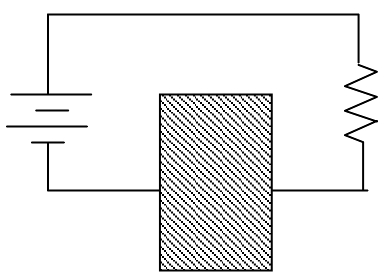


Photovoltaics and photoconductors

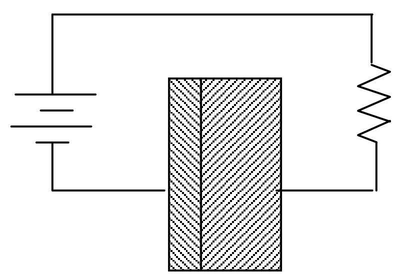
alternatively we may consider two other general categories: bulk and junction semiconductors
(avalanche diodes are junction device with bias)

junction devices: may be used as photovoltaic or photoconductive
- when unbiased operate as current of voltage generators
- when reverse biased and change of resistance is measurable

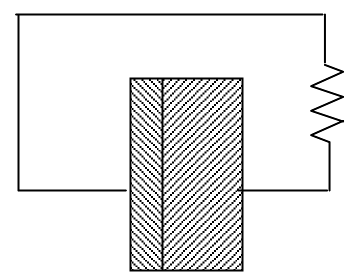
bulk devices: are biased and change of resistance is measurable



biased, bulk

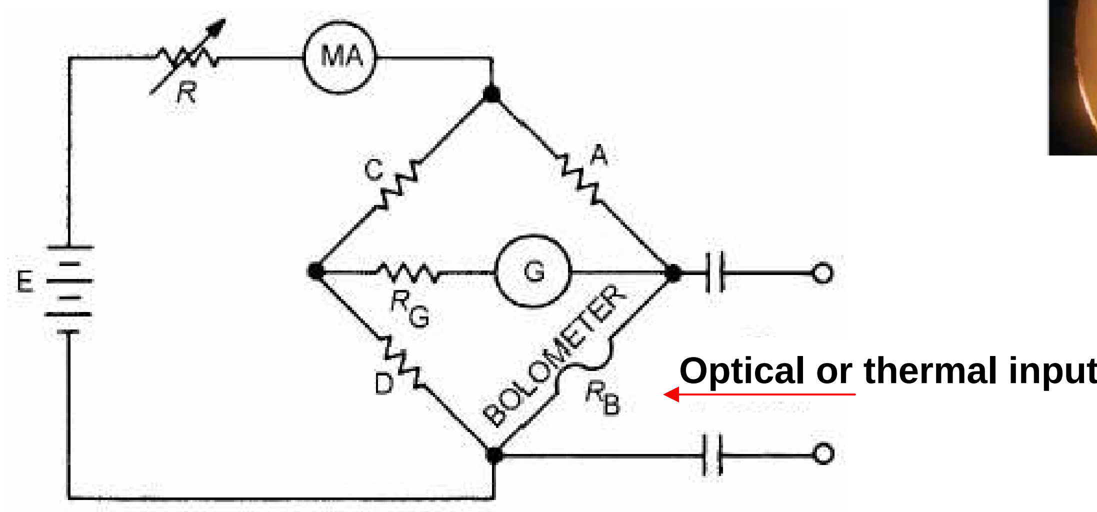


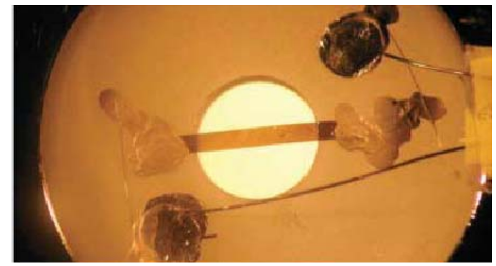
biased, junction, photoconductive



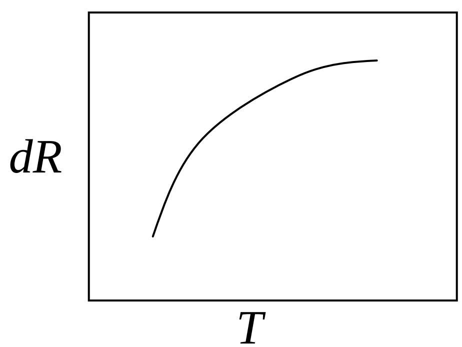
junction, photovoltaic

Bolometer





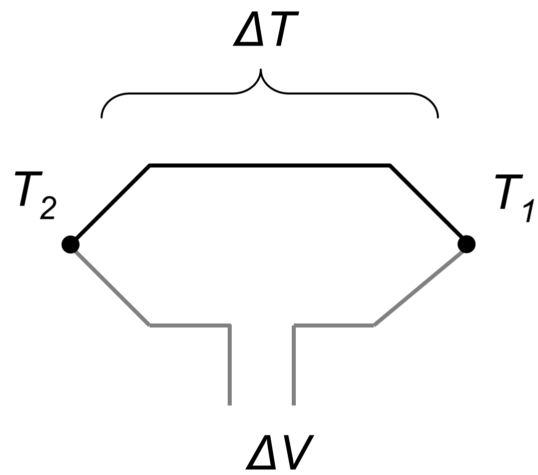
carbon nanotube bolometer



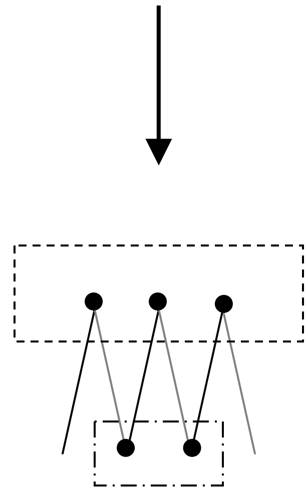
$$\alpha = \frac{dR}{RdT}$$

$$R(T) = R(T_s)(1+\alpha(T-T_S))$$

Thermopile



$$\Delta V = S\ \Delta T$$



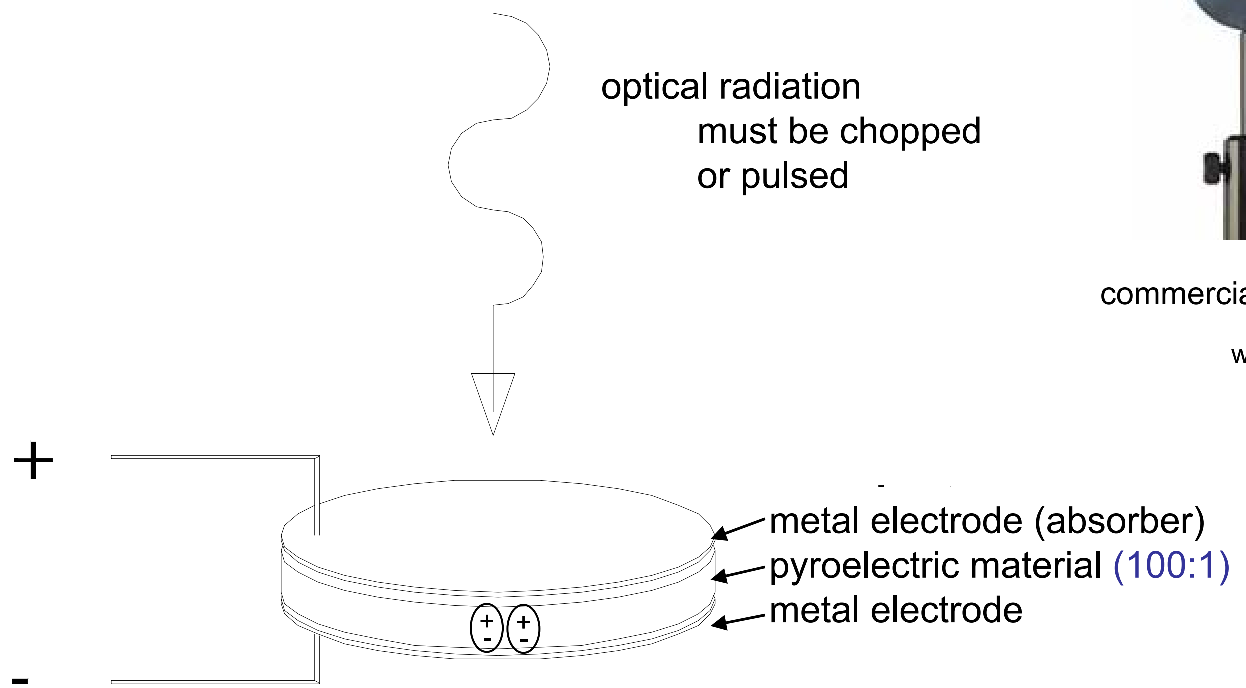
commercially available thermopile

www.gentec-eo.com

gradient vs. junction
different electric potential for identical temperature gradient
not a thermistor

Accuracy limit:
uniformity of
coating
junctions

Pyroelectric



commercially available pyroelectrics

www.gentec-eo.com

$$i = p\frac{A}{h}\int_0^h \frac{d\theta}{dt}dz$$

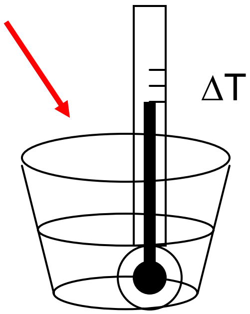
Accuracy limit:
amplifiers, filters
uniformity

Calorimeters and the like

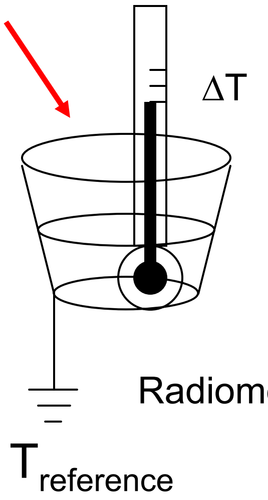
Thermistor heating

Cooling to maintain constant temperature

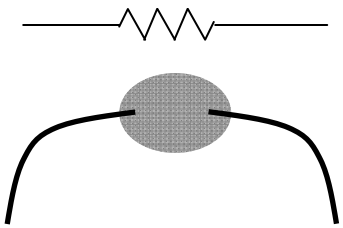
NIST calorimeter



Calorimeter



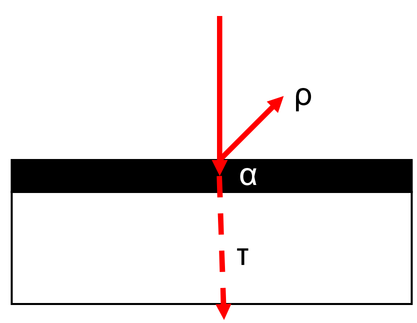
Radiometer



Thermistor

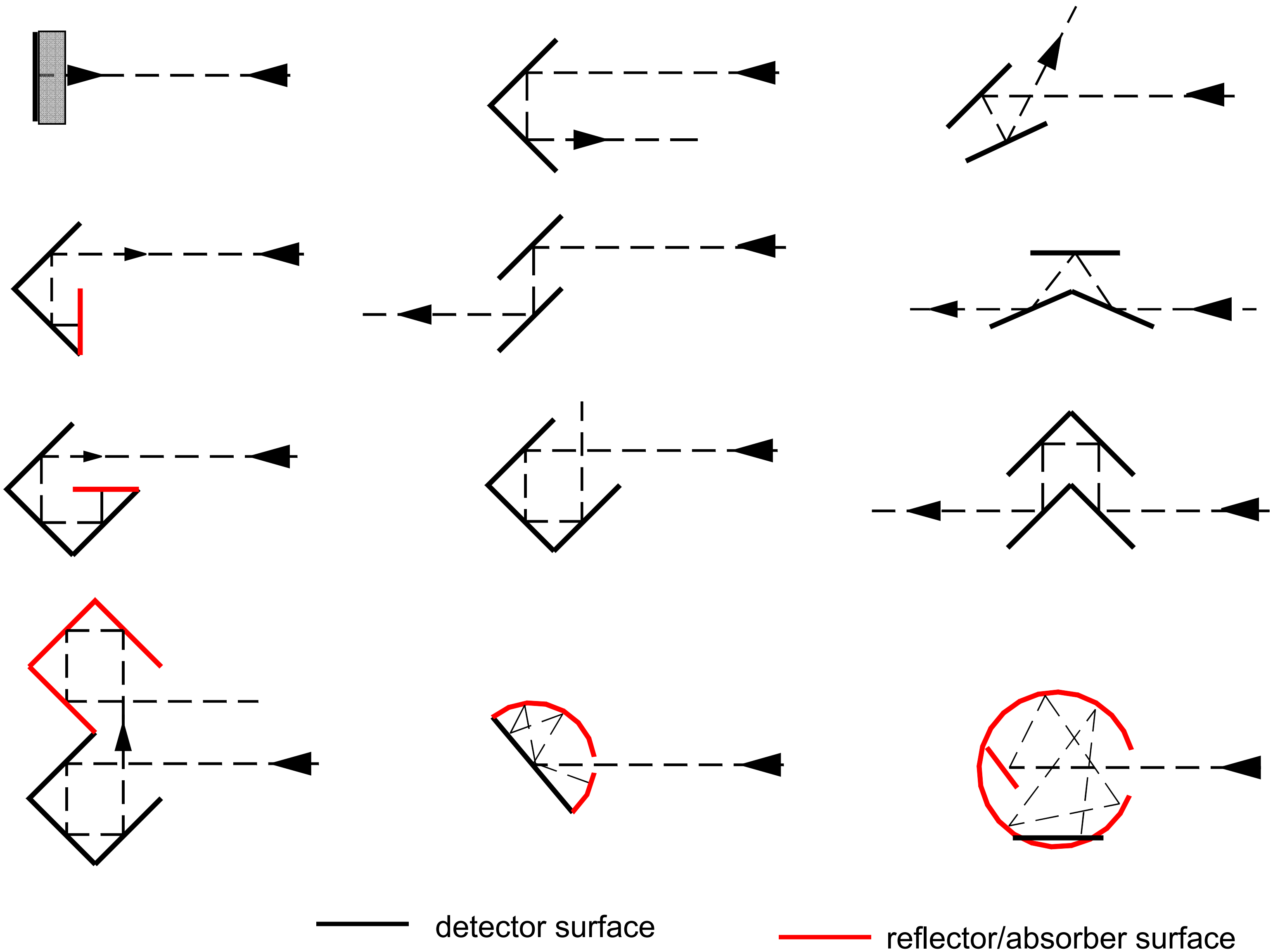
Managing losses
(efficiently and knowingly)

Laser radiometry distinguishes itself from other optical power measurements because we sometimes have *more* power than we need or want

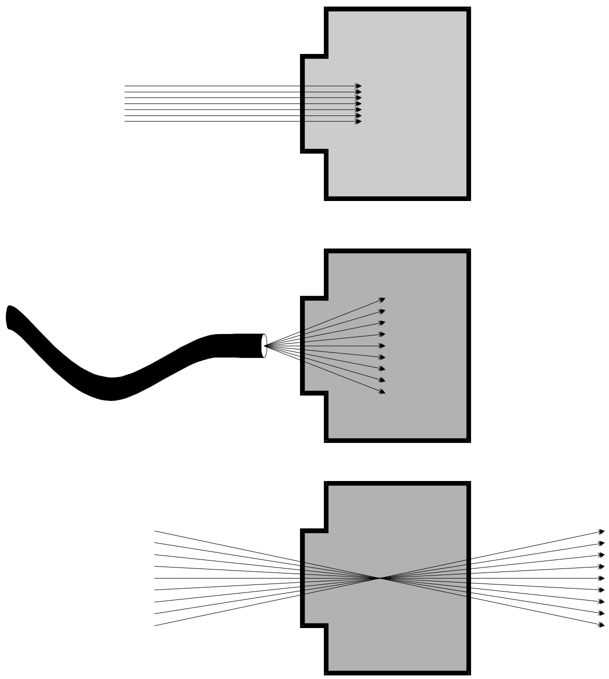


Managing losses

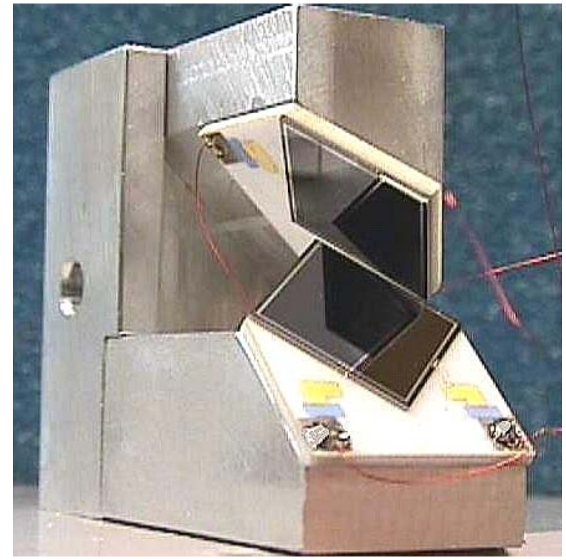
various detector schemes with traps, diffusers, reflectors, diffusers, etc.



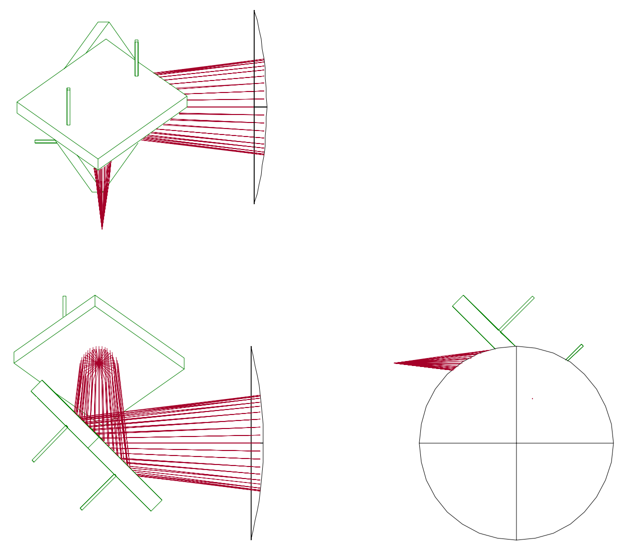
Trap detector



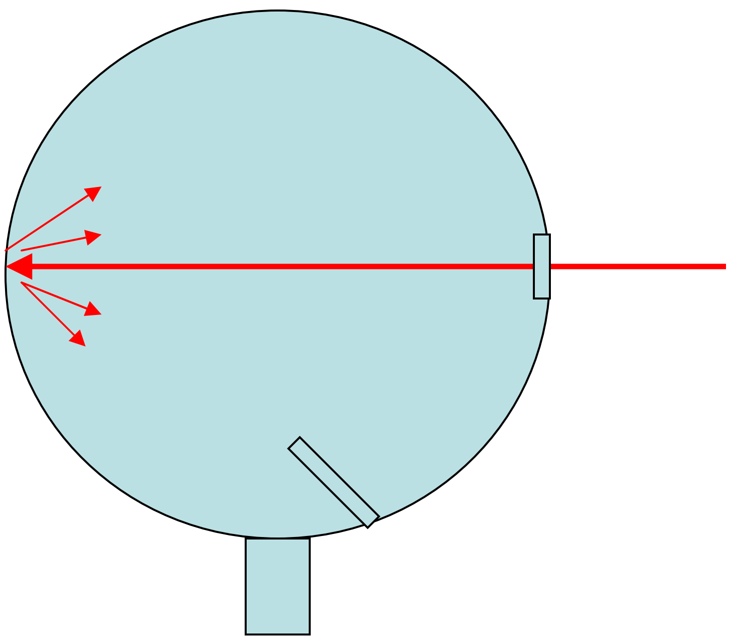
Various optical input conditions for laser measurements



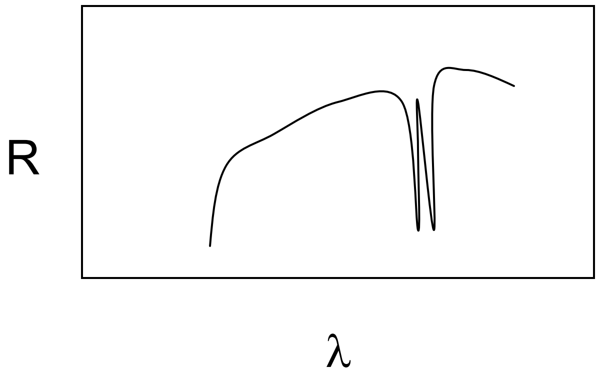
NIST Trap



A word about integrating spheres



Attenuation (good or bad)
Path length
Large uncertainties
    openings, baffles
Polarization
Speckle



For
- large divergence
- high power
- polarization

Amplifiers
(a whole other talk in two slides)

Voltage mode operation and current mode operation are fundamentally different amplification schemes with advantages and disadvantages that depend on the properties of the detector and the range of operation. In either mode the detector noise may be boosted along with the desired signal, or the amplifier itself may introduce noise that is comparable to that produced by the detector itself.

Voltage mode incorporates a voltage amplifier, which is essentially a biased field effect transistor (FET), with a gain proportional to an impedance connected parallel to the detector. From the viewpoint of the output of the detector, in voltage mode, the detector electrodes are essentially an open circuit.

A *current mode* amplifier relies on an inverting op-amp configuration with the gain proportional to the impedance situated electrically parallel to the op-amp. In current mode, the detector electrodes are effectively shorted.

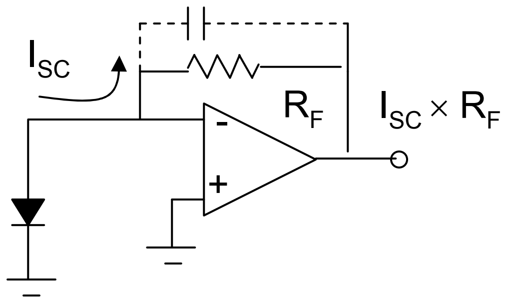
Amplifiers

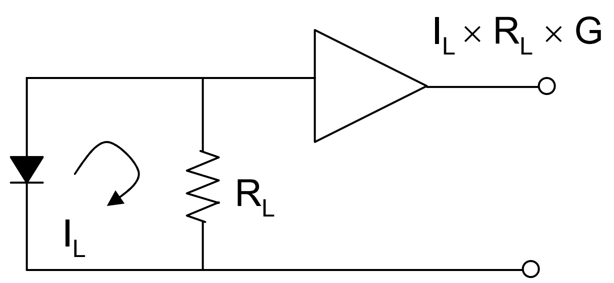
current amplifier
"current to voltage converter"

~ short circuit
better linearity?
noise ($\propto$ R)
capacitance

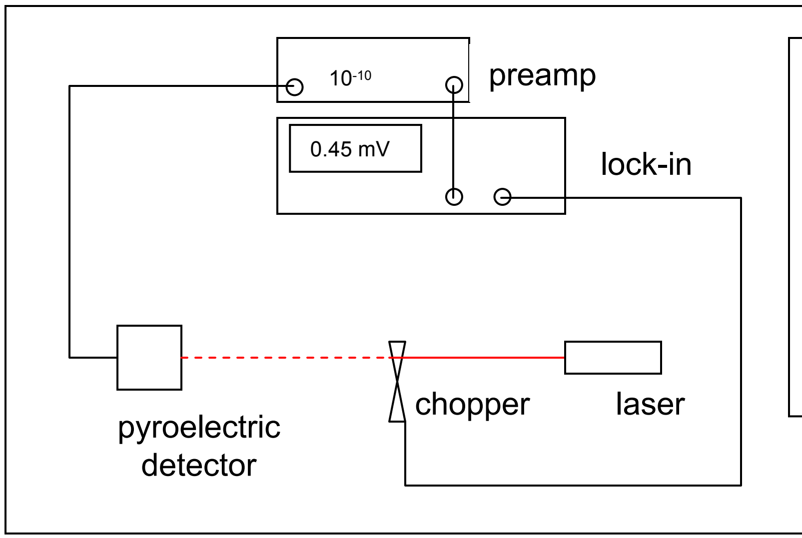
voltage amplifier

~ open circuit (high impedence)
linearity limitations?
lower noise?
faster

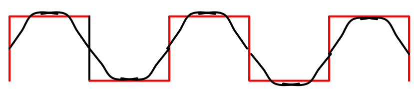




Amplifiers



Lock-in amplifier
- requires modulation
- challenging for absolute measurements
- good for noise/background

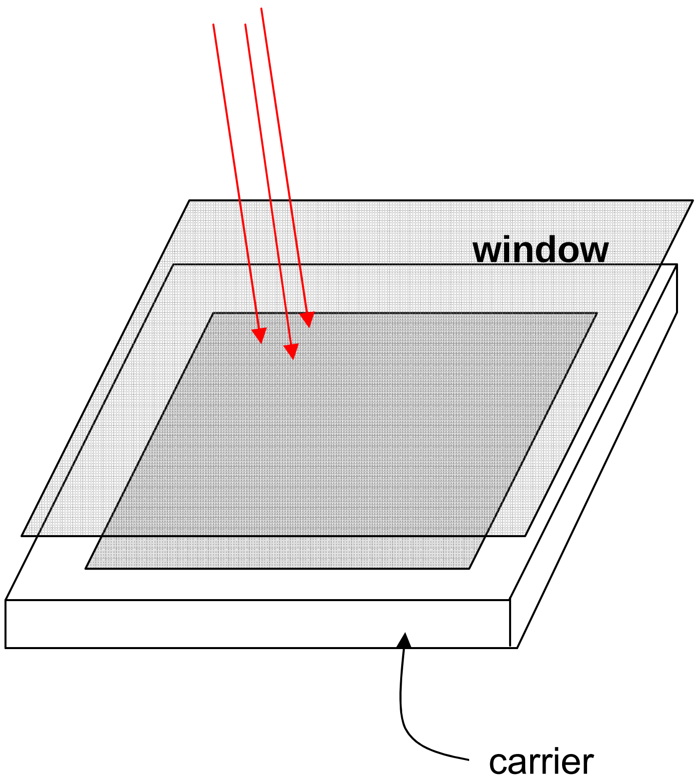


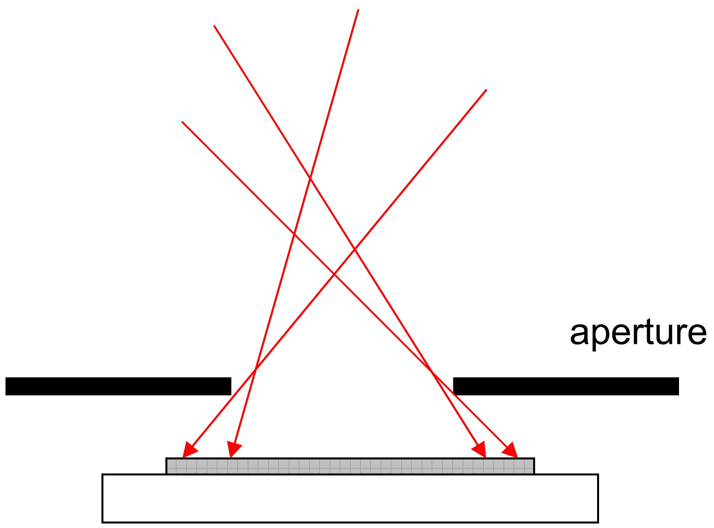
Terminology

Detector Properties

Active area or entrance aperture
Spatial and angular Uniformity
Damage Threshold
Detector Speed
Spectral Responsivity
Noise Equivalent Power
Normalized Detectivity

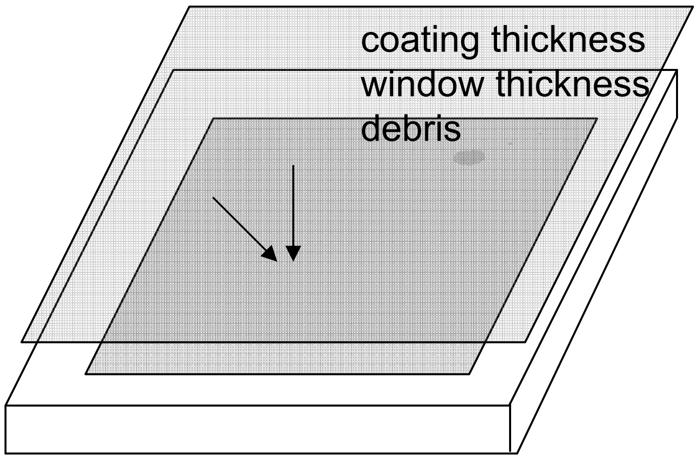
Active Area



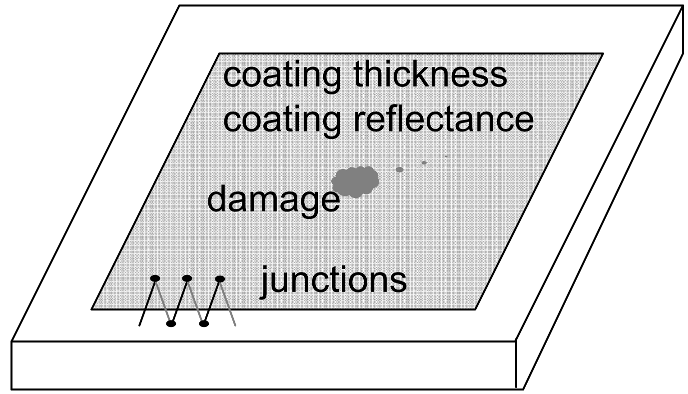


Uniformity

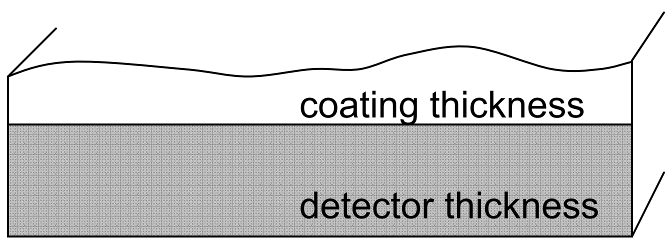
Detector response as a function position or angle of incidence
(is typically also a function of wavelength)



photodiode



thermopile



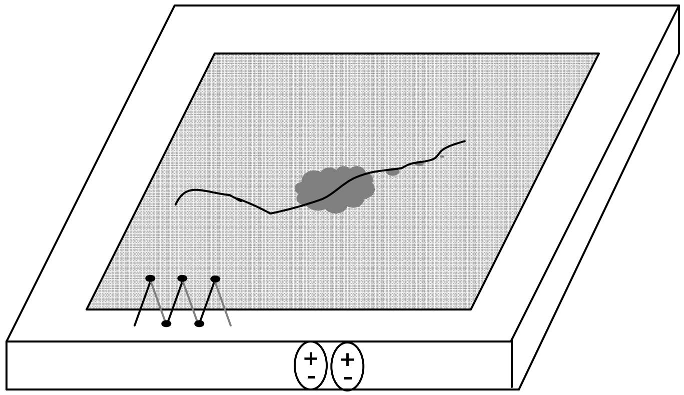
pyroelectric

Damage threshold

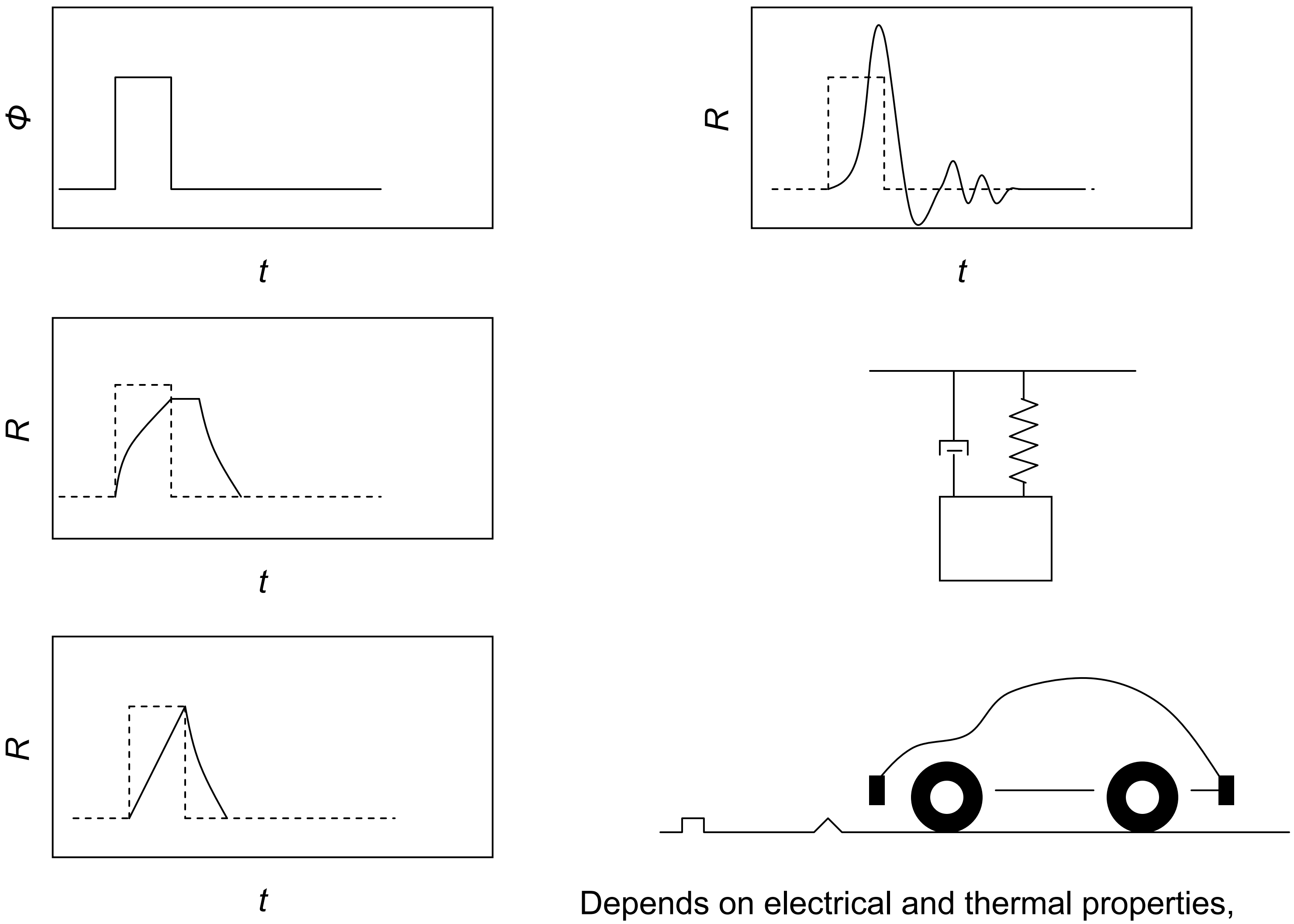
Thermopile
- junction overheating
- coating ablation

Pyroelectric
- depoling
- coating ablation or melting

Photodiode
- over bias
- overheating e.g. cracking
- ablation

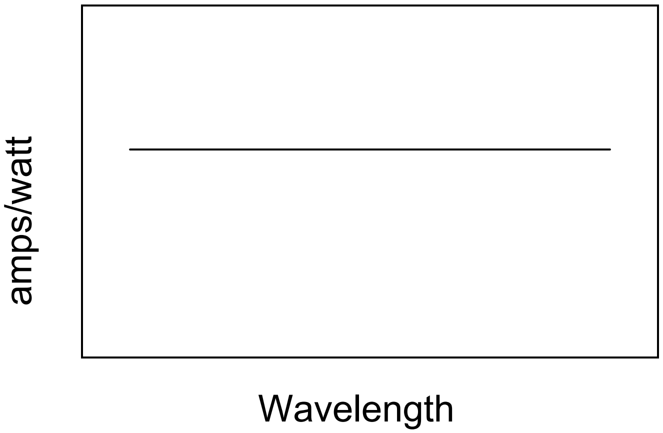


Speed (temporal response)
(a whole other talk)



Depends on electrical and thermal properties,
but may be understood with a mechanical analogy.

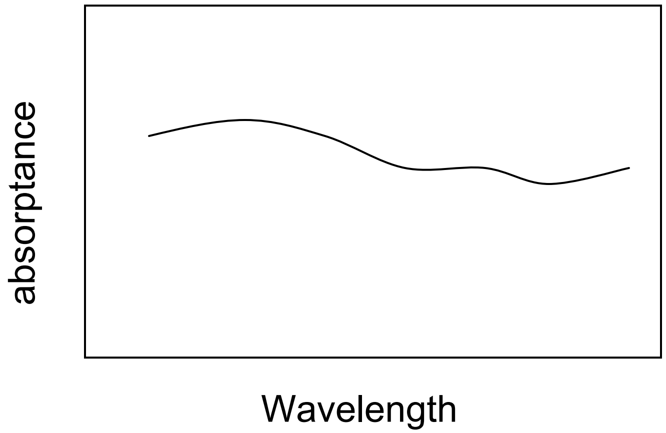
Ideal responsivity (thermal detector)



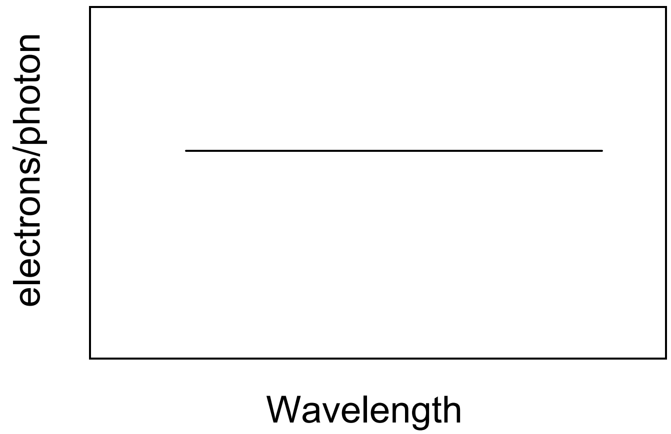
$$Response_{pyro} = \frac{V}{\Phi_{\omega}} = \frac{\eta(\omega pAR_E / G)}{(1+\omega^2\tau_\theta^2)^{1/2}(1+\omega^2\tau_E^2)^{1/2}}$$

no wavelength here

limited by
coating
temperature



Ideal responsivity (photovoltaic)

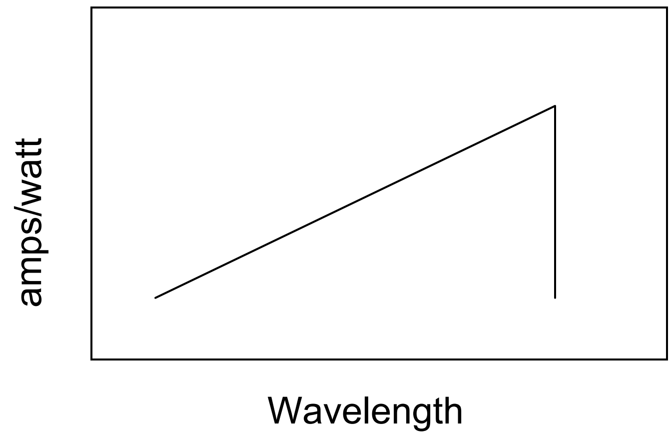


$$i = en_e = e\eta n_o = e\eta \frac{\Phi}{E_o} = e\eta\Phi \frac{\lambda}{hc}$$

$$Response_{photovoltaic} = \frac{i}{\Phi} = \eta \frac{\lambda}{1.239}$$

limited by

- conversion efficiency
- coatings
- temperature



$\lambda = wavelength$

$h = Planck\ constant$

$c = speed\ of\ light\ in\ vacuum$

$\Phi = optical\ power$

$e = electronic\ charge$

$n_e = electrons / second$

$n_o = photons / second$

$E_o = energy / photon$

Noise equivalent power

Noise equivalent power (NEP) is the amount of optical power input necessary to achieve a signal to noise ratio of one.

By convention, NEP
- Requires knowledge of the optical sensitivity
- is frequency (and bandwidth) dependent
- is area dependent
- is temperature dependent

There is no convention for acoustic basis
The amplifier may overwhelm all other noise

Relationship of NEP and detectivity

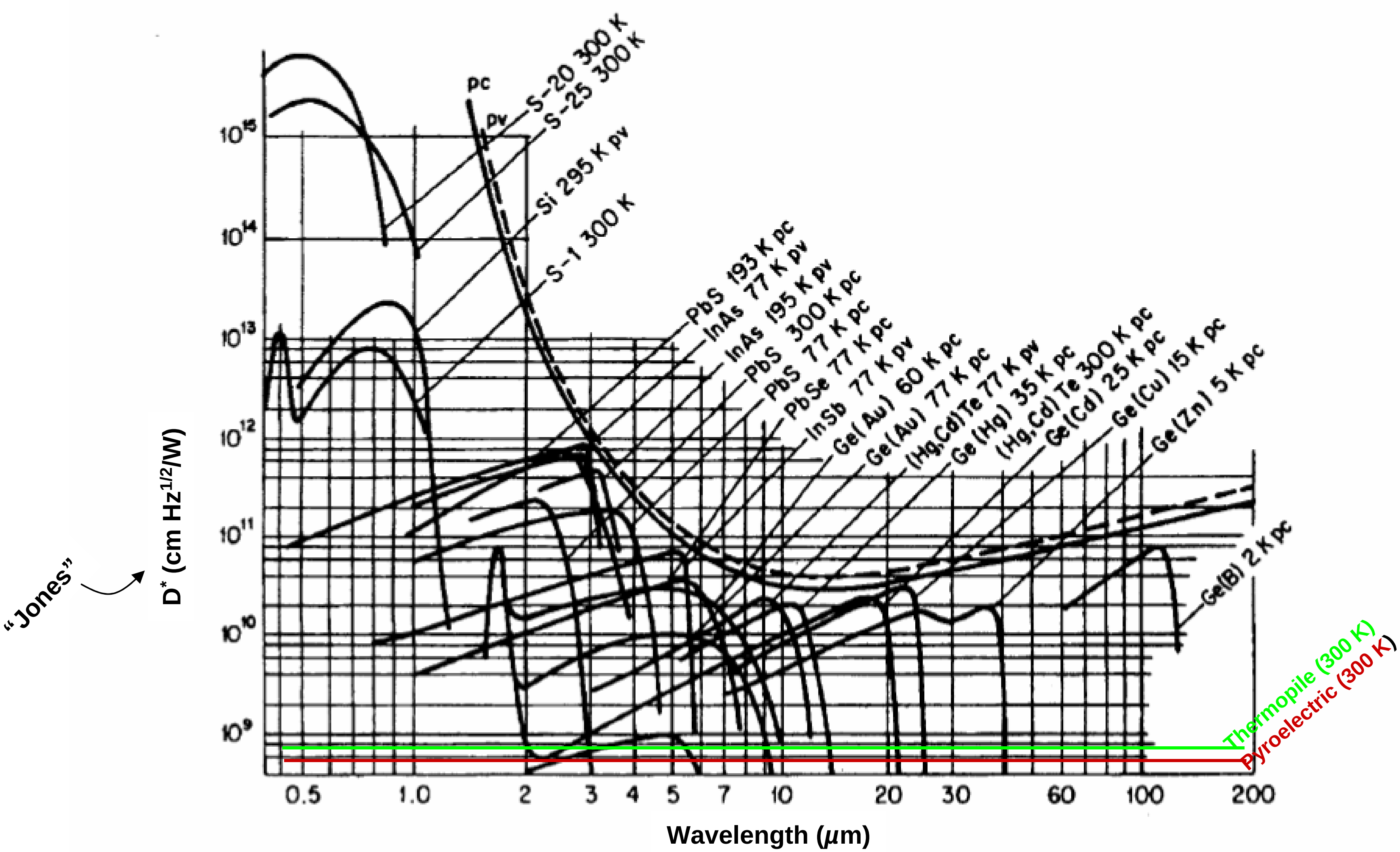
$$NEP = \frac{Power \times Area}{Response \times bandwidth^{1/2}}$$

$$D^* = \frac{Area^{1/2}}{NEP}$$

$$Response_{photovoltaic} = \eta \frac{\lambda}{1.239}$$

$$Response_{pyro} = \frac{V}{\Phi_\omega} = \frac{\eta(\omega pAR_E / G)}{(1+\omega^2\tau_\theta^2)^{1/2}(1+\omega^2\tau_E^2)^{1/2}}$$

Detectivity



180° FoV, 1 cm², 1 Hz

C. Carugno, http://www.slac.stanford.edu/pubs/icfa/fall98/paper2/paper2.pdf

Summary of noise sources and principles of behavior

Noise description	Basic Principle or measurable behavior	Device
Johnson (also called Nyquist or thermal noise)	Thermal agitation of electrons in resistive materials	Photovoltaic Photoconductor Pyroelectric Amplifier
Shot	Discrete electron generation (statistical variation) of an electric- potential barrier device	Photovoltaic Amplifier
Temperature fluctuation	Temperature fluctuation of the detector element not attributable to the source. Also called phonon noise if strictly by conduction	Thermal detector
Generation-recombination noise	Fluctuation in generation, recombination, or trapping in a semiconductor	Photoconductor Amplifier
1/f	Observed at low frequency (long time-constant measurements). Due to fluctuation in that part of electron mobility, rather than number, due to lattice scattering."[7]	Photovoltaic Photoconductor Bolometer detectors that require current bias
Microphonic or acoustic	Mechanical displacement of wiring and material elements	Pyroelectric (possibly any detector/amplifier)
Amplifier Current	Combined electrical noise including Johnson noise, shot noise and 1/f noise of the current amplifier	Transimpedance amplifier
Amplifier voltage	Combined electrical noise other than Johnson noise	Voltage amplifier with FET and bias configuration
Photon	Source or background fluctuation of incident optical radiation	Source

Summary of basic formulae for detector and amplifier noise

Noise spectral density [A^2 Hz^{-1}]	Basic formulae	Comments
Johnson $\langle i_n^2 \rangle_J$	$\frac{4k\theta_0}{\mathrm{Re}(Z)}$	Applies independently to detector or amplifier; k Boltzmann's constant θ_0 temperature, real impedance $\mathrm{Re}(Z)$.
Shot $\langle i_n^2 \rangle_s$	$2e^2 n_e / t$	Applies to amplifier (or photodiode); e electron charge n average number of photons produced in time period t.
Generation-recombination noise $\langle i_n^2 \rangle_{GR}$	$(2qn_p)^2 \eta_p \Phi_p A$	Applies to amplifier (or photoconductor); n_p number of electrons generated per photon-generated electrons (or photoconductive gain), Φ_p photon irradiance, η_p quantum efficiency, A detector area.
1/f $\langle i_n^2 \rangle_f$	$a \frac{i_b^\alpha}{f^\beta}$	Applies independently to detector or amplifier; i_b current through the detector, $\alpha \sim 1$, $\beta \sim 2$, a proportionality constant.
Amplifier noise $\langle i_n^2 \rangle_a$	$\left[\left(\langle i_n^2 \rangle_J\right)^2 + \left(\langle i_n^2 \rangle_s\right)^2 + \left(\langle i_n^2 \rangle_f\right)^2\right]^{1/2}$	amplifier-specific quadrature sum of equations
Thermal detector temperature fluctuation $\langle i_n^2 \rangle_\theta$	$R_i^2 \left(4k\theta_0^2 G\right)$	Applies to thermal detector having current responsivity R_i and power spectral density $4k\theta_0^2 G$; G thermal conductance ; θ_0 surrounding temperature.

[i]. E.L. Dereniak, D.G. Crowe, *Optical Radiation Detectors*, (John Wiley & Sons, New York, 1984), pp. 36–43.

Limits

noise equivalent power

- Power/energy sensitivity
- noise

Spectral responsivity

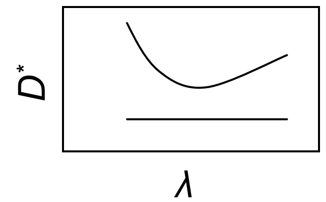
- coating
- material
- process
- composition

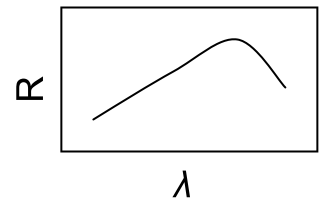
Uniformity (angular, spatial)

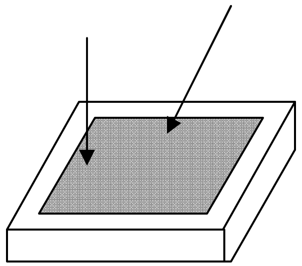
- AR coatings
- absorber coatings
- windows

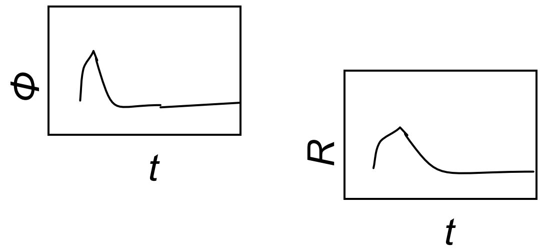
Speed

- area
- mass
- electronics (amp)





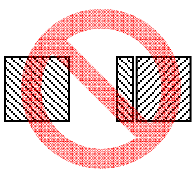


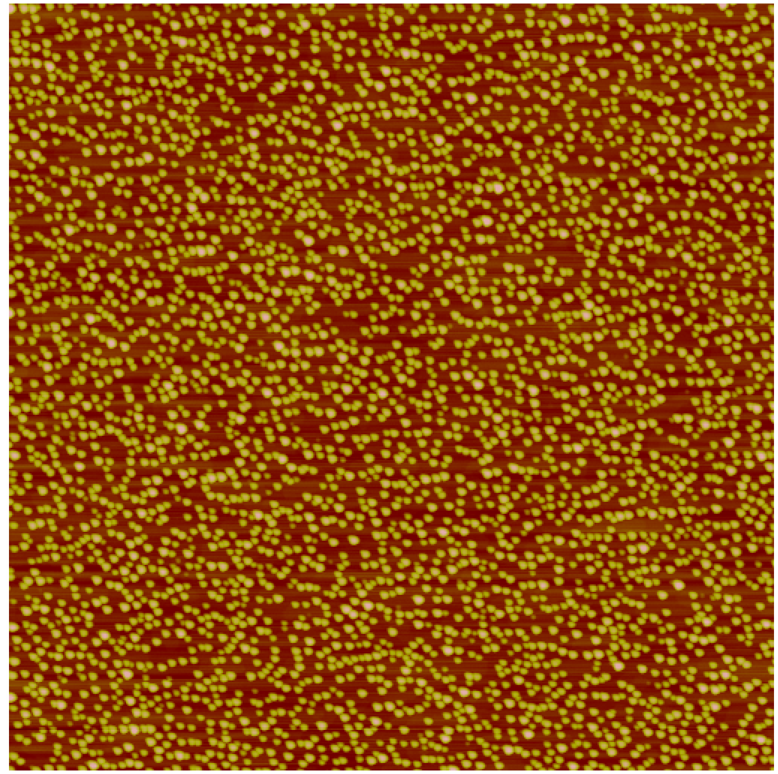


Future

Quantum dots

In **quantum dot infrared detector (QDIP)** structures, carriers are usually photoexcited out of the dots into the host material and they are collected by biased front and back contact layers. Important benefits of quantum dot structures are their high sensitivity for normal incident light and the enlarged spectral range of operation, compared to other structures.





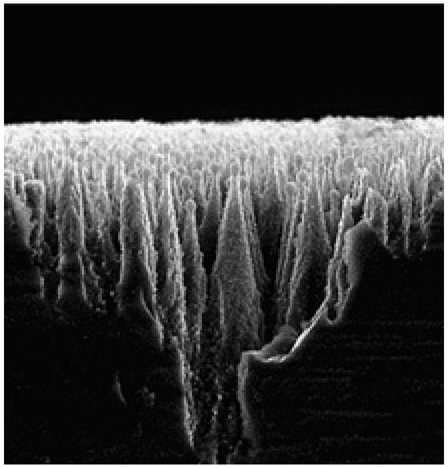
Large-scale AFM image showing a single layer of In(Ga)As quantum dots self-assembled on GaAs. The dots were deposited around 505°C and are fairly uniform in size with an areal density of 3.1 $x10^{10}$ cm^{-2}. The grey scale displayed is 15 nm. B. Lita, A Roshko, and K. A. Bertness

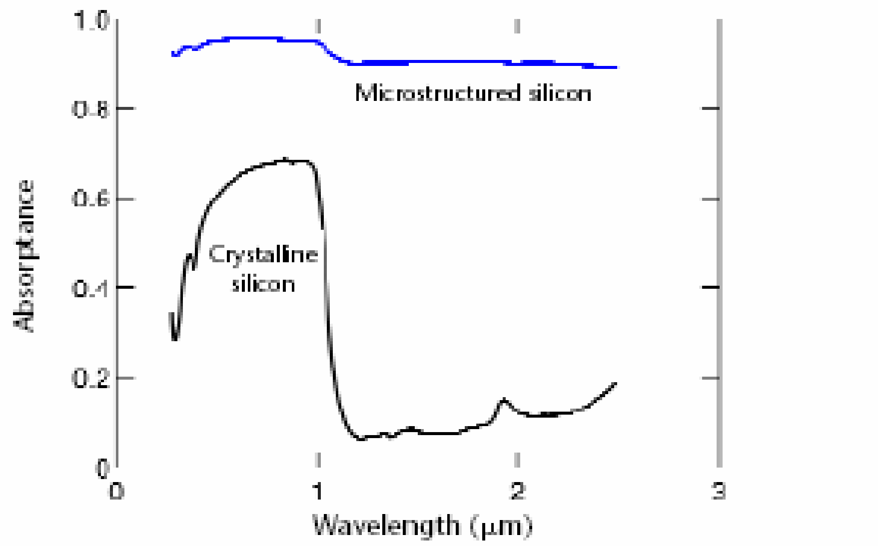
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 3, MAY/JUNE 2000
Semiconductor Quantum-Dot Nanostructures: Their Application in a New Class of Infrared Photodetectors
Elias Towe and Dong Pan

http://www.physics.mq.edu.au/research/materials/quant-dots-appl.html

http://www.wsi.tum.de/E24/research/qdevices/quantum_devices.htm

Microstructured silicon

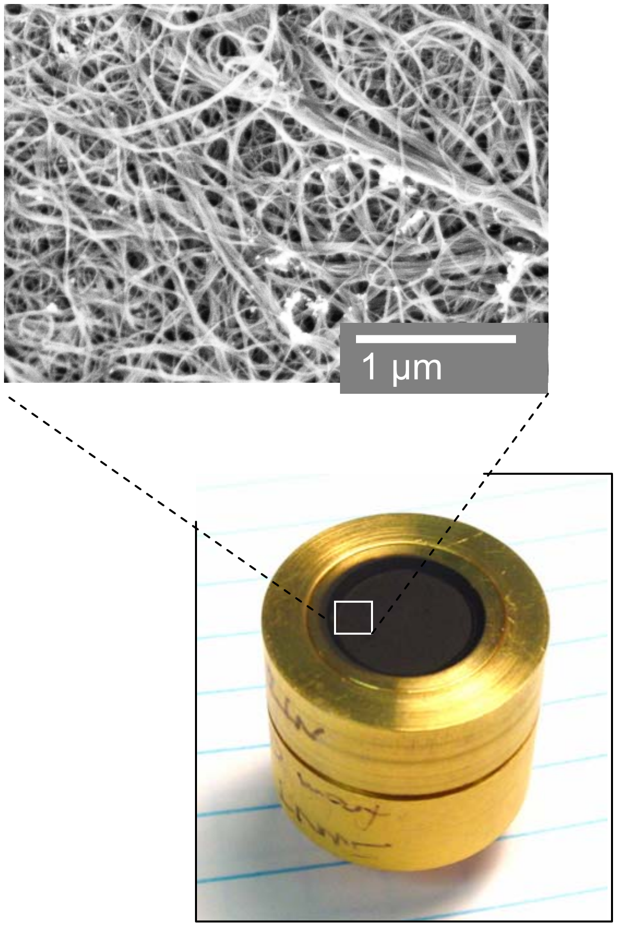




A silicon-based photodiode that is ten times more sensitive than commercial silicon PIN photodiodes at visible wavelengths and that can be used at wavelengths up to 1650 nm. At room temperature and –0.5 V the responsivity of the device is 54.4 A/W at 1000 nm, 38 mA/W at 1300 nm, and 25 mA/W at 1550 nm. The devices are fabricated by irradiating a crystalline silicon wafer with femtosecond laser pulses in the presence of sulfur hexaflouride. The irradiation creates a diode junction between the undisturbed substrate wafer and a highly disordered sulfur-doped surface layer.

Femtosecond-Laser-Assisted Microstructuring of Silicon Surfaces
James Carey, Catherine Crouch and Eric Mazur, *Optics and Photonics News, 32-36 (February 2003)*

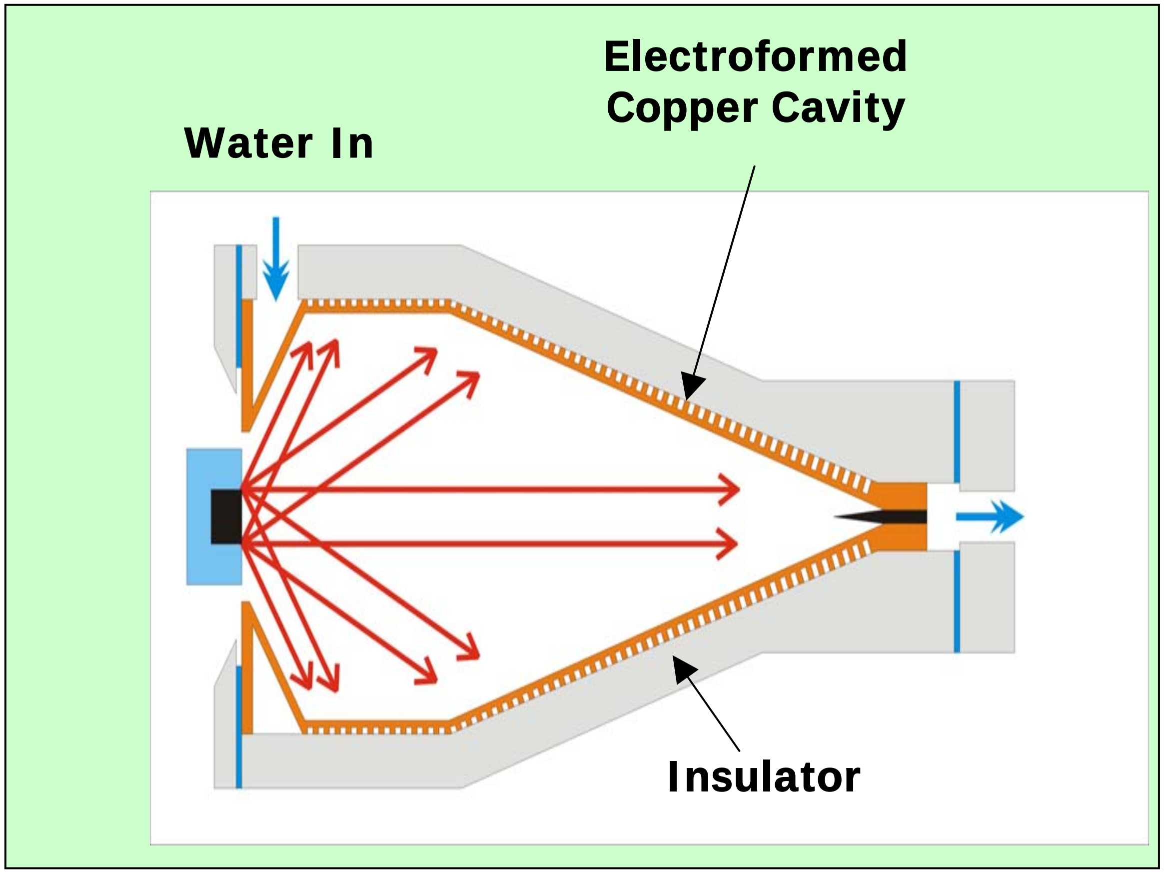
Carbon nanotubes for the next generation of black thermal coatings for NIST optical power and energy measurement standards



- High thermal conductivity (for speed)
- High damage threshold (for energy)
- Spectrally flat (for wavelength)

This pyroelectric detector coated with carbon nanotubes is the first of its kind and allows us to directly measure the optical and thermal properties of various tube compositions and topologies.

Flowing water power meter

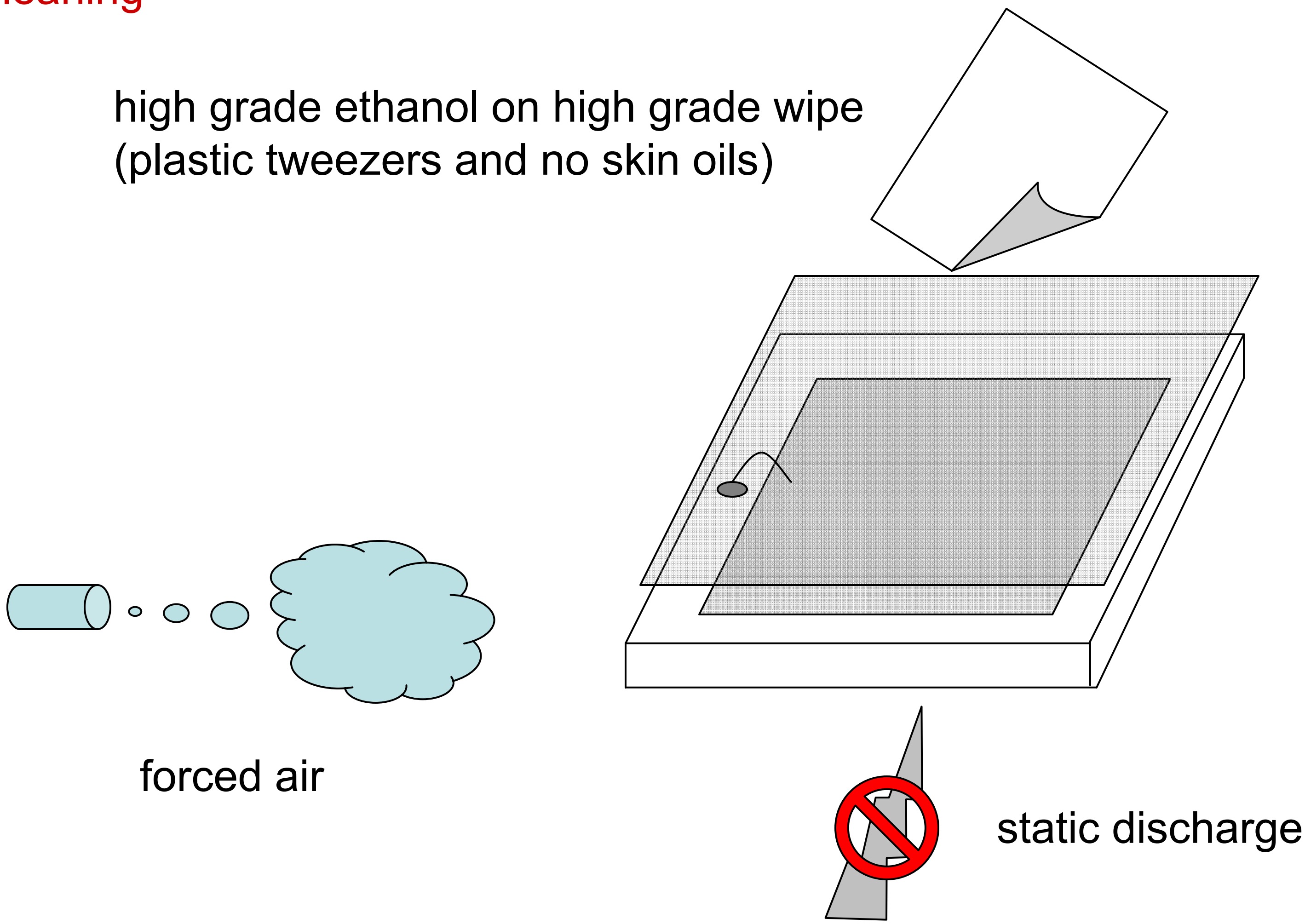


Scope and scale

80 to 800 Watts, CW at ~ 1μm and beyond

Practical matters

Cleaning


high grade ethanol on high grade wipe
(plastic tweezers and no skin oils)
forced air
static discharge

Quiz

Detector Quiz

Source

- 1 Watt, 1064nm, pulsed, 1 inch diameter beam

  1 2 3 4 5 6 7 8 9

- 20 µW, 1310 nm, CW, 2 mm beam

  1 2 3 4 5 6 7 8 9

- Left Hand (living, attached)

  1 2 3 4 5 6 7 8 9

- 20 µJ, 10 ns, 1550nm, 100 Hz, 50 mm diameter beam

  1 2 3 4 5 6 7 8 9

- The Sun

  1 2 3 4 5 6 7 8 9

- 0.1 µW, 5 µm, 5 mm diameter beam

  1 2 3 4 5 6 7 8 9

Detector

1. germanium photodiode 1 cm diameter
2. 2 mm diameter pyroelectric detector
3. 5 mm diameter silicon photovoltaic
4. Sapphire Bolometer
5. Biased InGaAs
6. HgCdTe photoconductor
7. CdS (cadmium sulfide) cell
8. Silicon bicell
9. 2 inch diameter thermopile

Detector Quiz

Source

- 1 Watt, 1064nm, pulsed, 1 inch diameter beam

1	2	3	4	5	6	7	8	9

- 20 µW, 1310 nm, CW, 2 mm beam

1	2	3	4	5	6	7	8	9

- Left Hand (living, attached)

1	2	3	4	5	6	7	8	9

- 20 µJ, 10 ns, 1550nm, 100 Hz, 50 mm diameter beam

1	2	3	4	5	6	7	8	9

- The Sun

1	2	3	4	5	6	7	8	9

- 0.1 µW, 5 µm, 5 mm diameter beam

1	2	3	4	5	6	7	8	9

Detector

1. germanium photodiode 1 cm diameter
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