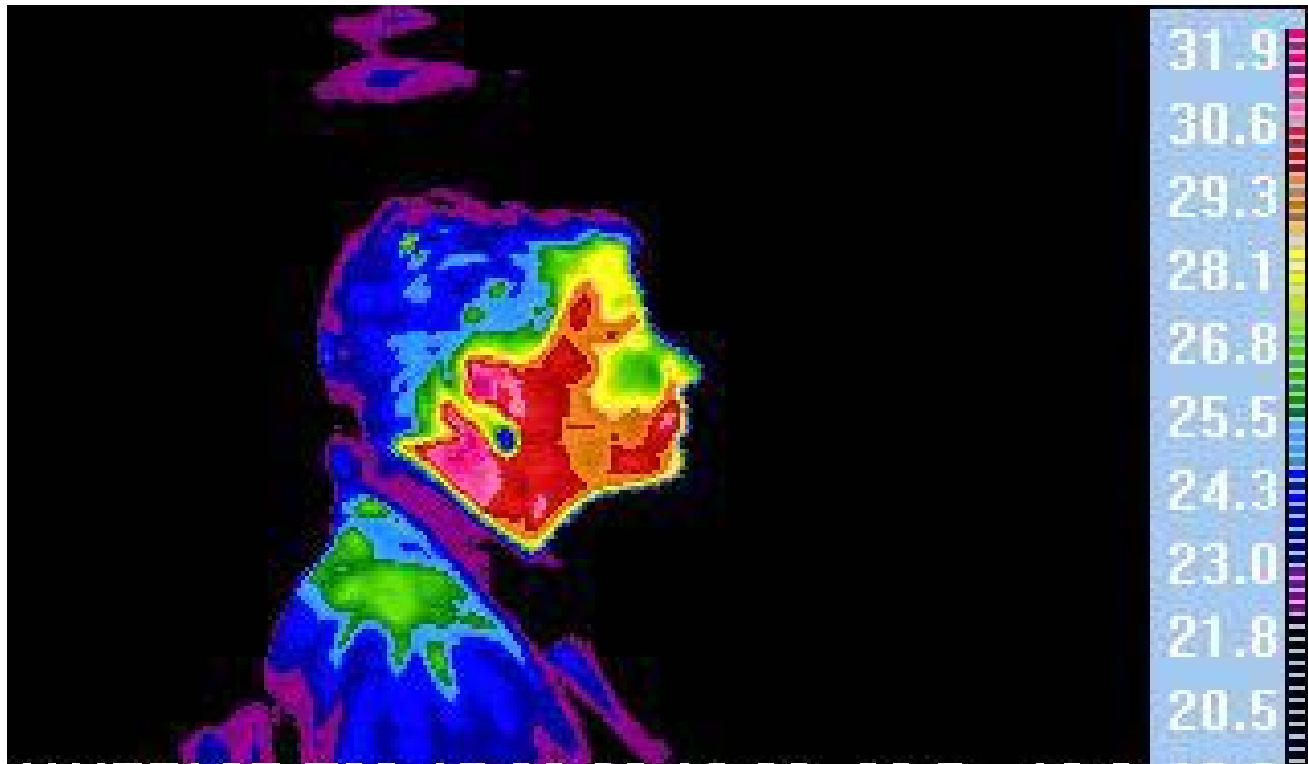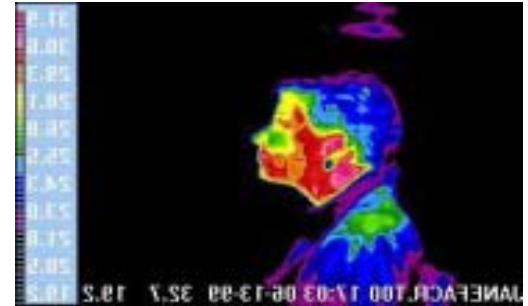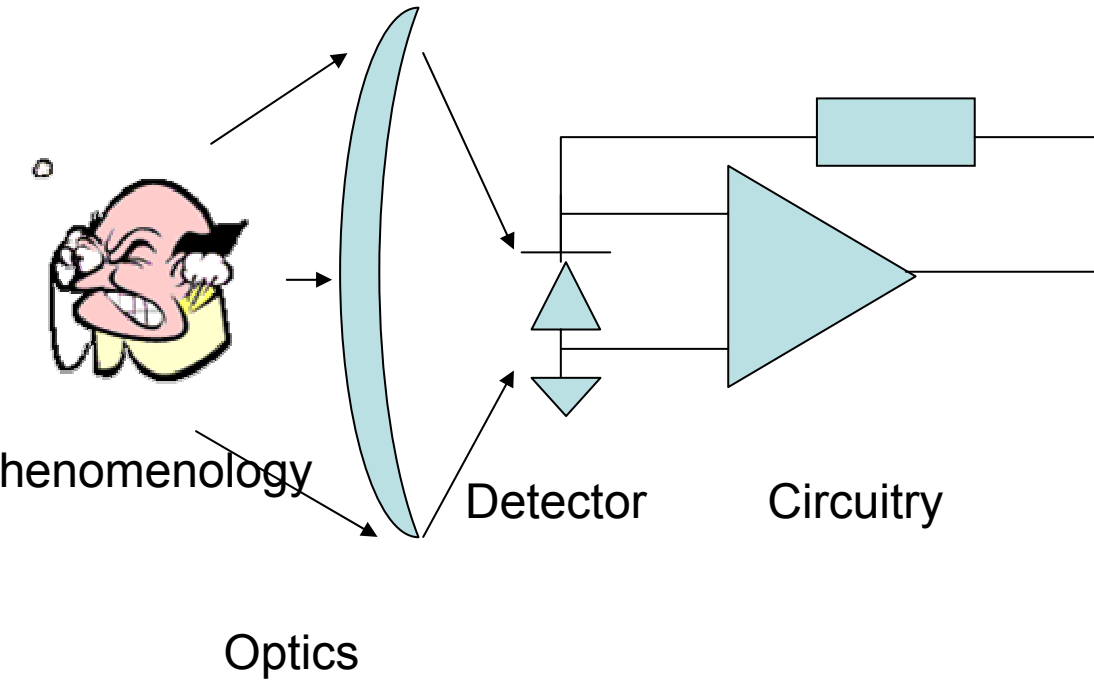# Thermal Infrared Systems

Lecturer: B T Yang 楊丙邨 March 2005 NTU
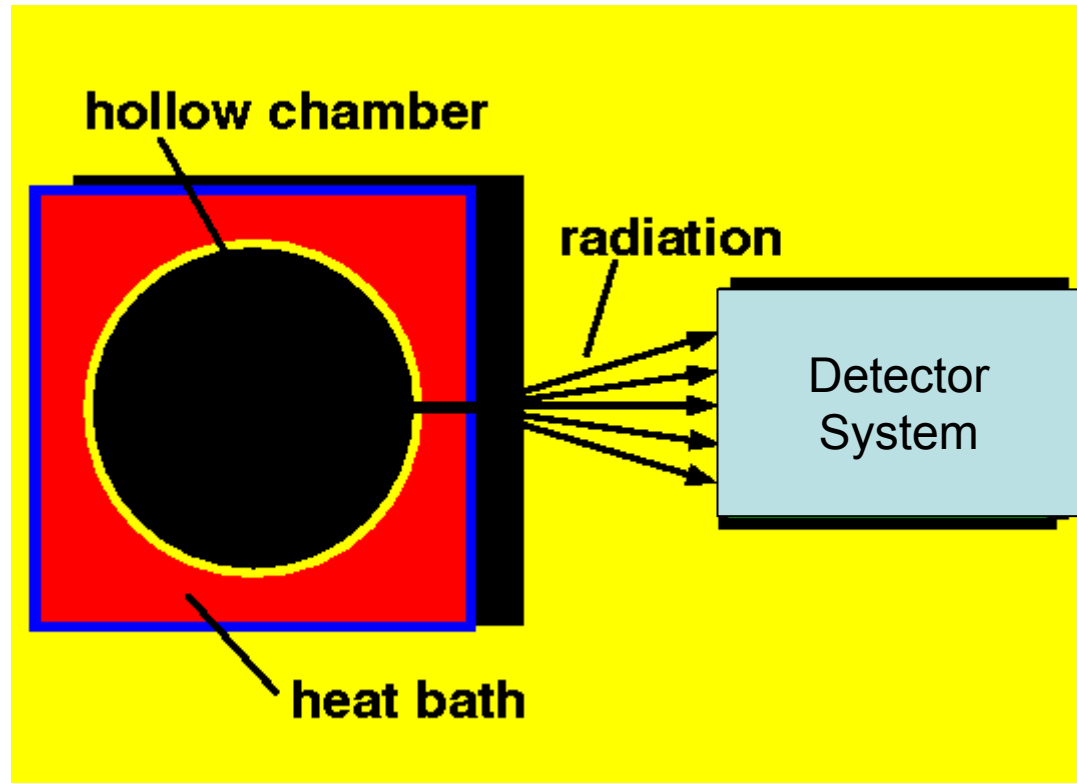
Lecture Outline

1. Phenomenology: "What is"

2. Optics

3. IR Detectors: Thermal, PC, PV

4. IR Detector Circuitry and Noises

5. IR Systems and Applications

Typical IR System

Phenomenology

Optics

Detector

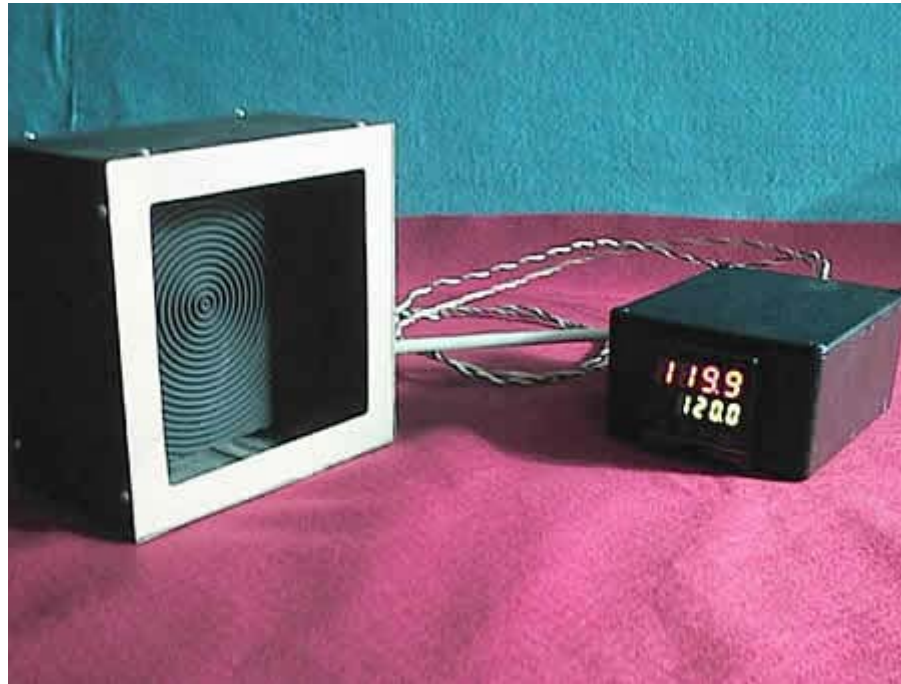Circuitry

Signal Processing
and Display

IR is Never Complete without Introducing the "Blackbody"

"Black" means No Light is Reflected, but "Light" can be emitted!

Grooved Planar Black Body Source

- "Grooved surface enhancing the emissivity

Absolute Blackbody Radiance Calibration Standard: Metal Freeze Temperature

| Pure Metal	Freeze Temp* (°C)	Pure Metal	Freeze Temp* (℃)
Gallium	29.7646**	**Aluminum**	660.323
Indium	156.5985	**Silver**	961.78
Tin	231.928	**Gold**	1064.18
Zinc	419.527	**Copper**	1084.62

Definition of a Black Body

- **A blackbody absorbs all incident radiation; r=0**

- **At a given temperature, no surface can emit more energy than a blackbody**

- **A blackbody is a "diffuse" emitter that follows the "Lambertian Laws"**

Lambertian Law

- Specular Surface (reflective)
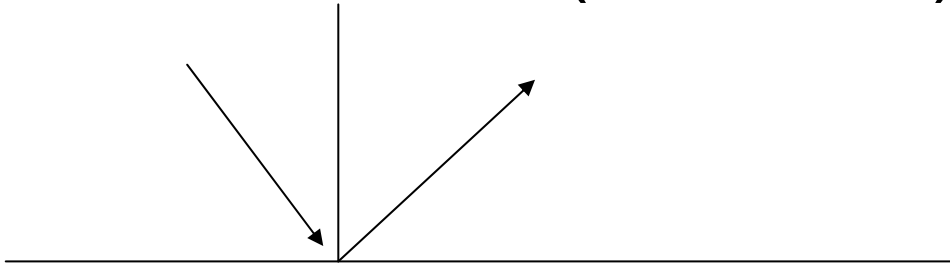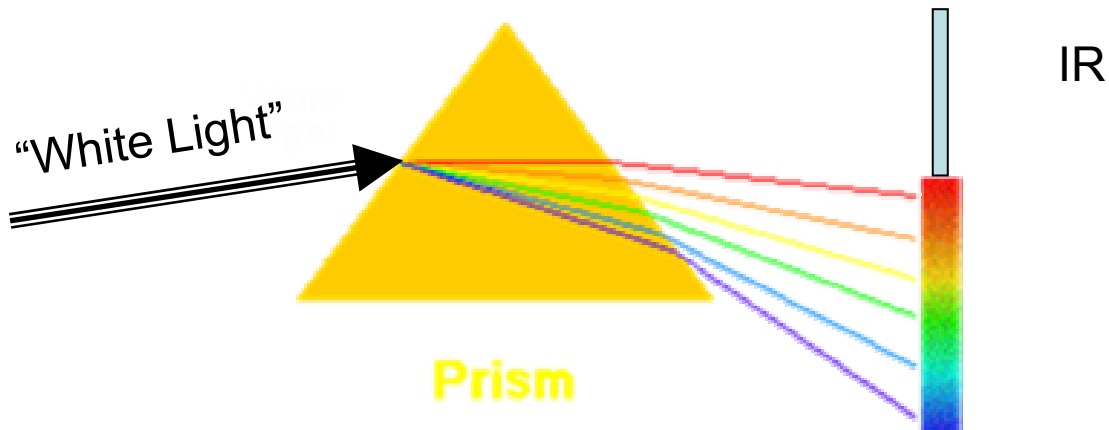
- Lambertian Surface (diffuse surface)

R0

R

Θ
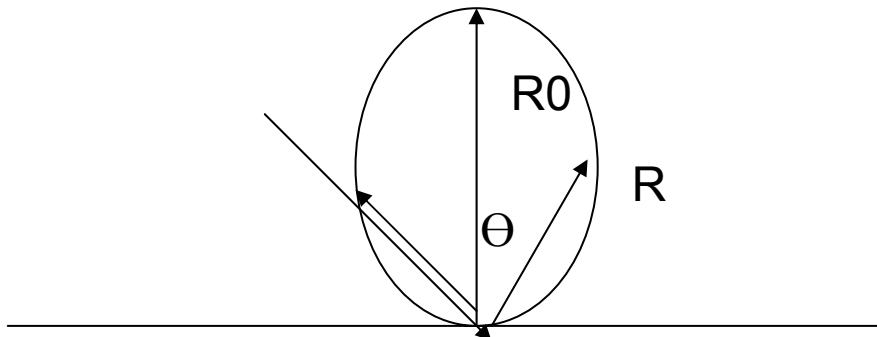
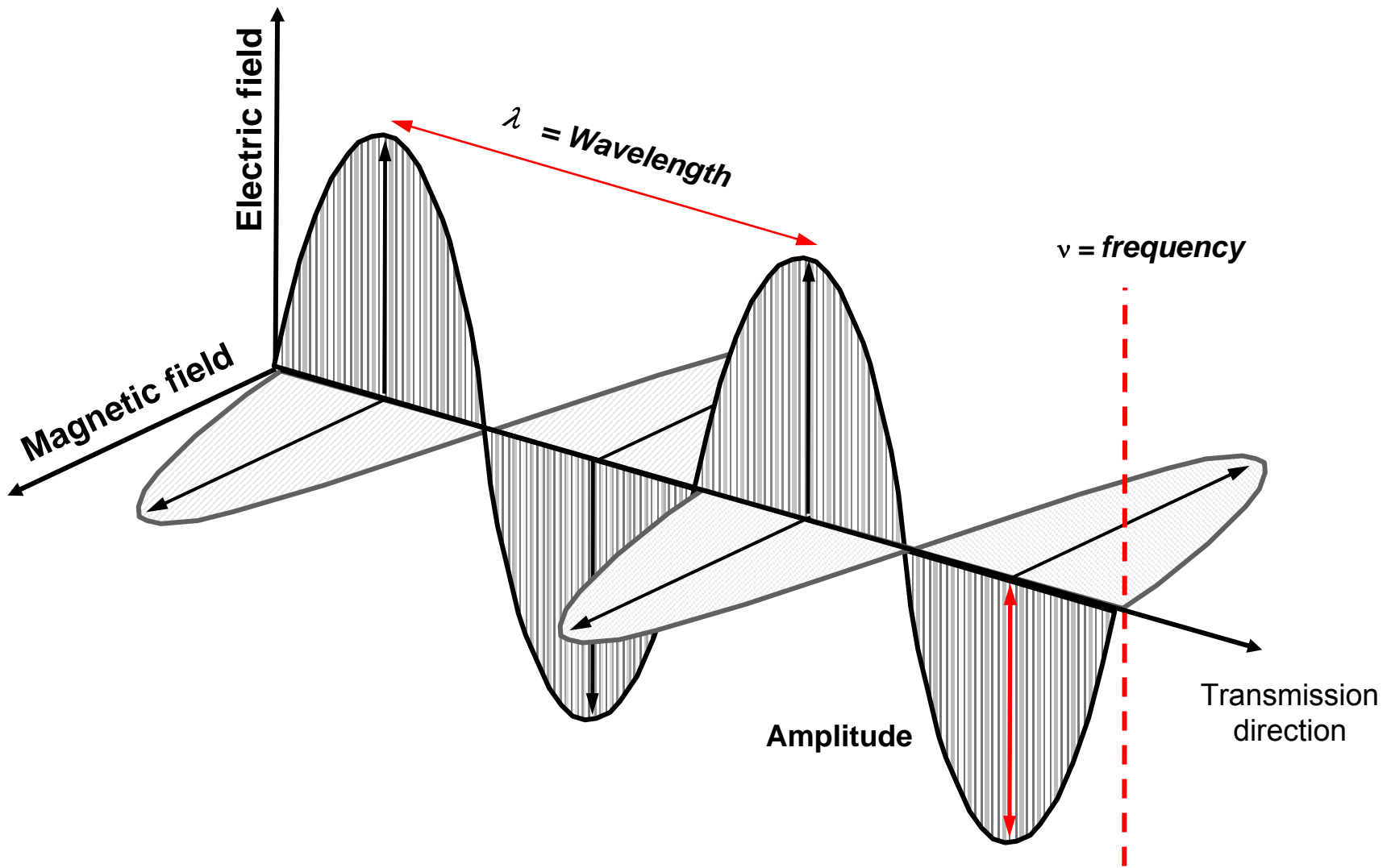$R=R_0 \cos\Theta$

The beginning of Infrared
Infra= Ln. below

- In 1800, Sir William Herschel, using a prism to spread sunlight, observed the heating "beyond the red end" of the visible light spectrum
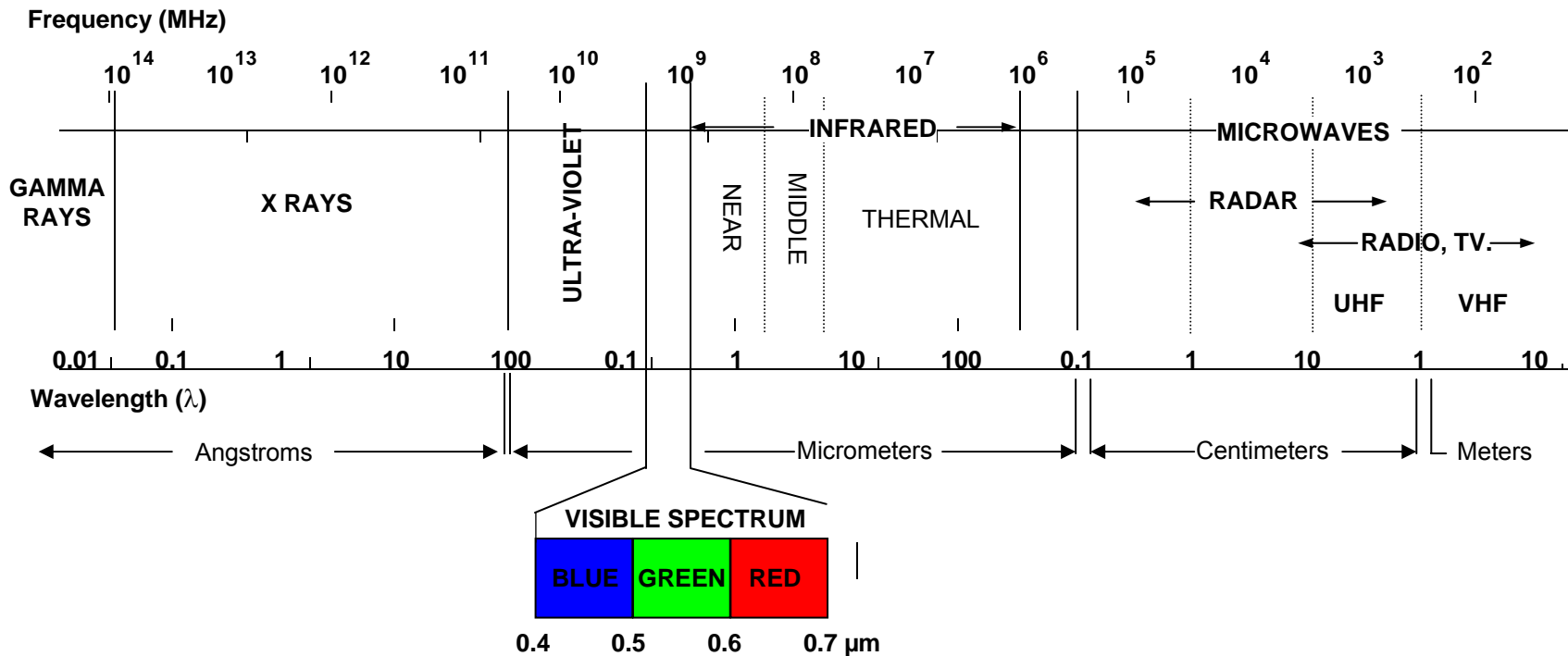
"White Light"

Prism

IR

IR: Heat?

- A known effect of infrared light on skin is dilation of blood vessels that transport blood to and from the skin for cooling=> sensation of heat!

- According to Kirchhoff Law, if r=0

$$\varepsilon(\text{absorptivity})=\sigma(\text{emissivity})$$

- Since skin is a good IR emitter then it must be a good IR absorber!

Light: An Electromagnetic wave

The Electromagnetic Spectrum

Frequency (MHz)

| 10^{14} | 10^{13} | 10^{12} | 10^{11} | 10^{10} | 10^{9} | 10^{8} | 10^{7} | 10^{6} | 10^{5} | 10^{4} | 10^{3} | 10^{2} |

INFRARED

MICROWAVES

GAMMA RAYS

X RAYS

ULTRA-VIOLET

NEAR

MIDDLE

THERMAL

RADAR

RADIO, TV.

UHF   VHF

| 0.01 | 0.1 | 1 | 10 | 100 | 0.1 | 1 | 10 | 100 | 0.1 | 1 | 10 | 1 | 10 |

Wavelength (λ)

◄— Angstroms —► ◄— Micrometers —► ◄— Centimeters —► Meters

VISIBLE SPECTRUM

| BLUE | GREEN | RED |

0.4   0.5   0.6   0.7 µm

IR Frequency and Energy

- Frequencies: $.003 \times 10^{14}$ to 4.3×10^{14} Hz
- Wavelengths: 1 mm – 0.7 μm
- Quantum energies: 0.0012 - 1.16 eV

$\triangle$E [eV]=1.24 / λ [μm]

For Si, $\triangle$E =1.13eV; λ_{cutoff}=1.1 μm

Planck's Equation

M_λ: Spectral Exitance [W·cm^{-2} · μm^{-1}]

λ: wavelength [μm]

T: absolute temperature [K]

h= Planck's constant =6.63x10^{-34} W sec^2

C= 3x10^{14} μm /sec

k= Boltzmann's constant 1.38x10^{-23} W sec K^{-1})

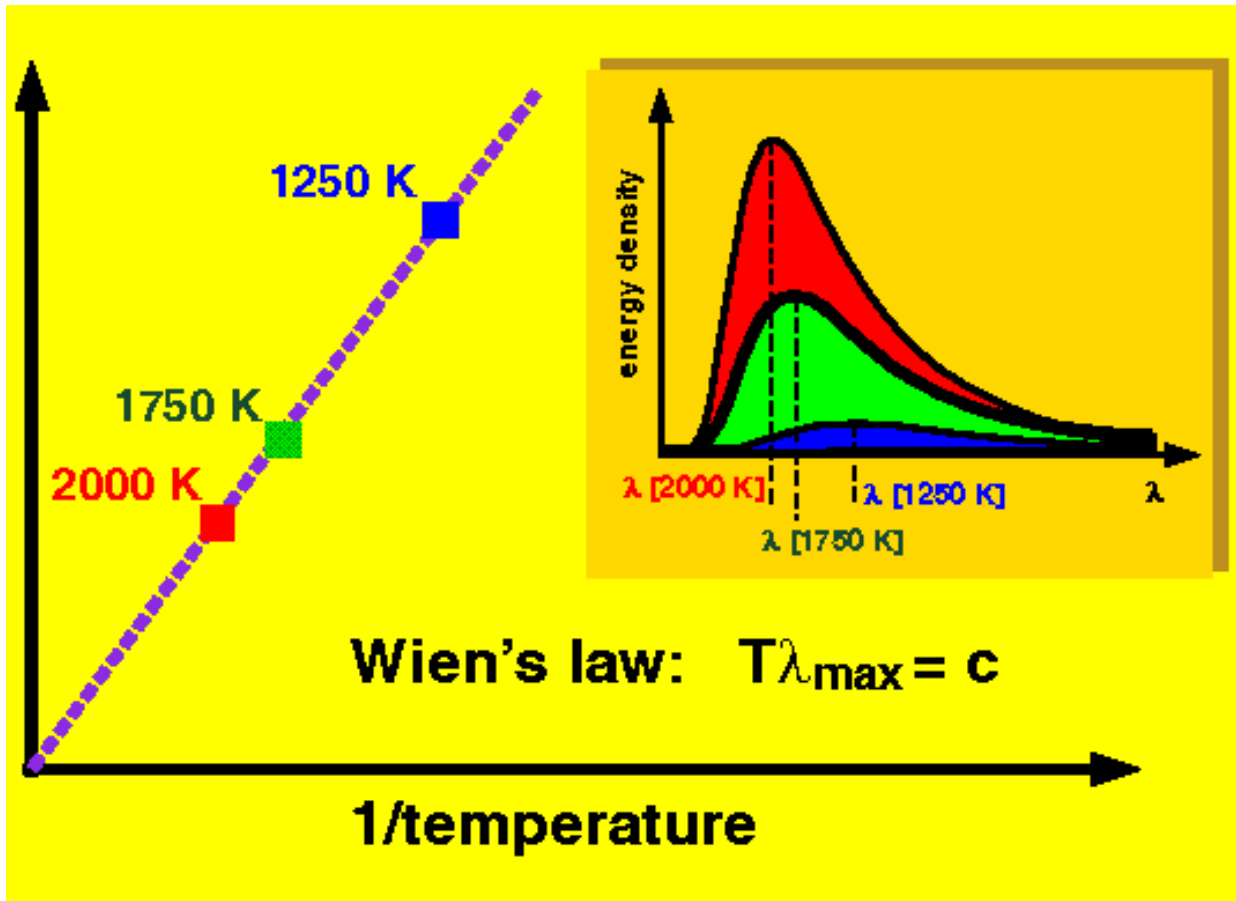$$M_\lambda(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hC}{\lambda k T}} - 1}$$

$$= \frac{3.74 \ x \ 10^4}{\lambda^5 \left[e^{1.44 \ x \ 10^4 / \lambda T} - 1 \right]}$$

# Spectral exitance of a blackbody

Visible radiant energy

Blackbody radiation curve at the Sun's temperature

Blackbody radiation curve at the Earth's temperature

Spectral Radiant Exitance M_λ (W $\cdot$ cm^{-2} $\cdot$ μm^1)

10^5

10^4

10^3

10^2

1

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

6000° K

4000° K

3000° K

2000° K

1000° K

500° K

300° K

200° K

λ

0.1 0.2 0.5 1 2 5 10 20 50 100 μm
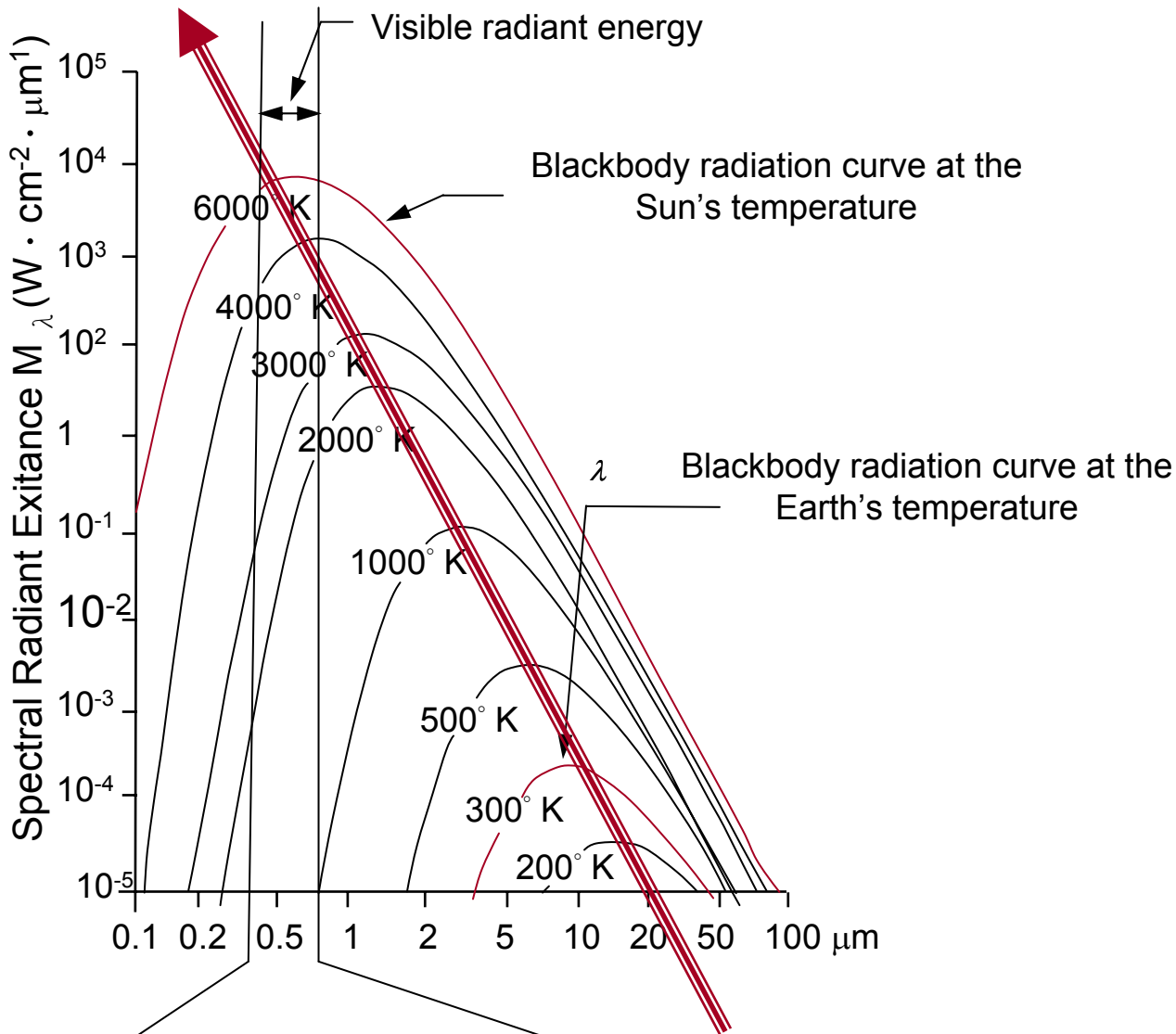
Wien's Law

- $\lambda_{max}T \sim 3000 \ \mu m\text{-}K$

Stefan-Boltzmann's Equation of Radiation

- **M(T)= ∫ M$_\lambda$(λ , T) dλ = σ T^4 [W·cm^{-2}]**
- **M(T): Exitance (not Spectral Exitance)**

- σ **: Stefan-Boltzmann's constant 5.67x10^{-12} W · cm^{-2} · K^{-4}**
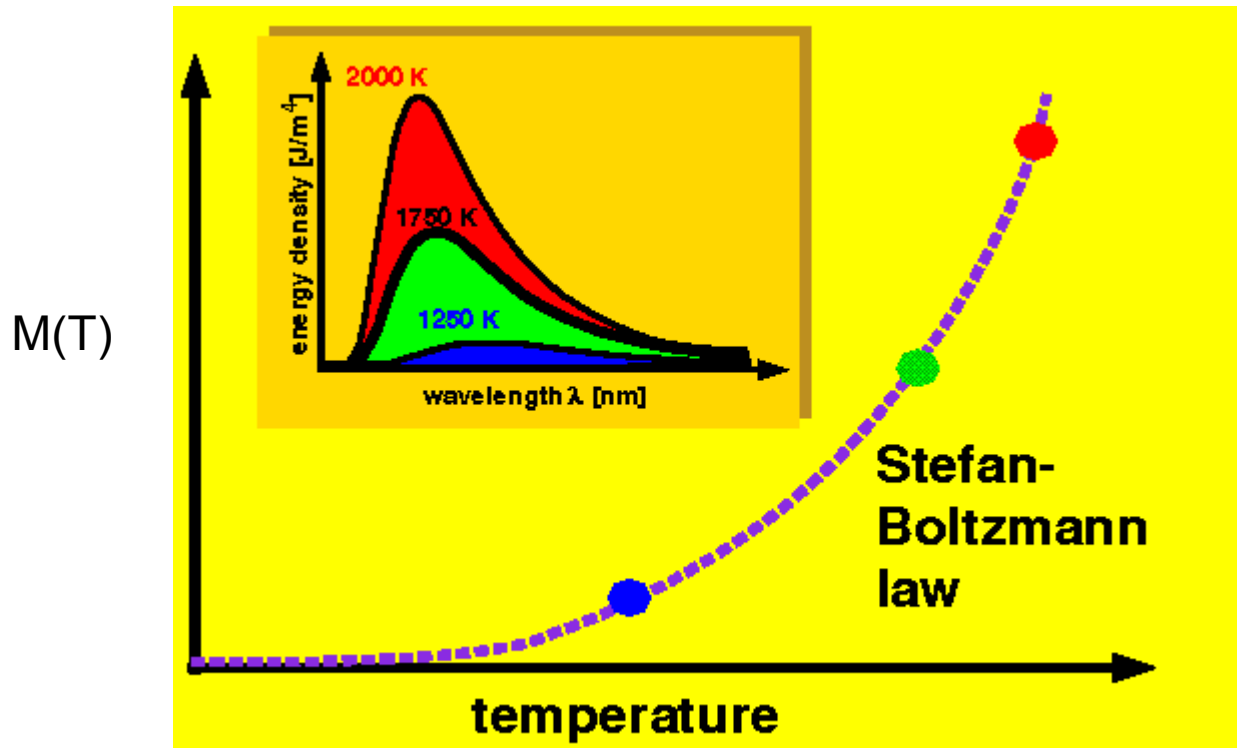
Grey Body?

- When emissivity ε is not unity
- Most physical surfaces are grey bodies

  ε_{skin} ~ 0.95, then it must be "Approximated as a Blackbody

  $M_\lambda = \varepsilon M_\lambda$

  $M = \varepsilon \sigma T^4$

Atmospheric Transmission Spectra

UV   **VNIR**   **SWIR**   **MWIR**   **LWIR**

For Ref:

NIR: 0.7-1.1 μm; SWIR:1.1-3.0 μm; MΩIP:3–5 $\mu\mu$;
LWIR: 8-14 μm; VLIR: > 14 μm
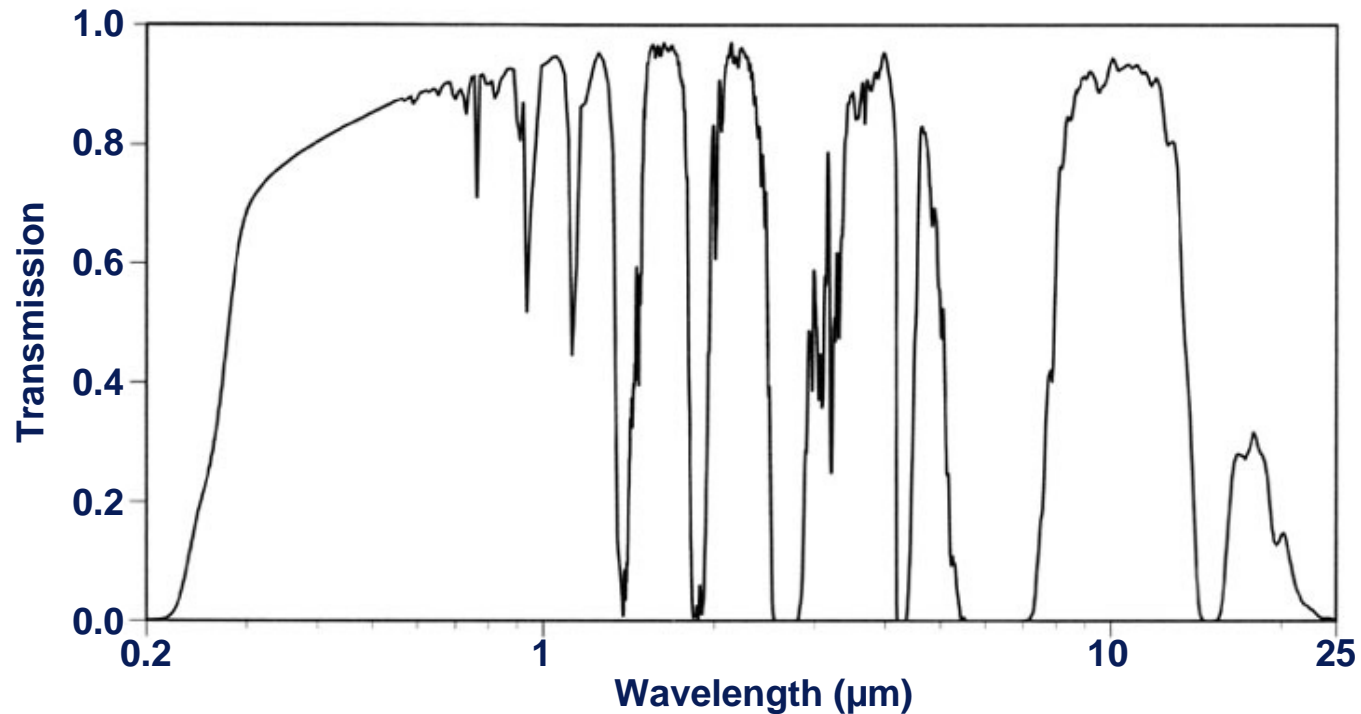
Infrared Interactions

- . The result of infrared absorption is heating of the tissue since it increases molecular vibrational activity..

Infrared radiation vibrates molecules

Infrared

Molecular vibration

-

Discrete Energy State

- Planck's 1900's "lucky Guess" $\Delta E = h\nu$
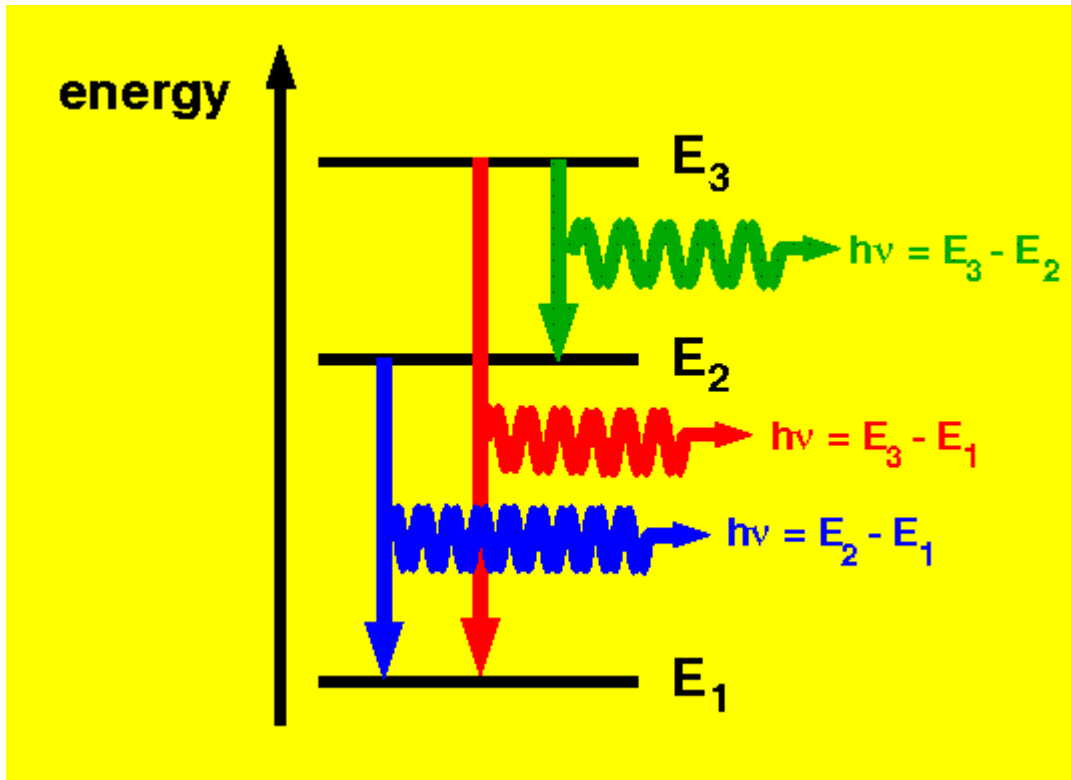
Photo-Electric Effect

- Eienstein 1905's Paper Confirming the Discret Energy

$eV_{max} = h\nu - \text{Ø}$

$h\nu_{thr} = \text{Ø}$
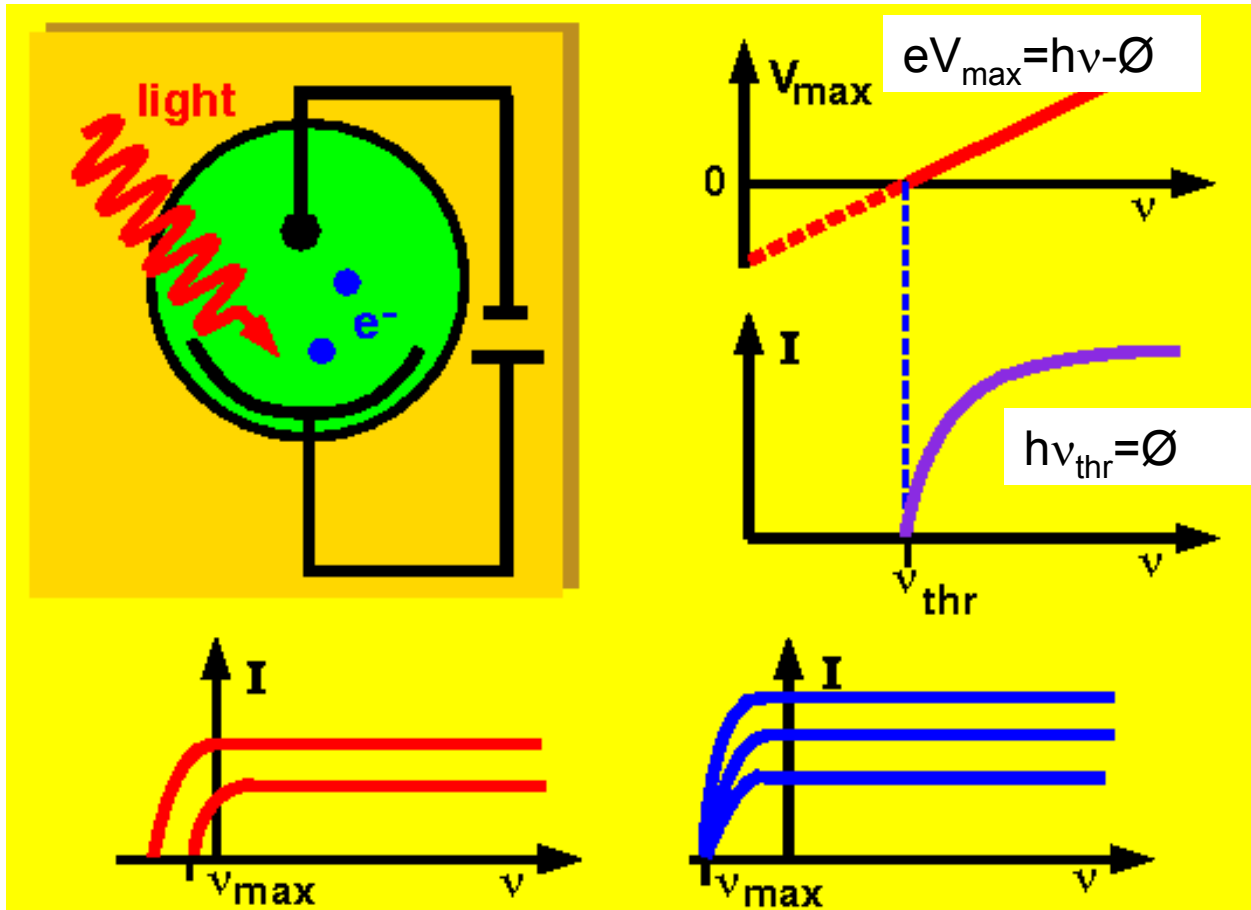
Varying ν

Same ν, varying intensity

Visible Spectral Range

- Visible Band: 400nm to 700nm

400nm   500nm   600nm   700nm
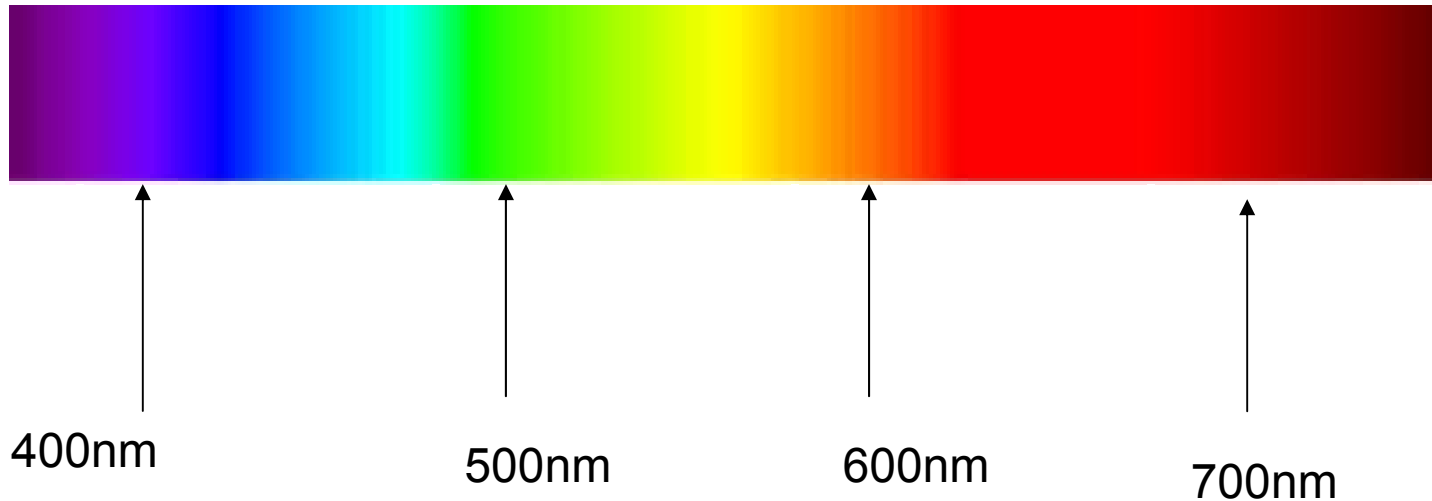
Eye's Cones' (3) and Rods' Responses

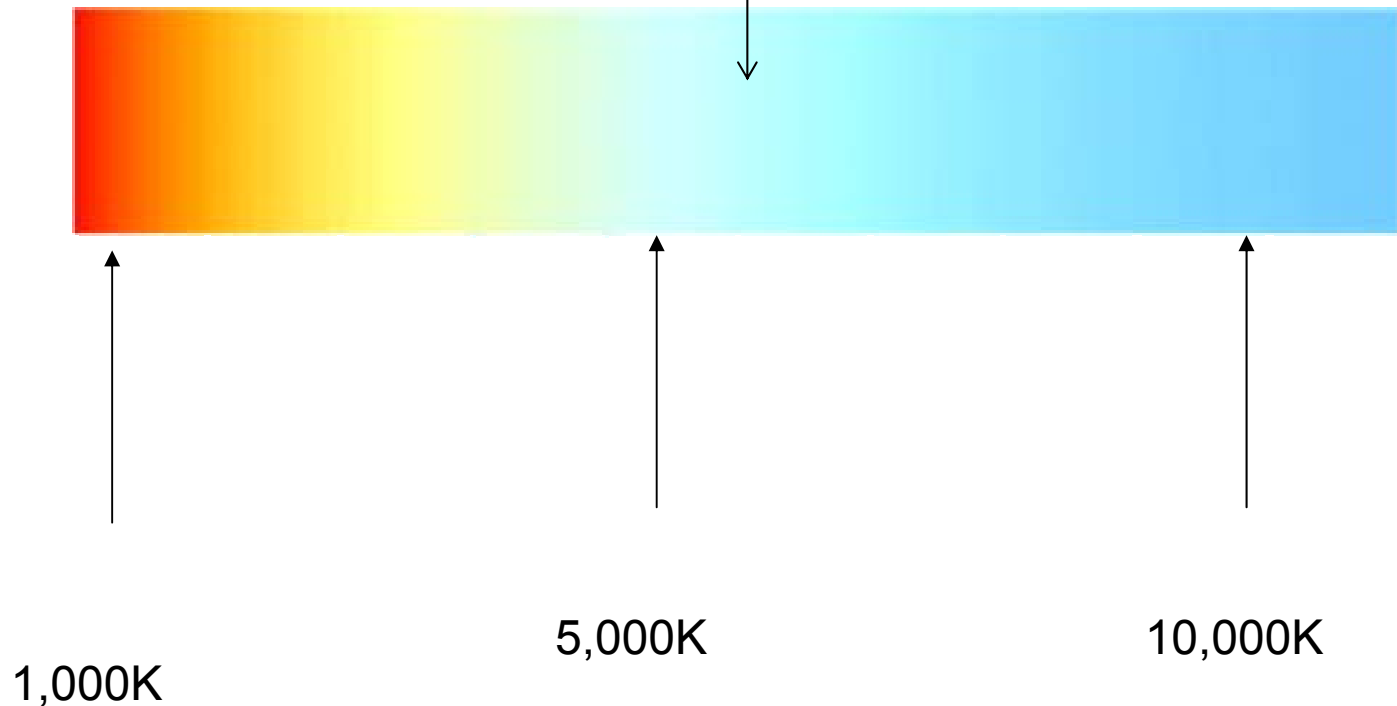- Rods for night vision (more sensitive)
- Cones for color day vision

Dowling, 1987
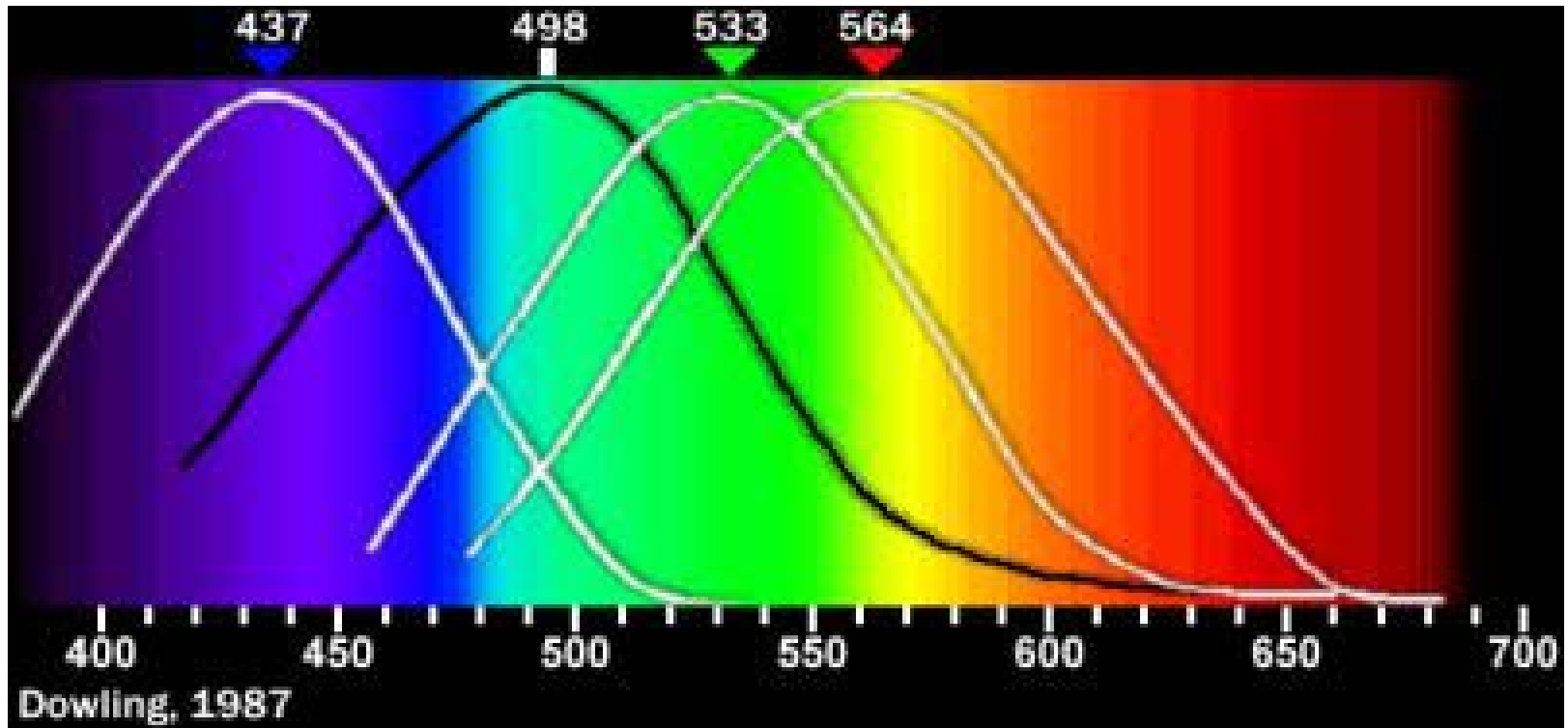
"Color" Temperature

An Apparent Visible Color of a Blackbody at T

At 800K, or Draper Point,
Blackbody Begins to be Visible

Sun~
6000K

5,000K

10,000K

1,000K

Night Goggles are "not" true Thermal Images

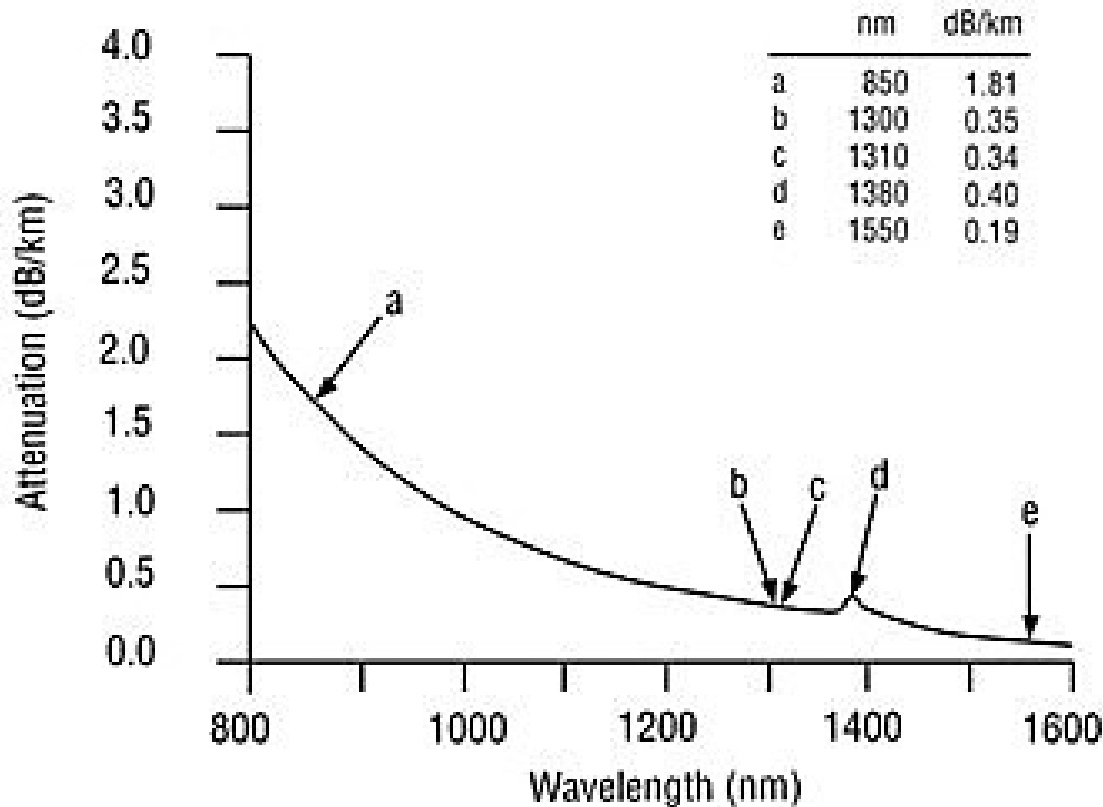- Night Goggle Images are "Reflected NIR Images", not "Emitted Thermal images"

Many Low-Cost Low-Light Detection Systems are NIR Systems

"Near IR Wavelength Used for Optical Communications

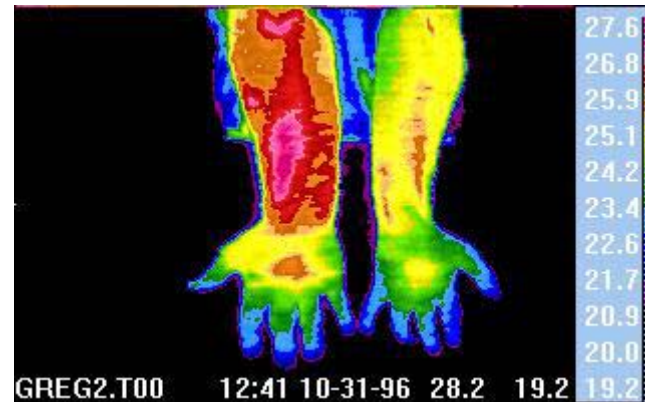"Single mode fiber"
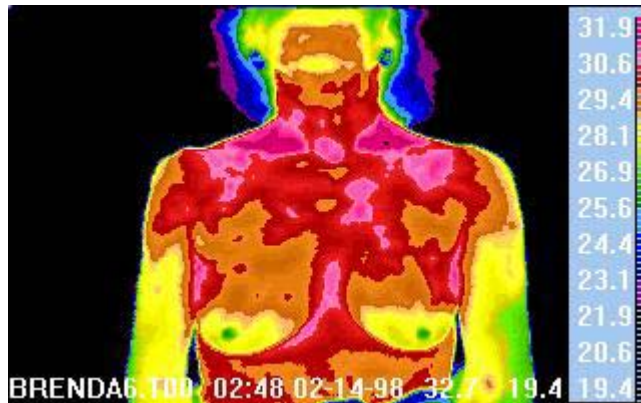single path through the fiber

Spectral Attenuation (typical fiber):

	nm	dB/km
a	850	1.81
b	1300	0.35
c	1310	0.34
d	1380	0.40
e	1550	0.19

Attenuation (dB/km) vs Wavelength (nm)
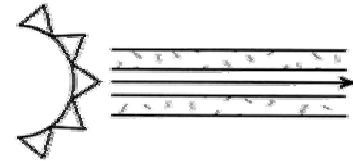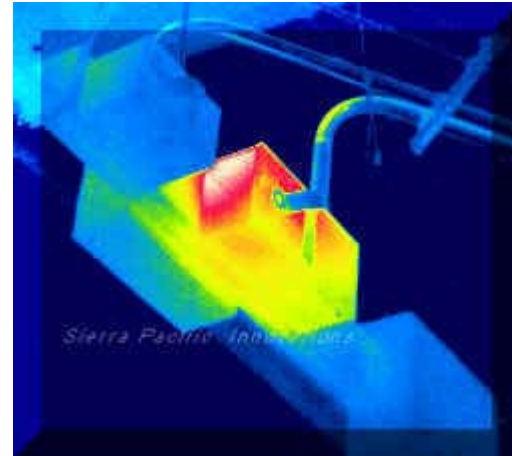
Singlemode Fibre 10/125
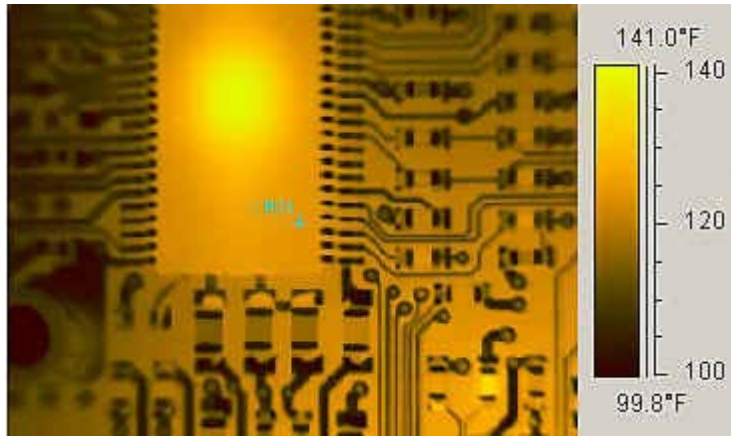
Human Thermal Images

- http://www.ir55.com/infrared_IR_camera.html
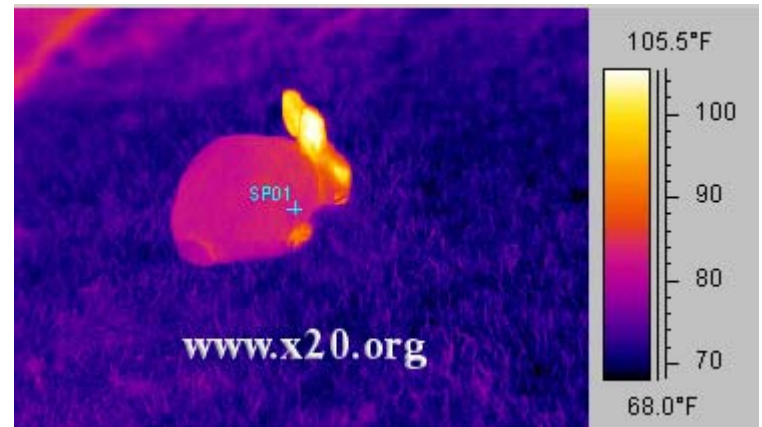
PC Board Localized Heating

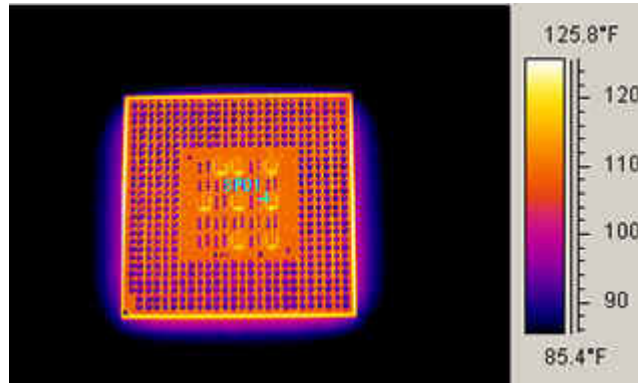# Localized IC Chip Detection

Burglar Detection

Underside Celeron Chip
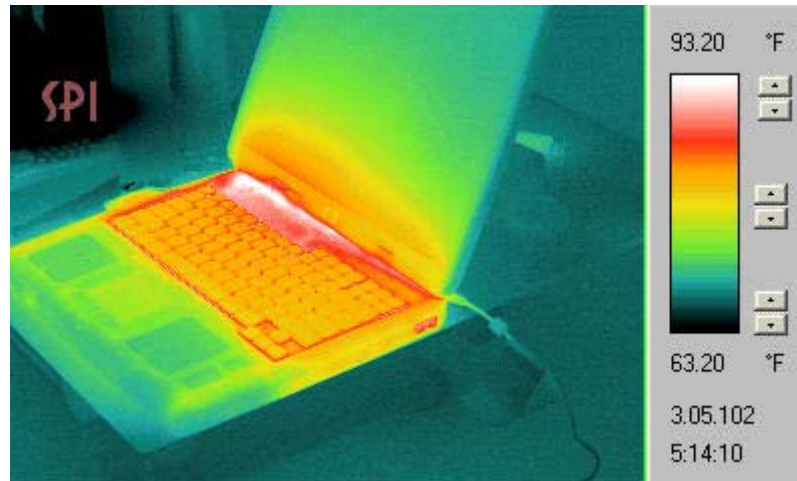
-

SARS Temperature Screening

-

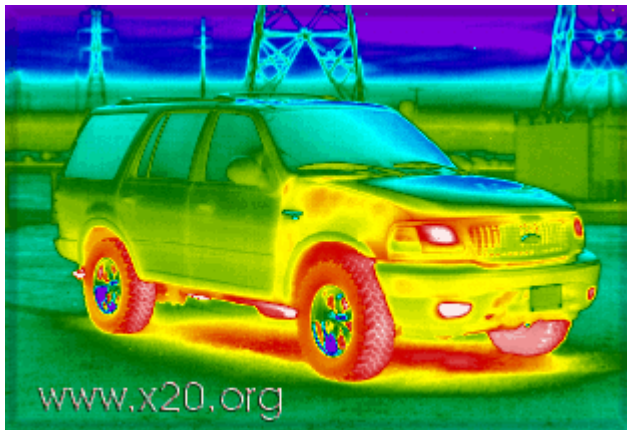# Preventive Maintenance

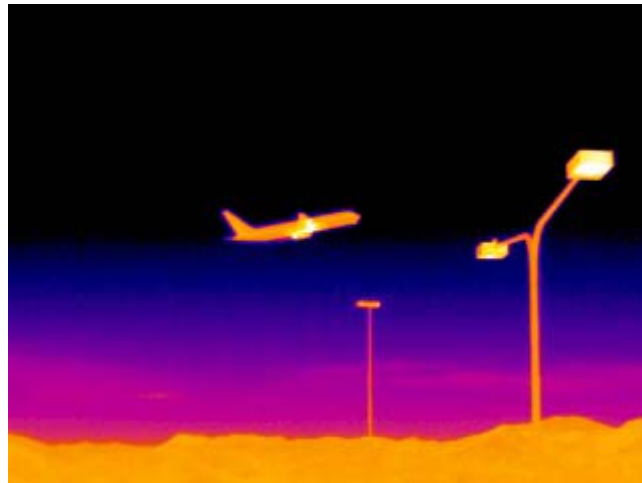- Electrical Fuse Thermal Image

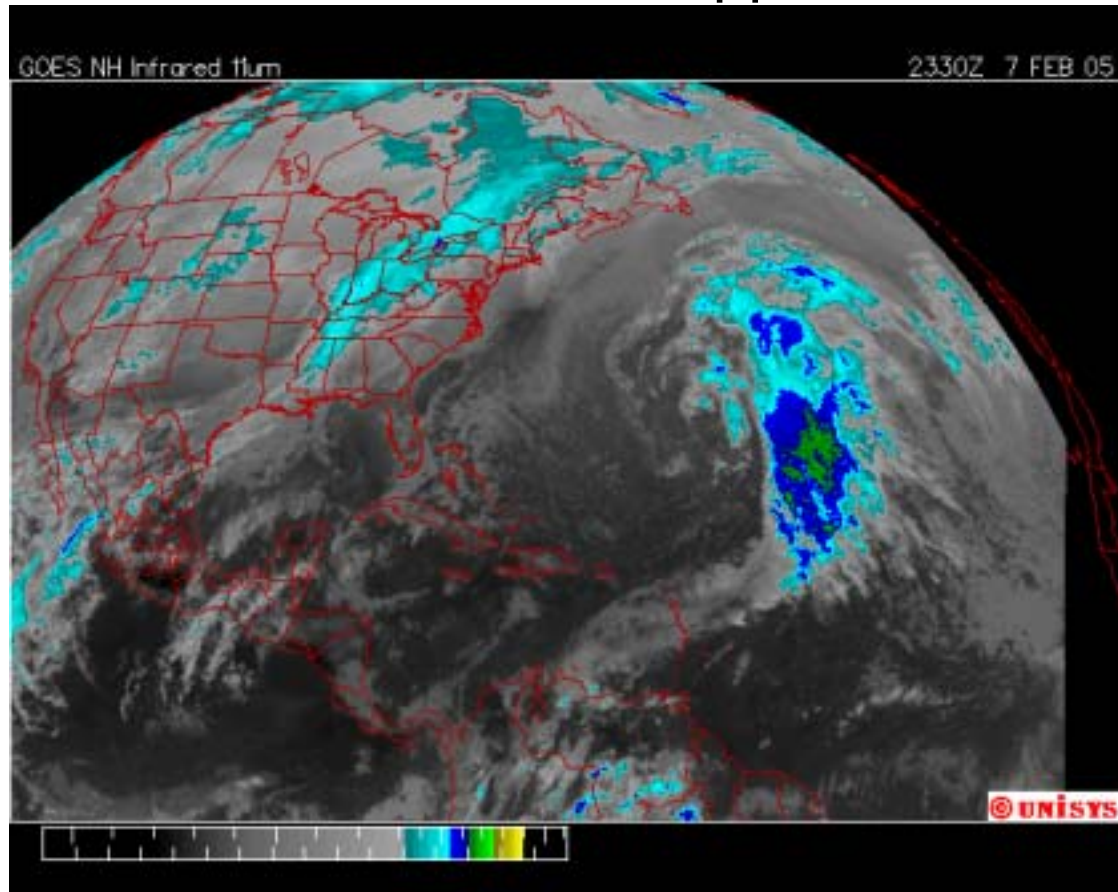# Thermal Management

-

Defense Applications

Sky Surveillance

- Collision Prevention

Weather Monitoring

- Geosynchronous Weather Satellite Application

What "Limits" Your Measurements?

1. Spatial (How Small an Area Can the System Resolved?):
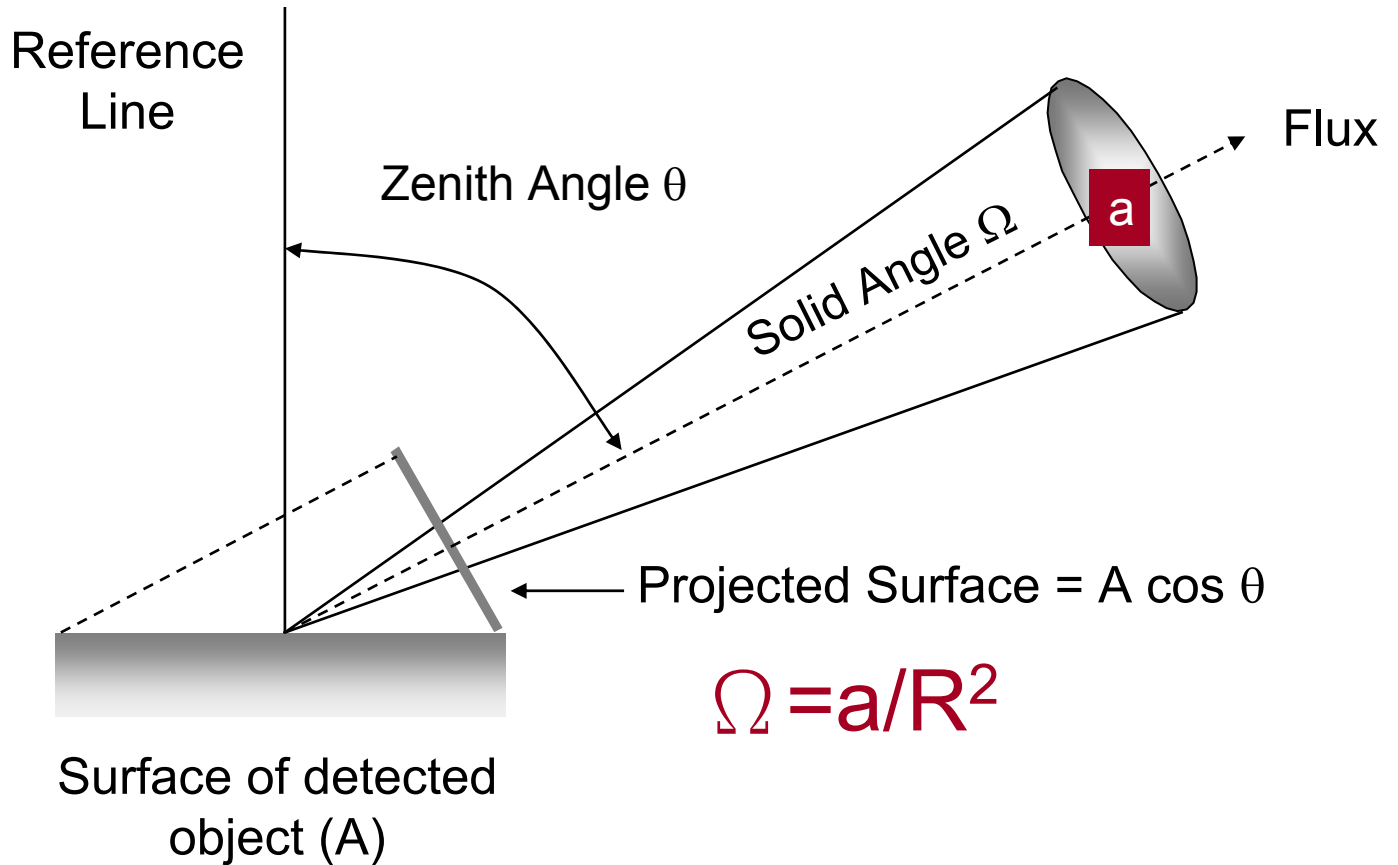
<center>Optics</center>

2. Temporal (How Fast Can the System Do?):

<center>Detector and Electronics Responses</center>

3. Resolution of the System (What is the Smallest Temperature the System can resolve?):

<center>NEP</center>

Solid Angle Concept

Reference
Line

Zenith Angle θ

Solid Angle Ω

Flux

a

Projected Surface = A cos θ

$\Omega = a/R^2$

Surface of detected
object (A)

Radiance L

- Radiance is Defined as the Power per Unit Area per Steradian(Sr)

$$L[W\ m^{-2}\ Sr^{-1}]=M(T)/\pi$$

And

The so is the "Spectral Radiance"

$$L_\lambda[W\ m^{-2}\ Sr^{-1}]=M_\lambda(T)/\pi$$

Solar Constant K_{solar}(Example)

- Solar disk "subtends" 1/2º(or 9 mRadians) in view, the solar constant is the total Radiance Power per unit area

- Since the Radiance is

  L=1/π M(6000K)=(σ/π)x6000^4=2.34x10^{7}W · m^{-2} Sr^{-1}

- The solid angle of the sun is

- Ω=(π/4)(0.009/2)^2~6.4x10^{-5} Sr

- The Solar Constant is then:

- K_{solar} =L · Ω ~1.5 KW/M^2

- σ : **Stefan-Boltzmann's constant 5.67x10^{-8} W · m-2 · K^{-4}**

Equilibrium Temperature Concept

- The Total Power Absorbed by a 1M^2 Plate Perpendicular to Sun Rays is a Solar Constant K$_{solar}$ of 1.5KW

- The Radiated Power is

- The Equilibrium Thermodynamic Condition Stipulates:

- σ T$_{plate}^4$= K$_{solar}$

- T$_{plate}$=(1500/σ)$^{1/4}$~403K=130ºC

$$= \sqrt[4]{\frac{solar}{\varepsilon \sigma}}$$

How to Manipulate the Equilibrium Temperature T_{equi}

- By varying Surfaces Solar Absorption Coefficient α and ε

- For α of 0.2 and ε of 0.9, $T_{equi} \sim 277K => 4^oC$!

- $\alpha \ K_{solar} = \varepsilon \ \sigma \ T_{plate}^4$

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon \sigma}}$$

- For α of 0.2 and ε of 0.9, $T_{equi} \sim 277K => 4^oC$!

Why is a Metal Surface so Warm in the Sun?

Polished Metal Surfaces have low α and ε

Assume $\alpha = \varepsilon = 0.2$

$$T_{equi} = \sqrt[4]{\frac{\alpha K_{solar}}{\varepsilon \sigma}} = \sqrt[4]{\frac{0.2 X 1500}{0.2 X 5.67 X 10^{-8}}} = 403K!$$

- σ : **Stefan-Boltzmann's constant 5.67x10^{-8} W · m-2 · K^{-4}**

Does "Absolute Temperature" Have to Do with Heat Transfer?

- Conduction

$\Delta Q \sim \Delta T$

- Convection

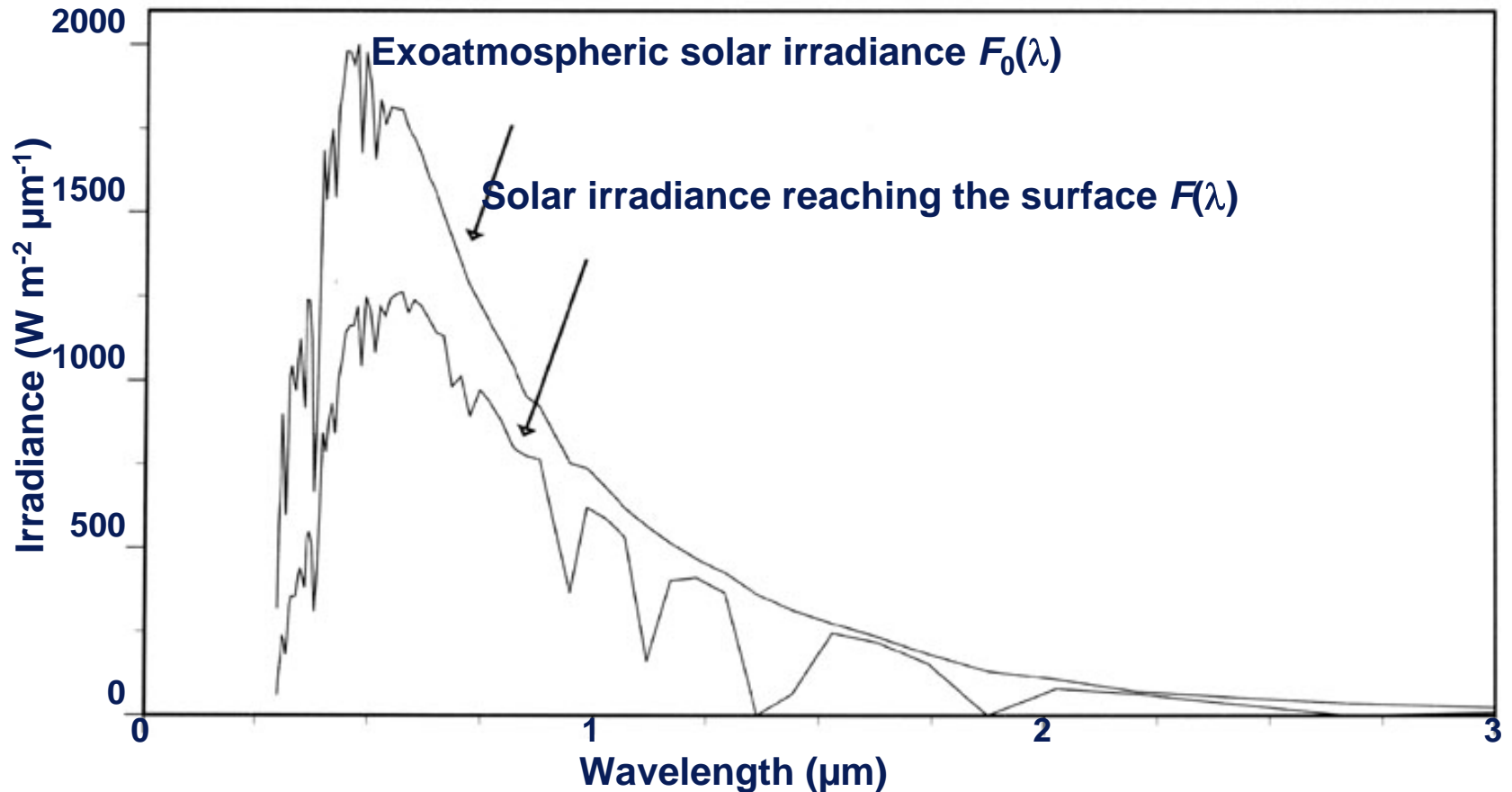$\Delta Q \sim \Delta T^{n;}\ n \neq 1$

- Radiation

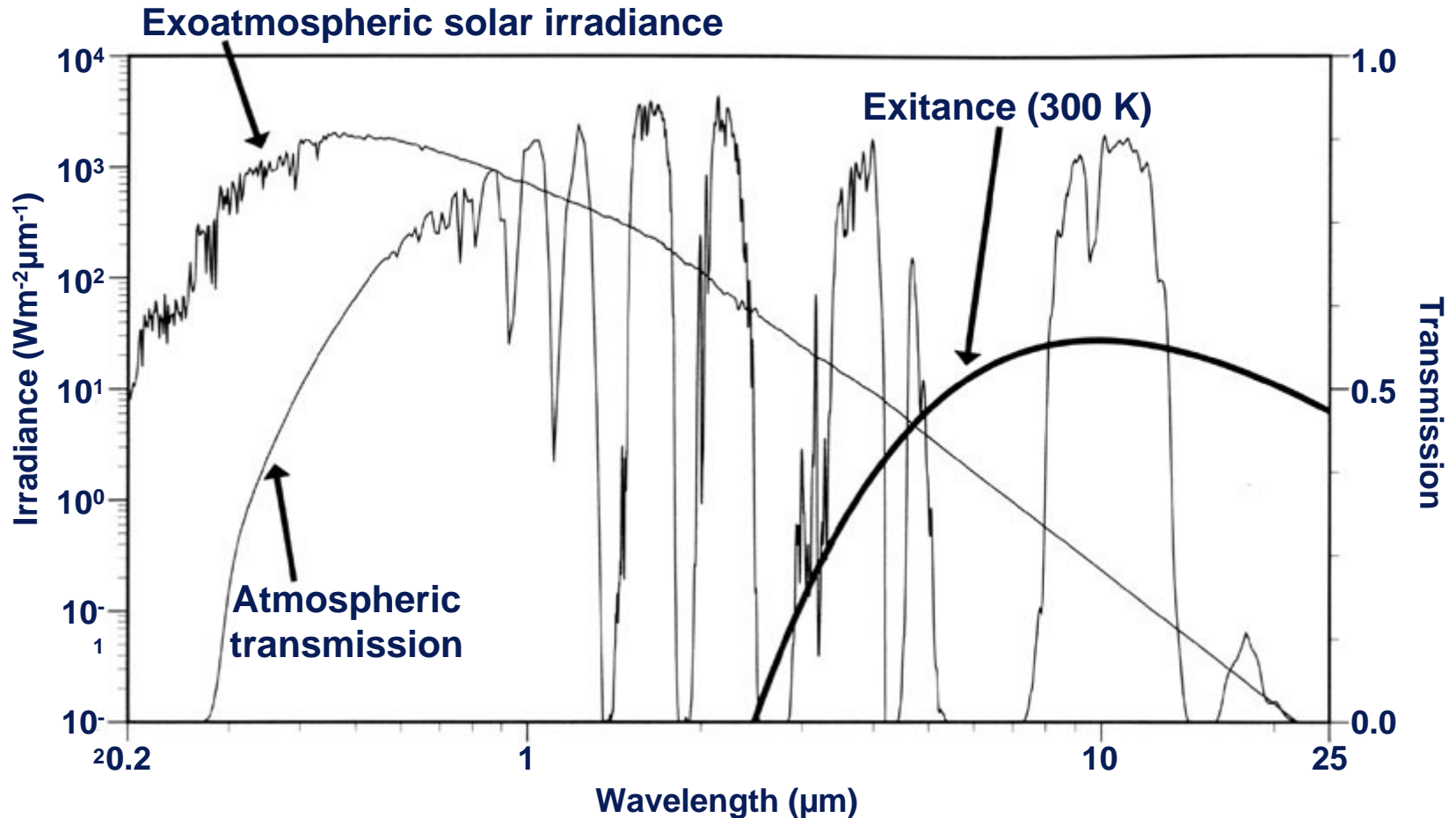$\Delta Q \sim \Delta (T_1^4 - T_2^4)$

Radiative Heat Transfer is the Only Form of Heat Transfer that requires the knowledge of Absolute Temperature instead of Temperature Difference

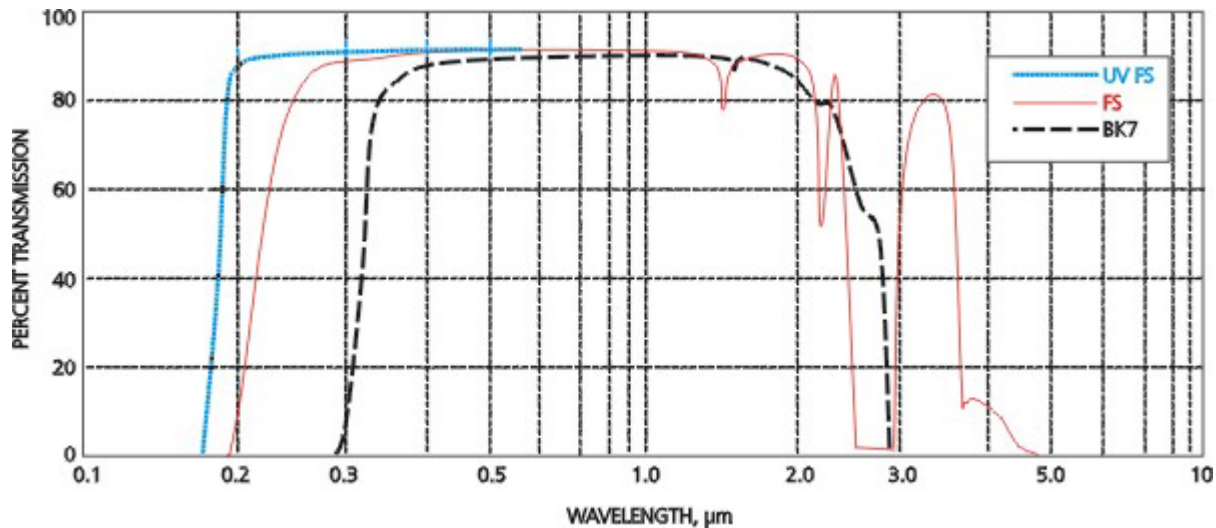# Scattering of Sunlight by the Earth-Atmosphere-Surface System

Atmospheric Transmission and Greenhouse Effects

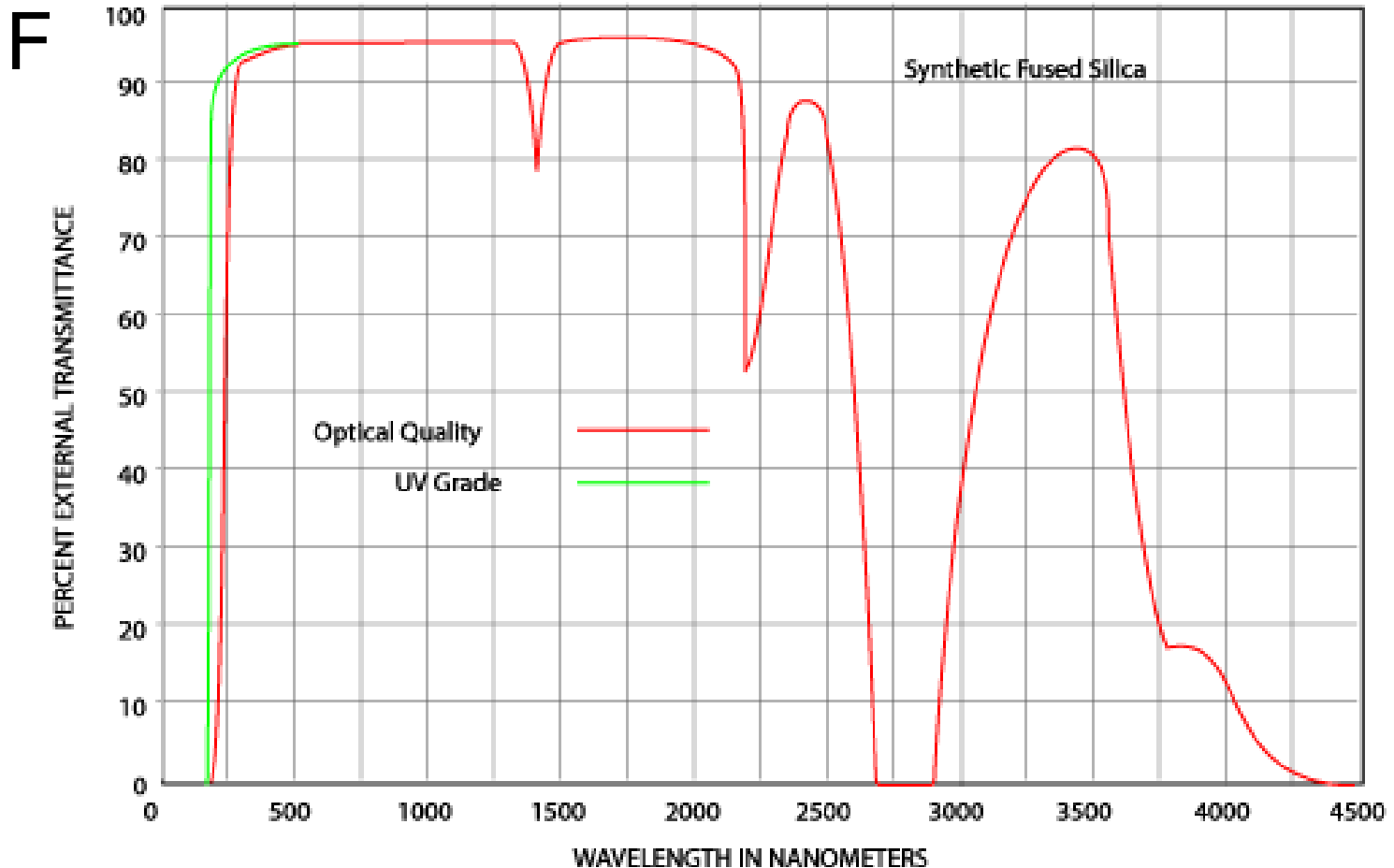http://tbrs.arizona.edu/education/553-2004/2004/Lect083104_Ch2.ppt-link.ppt#21

BK-7 Transmission Curve

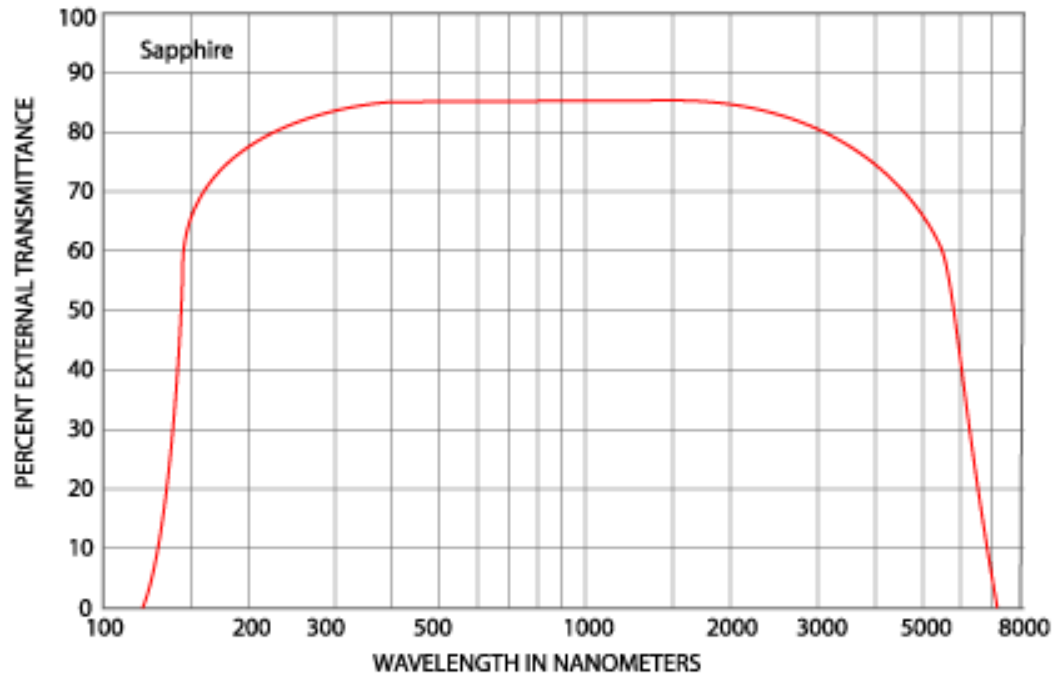- Most Plate Glass, Similar to BK7
- Plate Glass is Opaque to LWIR

Fuse Silica (quartz)Transmission

- F

Chart: PERCENT EXTERNAL TRANSMITTANCE vs WAVELENGTH IN NANOMETERS

Synthetic Fused Silica

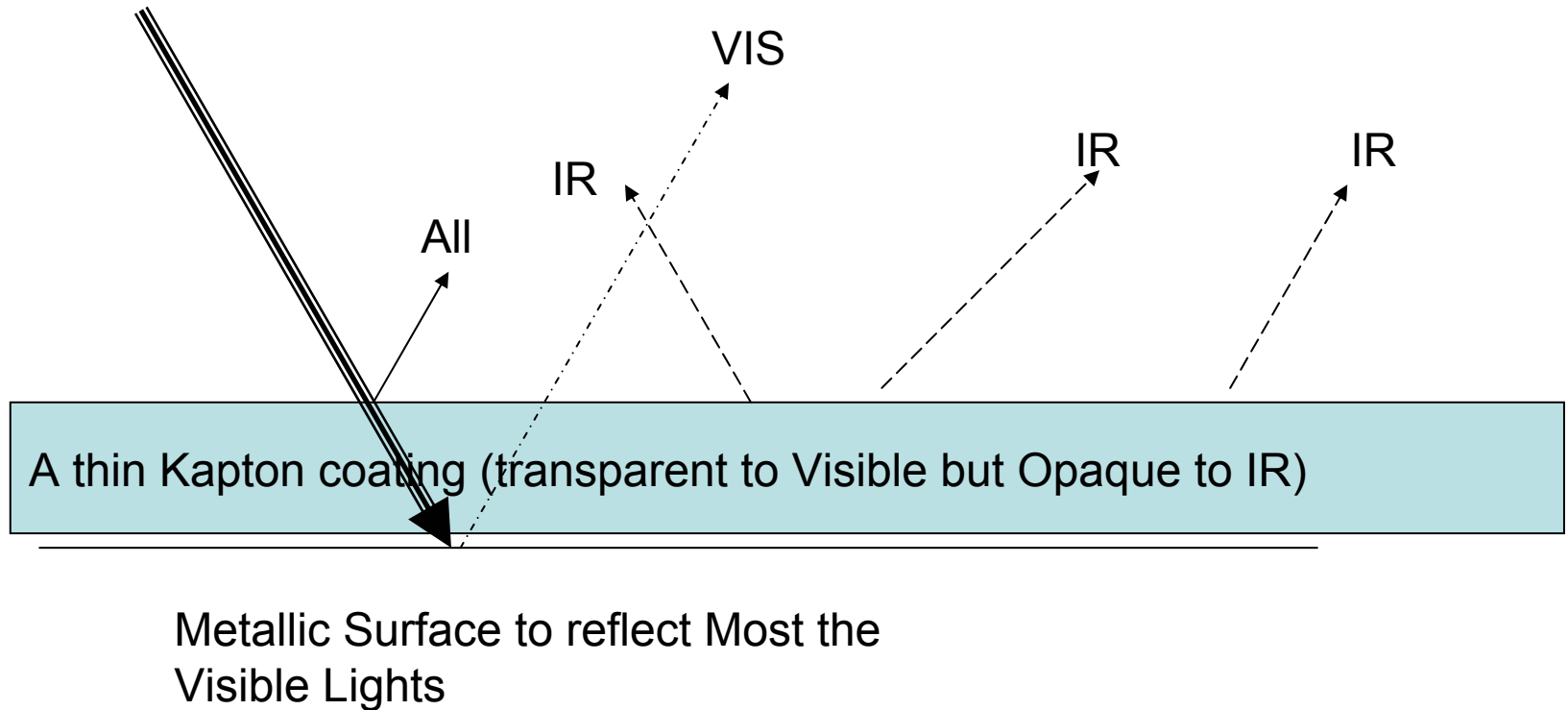Optical Quality
UV Grade

Sapphire Transmission

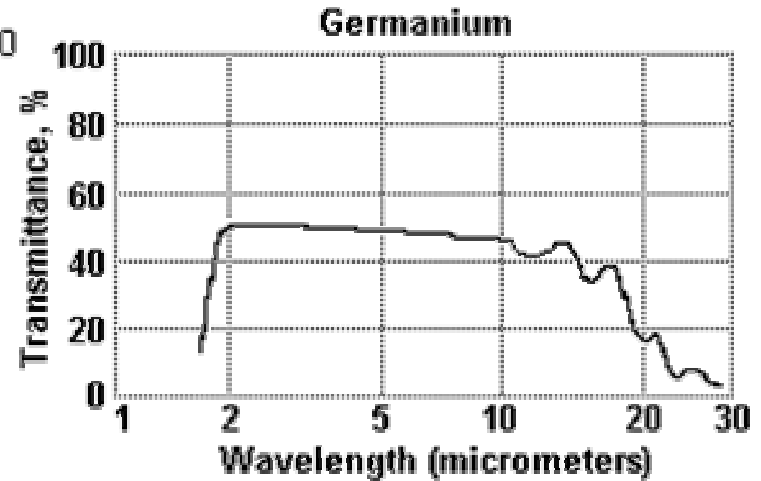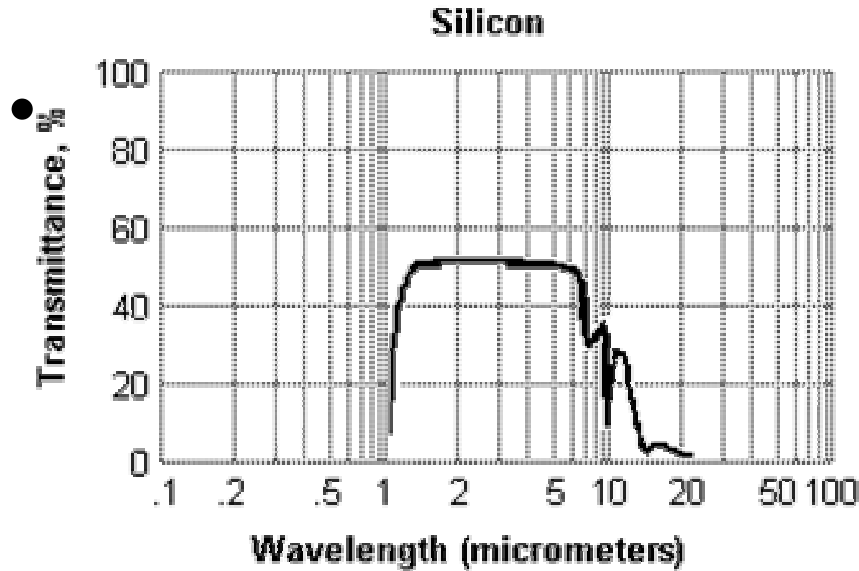# Why is the Interior of a Car so Warm in the Sun?

- Sun(6000K) warms a car with all wavelengths, but the interior of the car (300K-400K) emits IR (mostly around 10 μm) that can not pass through the glass.

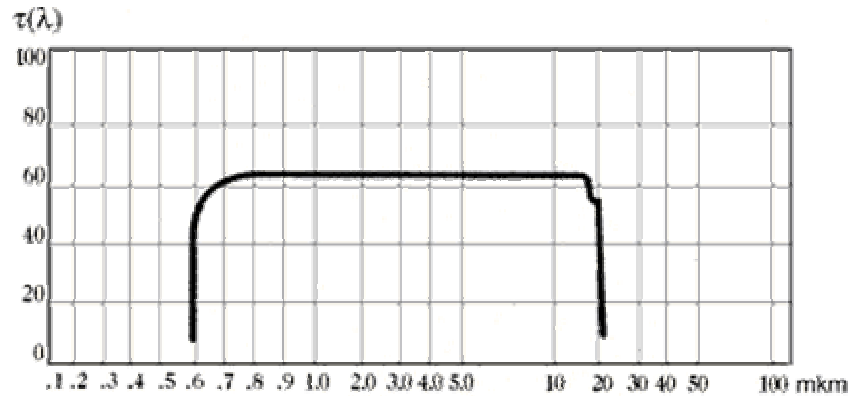# So How Does a Space Suit Work in the Sun?

- By a "Secondary Mirror" Surface!

VIS

IR   IR   IR

All

A thin Kapton coating (transparent to Visible but Opaque to IR)

Metallic Surface to reflect Most the
Visible Lights

Si and Ge IR Transmissions

ZnSe Transmission

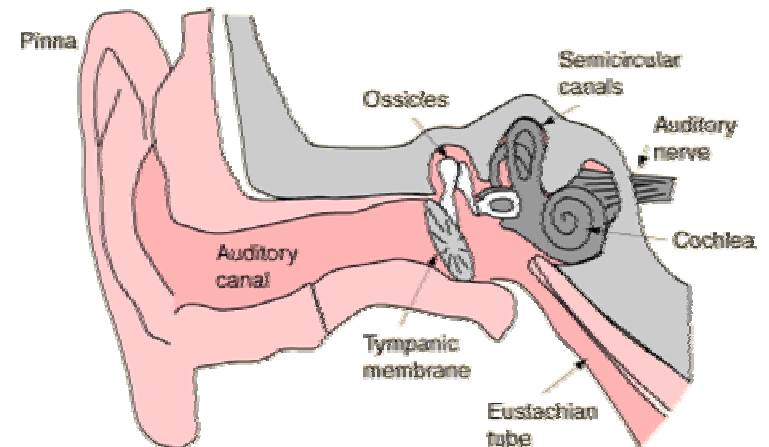- http://www.almazoptics.com/ZnSe.html

Regardless the "skin tone" difference, "all men are equal" in Infrared

- Yes, from 0.95-- 0.98; almost black!

What is an Aural Thermometer", or Infrared Aural sensor

- Tympanic cavity as a blackbody cavity

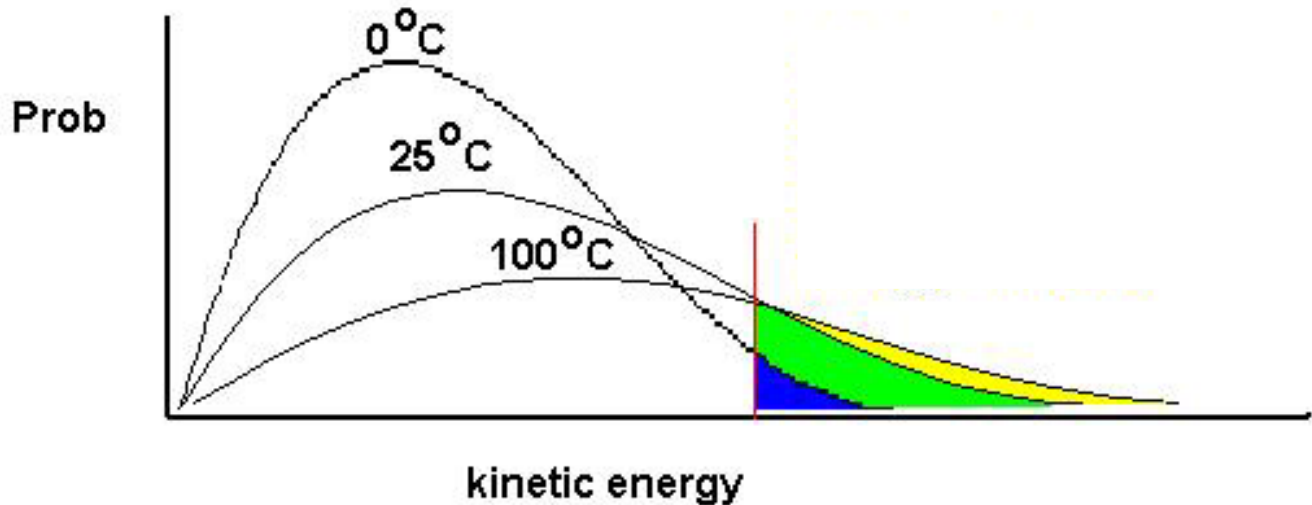- Emissivity~1.00

- Readily calibrated

- **Must be in a cavity!!

The Infamous SAR Fighter: Ear Cavity Thermometer

- a clinically reliable indicator of body core temperature
- Pyro-Electric Transducer

Electron Thermal Energy: Why IR Detectors Must be Cooled!

- $$KE_{avg} = \left[\overline{\frac{1}{2}mv^2}\right] = \frac{3}{2}kT$$

NEP Concept

- If we use the entire spectrum, then to detect 38ºC (vs. 37 ºC), the difference is

  $[(38 + 273)/(37 + 273)]^4 = 1.013\%$

So to resolve 1ºC the "system" must be able to resolve 1.3% difference

=>Noise Equivalent Power or NEP

How good is my System Stacking Against the Others?

$$D^* [\text{cm-}\sqrt{\text{Hz}}/\text{W}] = (A_{det}\, \Delta f)^{1/2}/\text{NEP}$$
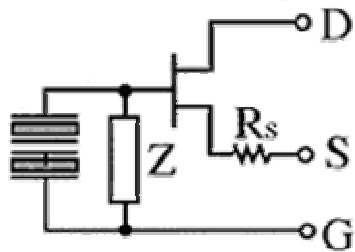
Pyro-electric Detectors

- Pyro: Gk "Fire"
- Pyro-electric: electrical output caused by heat
- Sometimes used for "fiery sparks" display for stage effects
- Low sensitivity, low cost
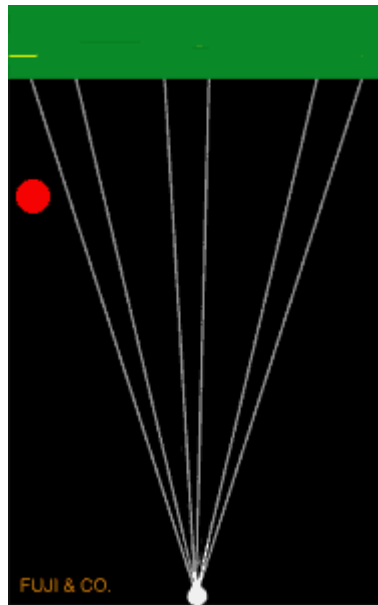- Usually for intrusion detection only

Pyro-electric Detector

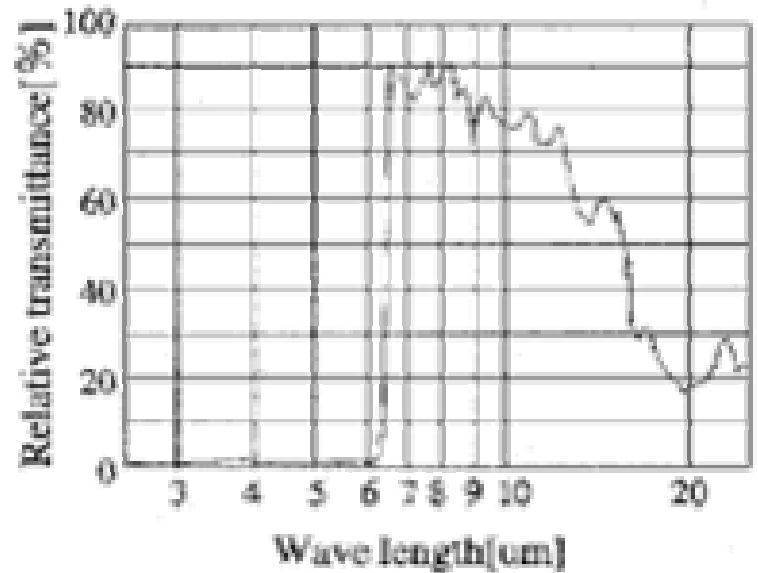polyethylene Fresnel lens are typically used for their low costs

TGS (Tri-glicine-sulfate)

http://www.fuji-piezo.com/TechGen.htm

PV Hg$_x$C$_{1-x}$Te

- Short for "photo-voltaic Mer-Cad-Telluride",,or, "Mer-Cad"

- Chemical compound of HgTe and CdTe

- Response ranging from 1μm to 5.5μm, and 8μm up to 13μm, depending on the Hg to Cd ratio

- "Sprite" Detector: Signal-Processing-in-the-Element

- Most versatile IR detector

PC HgCTe

- Response to 18 microns
- Intrinsic Detectors
- Need "chopping" because of large 1/F noise
- Response varying with temperature
- Operative in higher temperature than PV

# Thermal Transducer is "Export Control" Items

- InSb, HgCdTe, and room-temperature Thermal-pile Focal Plane Arrays (FPA) are all "Strategically sensitive" items

References

- *Electro-Optics* by Lewis J Pinson, John Wiley & Sons, Inc., (1985)
- *Modern Physics* by Serway, Moses, and Moyer, Saunders College Publishing, 1997
- *Optical Radiation Detectors* by Dereniak and Crowe, John Wiley and Sons
- *Infrared Handbook* by Wolfe etc., Environmental Research Institute of Michigan

Normalized Blackbody Equation

At T=6000K, λmax=0.5 μm
Since o.4<$\lambda_{vis}(\mu$m<0.7 or
$0.8 < \lambda / \lambda_{max} < 1.4$
So % visible energy is
0.45-0.1=0.35
or 35% of the total energy
At 3000K, the visible energy
~7%
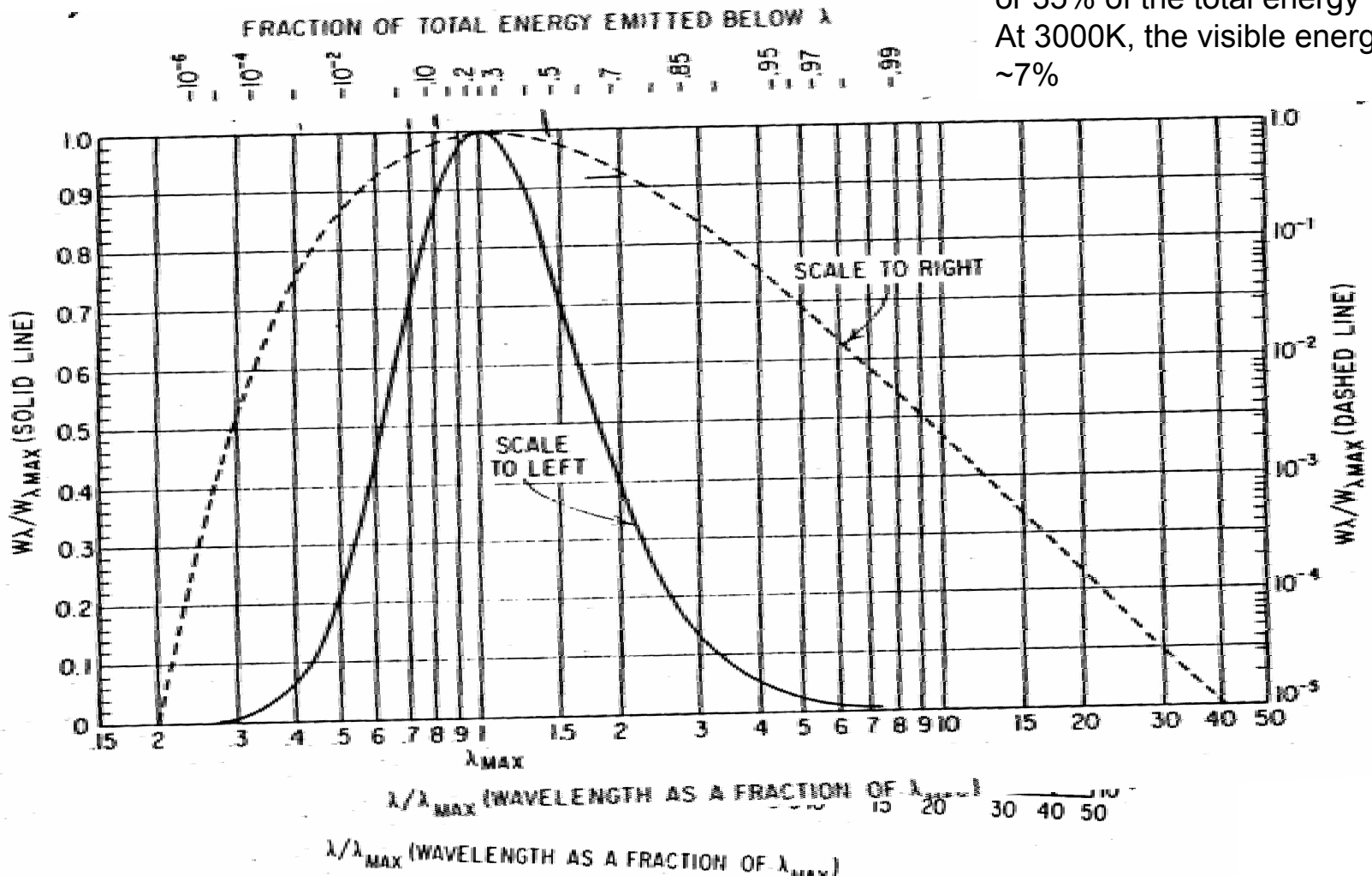
Homework(1)

- At the Daper point (800K), a blackbody begins to be visible, computer the visible exitance
- A 1-cm thick,1m square plate has one side perpendicular to the sun and a conductivity of 0.01 W/m/K. If the emissivities of both surfaces are all 1/5.67, and the shodow side of the surface temperature is 300K, compute the solar absorptivity of the surface facing the Sun
- Prove the blackbody equation can be normalized as $M_\lambda / M_{\lambda, max}$ vs. λ / λ_{max}
- Compute the percentage increase in visible energy for a 3000K blackbody to 3400K (incandescent tungsten to halogen)

IFOV and Solid Angles

detector

detector

ω and Ω in Sr

θ

Θ in radiance

f

H

ω

Ω

Object

Object
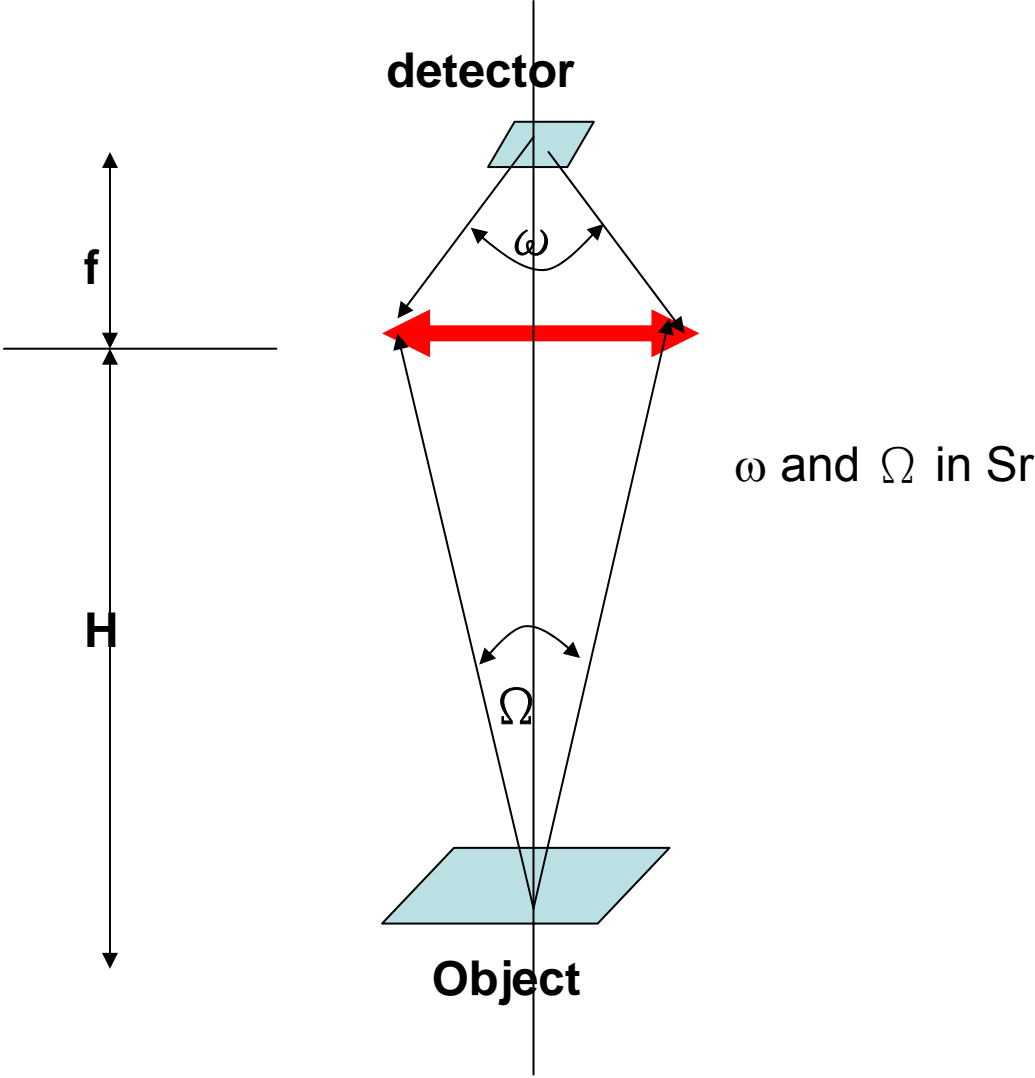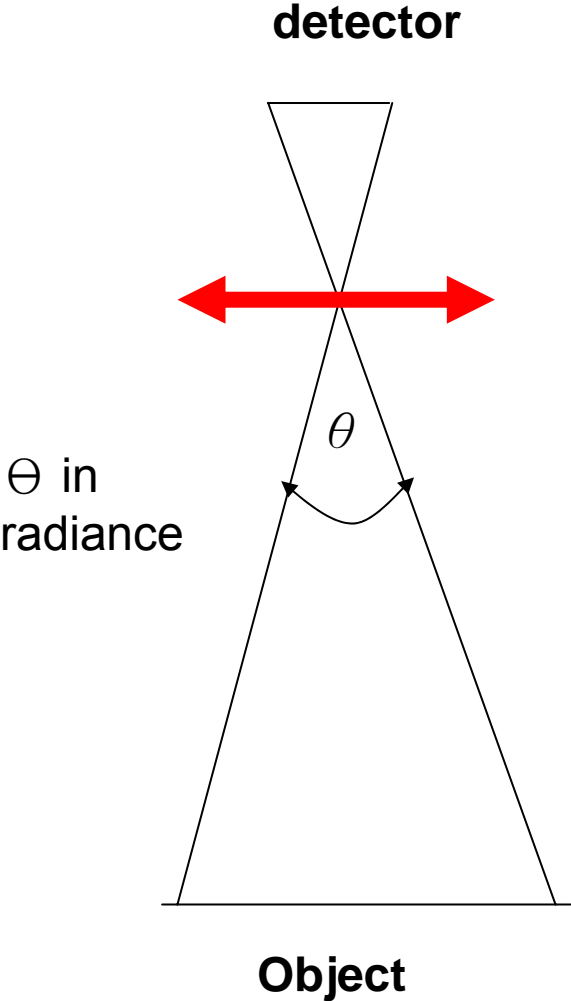
Radiometry Identity $a_d \omega = A \Omega$
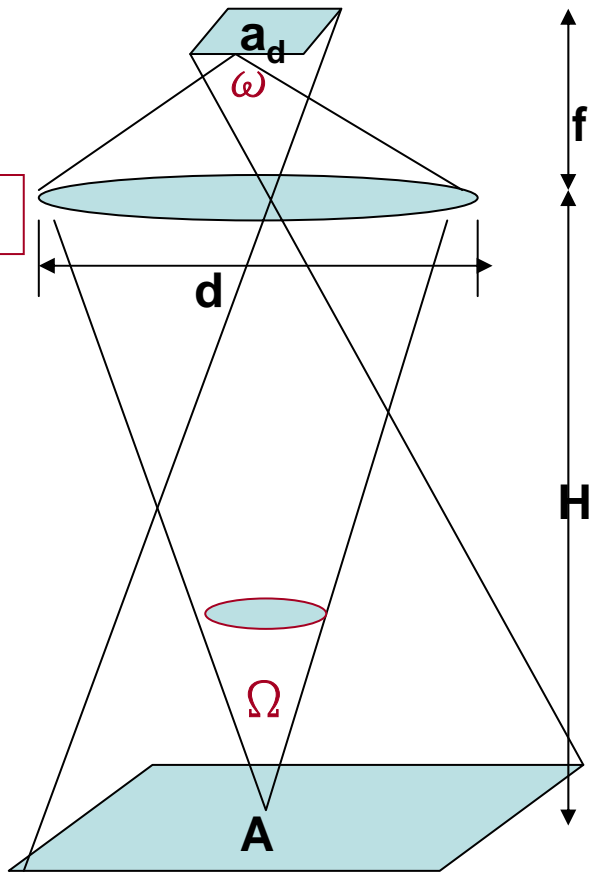
$$\frac{a_d}{f^2} = \frac{A}{H^2}$$

Multiplying both sides by $\pi d^2/4$ yields

$$\frac{\pi d^2}{4}\frac{a_d}{f^2} = \frac{\pi d^2}{4}\frac{A}{H^2}$$

Since $\omega = \pi d^2/4f^2$ and $\Omega = pd^2/4f^2$

Thus

$$a_d \omega = A \Omega$$

Aperture

a_d

ω

f

d

H

Ω

A

Optical Power on a Detector

- The Optical Power Falling on a Detector is:

P[W]
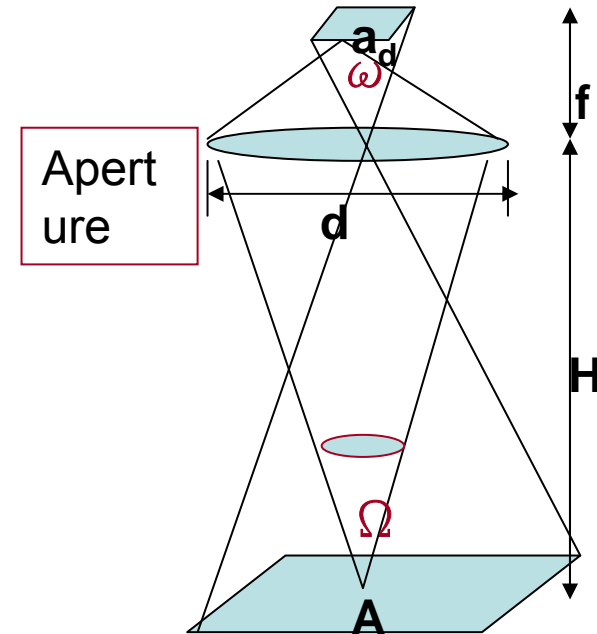
$= T_{opt} \cdot L[W\ Sr^{-1}\ m^2\ \mu m] \cdot \Omega A \cdot \Delta\lambda$

Substituting the Radiometry Identity yields:

$= T_{opt} \cdot L \cdot \omega a_{det} \cdot \Delta\lambda$

$= T_{opt} \cdot L \cdot \boxed{\dfrac{\pi}{4 \bullet (F/\#)^2}} a_{det} \cdot \Delta\lambda$

Since

$$\varpi = \frac{\pi d^2}{4 f^2} = \frac{\pi}{4(f/d)^2} = \frac{\pi}{4 \bullet (F/\#)^2}$$

Apert ure

Detector Responsivity

- An Ideal Detector Generates one e- for every Photon absorbed:

$$R_{ideal} = \frac{q}{h\nu} = \frac{q\lambda}{hc} \approx 0.8 \bullet \lambda [A/W]$$

An Actual Detector Responsivity is:
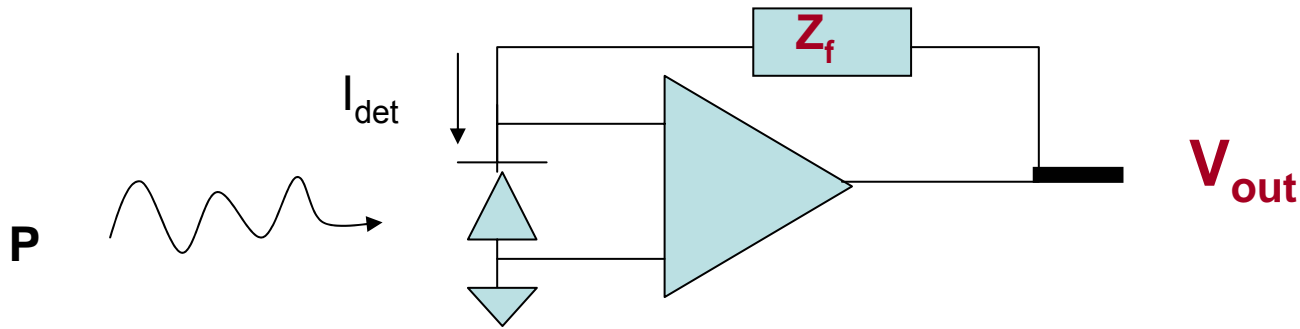
R[A/W]= η R$_{ideal}$= 0.8 η λ
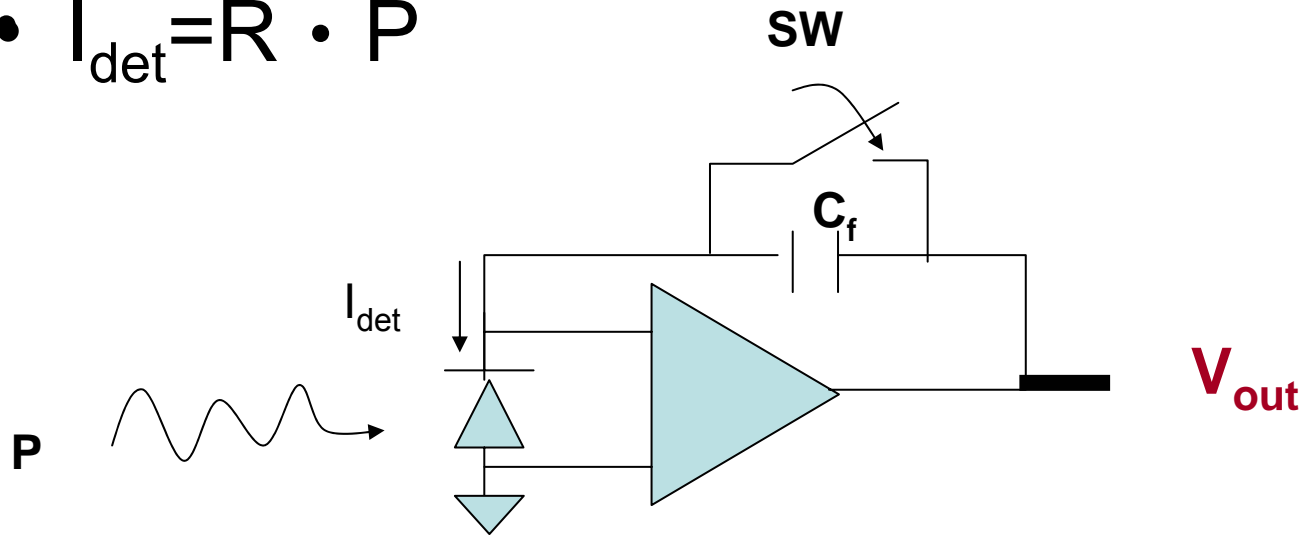
q=1.6x10^{-19} Amp-sec

Note: λ in μm

Theoretical Detector Output (TIA)

- $I_{det} = R \cdot P$
- $V_{out} = I_{det} \cdot Z_f$

Theoretical Detector Output (CTIA)

- $I_{det} = R \cdot P$

SW

C_f

I_{det}

P

V_{out}

$$V_{out} = \frac{I_{det} \bullet \tau_{int}}{C_f}$$

TIA Impedance Transfer Function

$$\frac{1}{Z_f} = \frac{1}{R_f} + \frac{1}{1/(j\varpi C_f)}$$
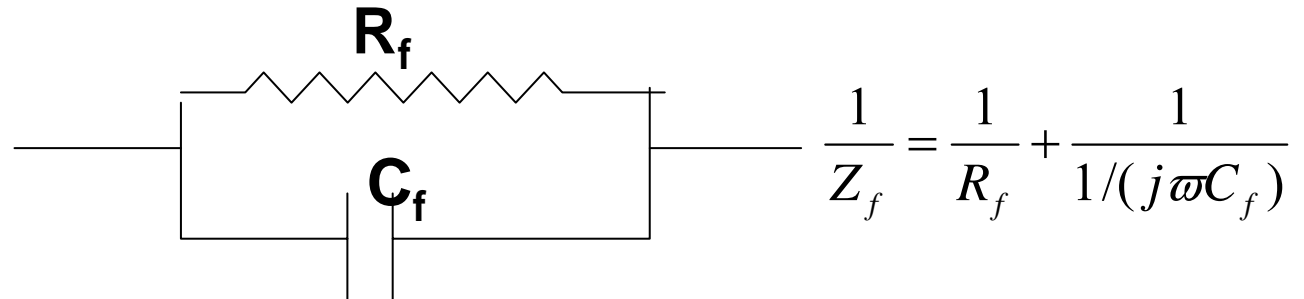
The Complex Impedance is

$$Z_f = \frac{R_f - j\varpi R_f^2 C_f}{1 + \varpi^2 R_f^2 C_f^2}$$

The Transfer Function is:

$$[\mathbf{Z_f}] = \frac{R_f}{\sqrt{1 + \varpi^2 R_f^2 C_f}}$$
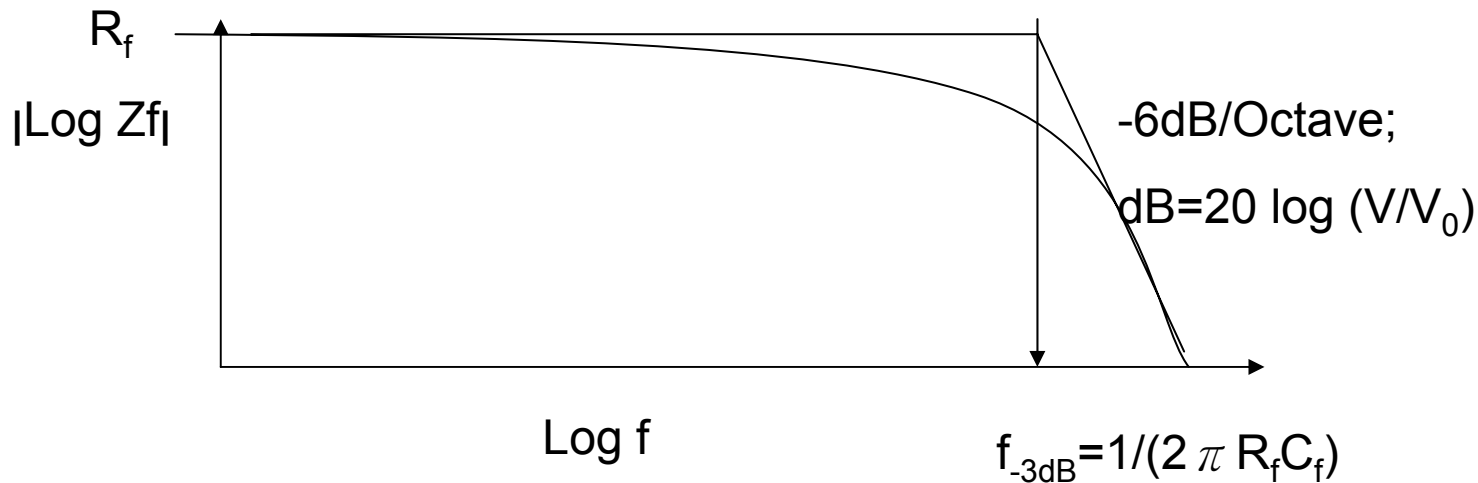
When $\omega = 1/RC$

$|Z_f| = Rf/\sqrt{2}$

Frequency Response of Z_f
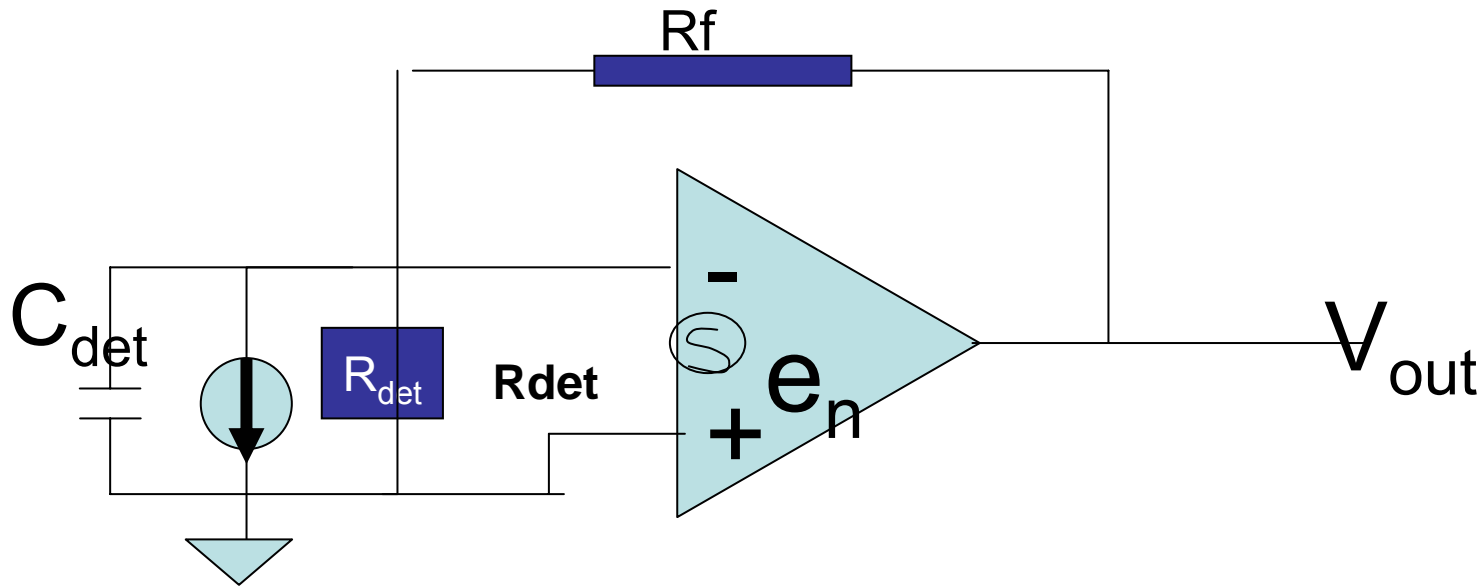
Since $\omega = 2\pi f$, and $f_{3db} = 1/(2\pi R_f C_f)$

$|Z_f| = R_f/\sqrt{2} = 0.707\ R_f$ @ $f_{-3dB} = 1/(2\pi R_f C_f)$

dB = 20 log (0.707) = -3 dB

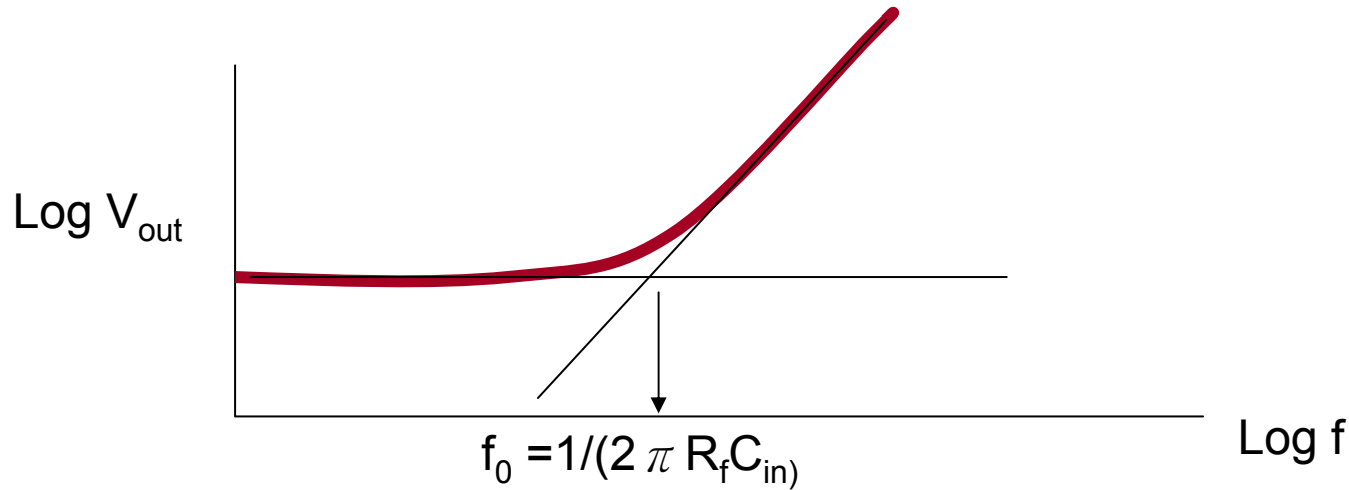$$[\mathbf{Z_f}] = \frac{R_f}{\sqrt{1 + \varpi^2 R_f{}^2 C_f}}$$

R_f

$|Log\ Zf|$

-6dB/Octave;

dB = 20 log (V/V$_0$)

Log f

$f_{-3dB} = 1/(2\pi R_f C_f)$

Why is that Detector Impedance needs to be High

Rf

C_{det}

R_{det} **Rdet**

e_n

V_{out}

If R_{det}>>R_f

$$V_{out} = e_n(1 + \frac{R_f}{R_{det}}) \approx e_n$$

"Boosted Input Noise from C_{in}"

Log V_{out}

$f_0 = 1/(2\pi R_f C_{in})$

Log f

$$V_{out} = e_n(1 + \frac{R_f}{1/j\varpi C_{in}}) = e_n(1 - j\varpi R_f C_{in})$$

$$|V_{out}| = e_n \sqrt{(1 + \omega^2 R_f^2 C_{in}^2)}$$

When $f_0 = 1/(2\pi RC)$

$|V_{out}| = \sqrt{2}\, en$

Chopping is Essential for "Drifting Signal"

- Chopping Effectively "De-couples" the Slow Drifting "1/f" Noise (including D.C. Level)

- In CCD, A "Correlated Double Sampling" is Used to Eliminate Drif
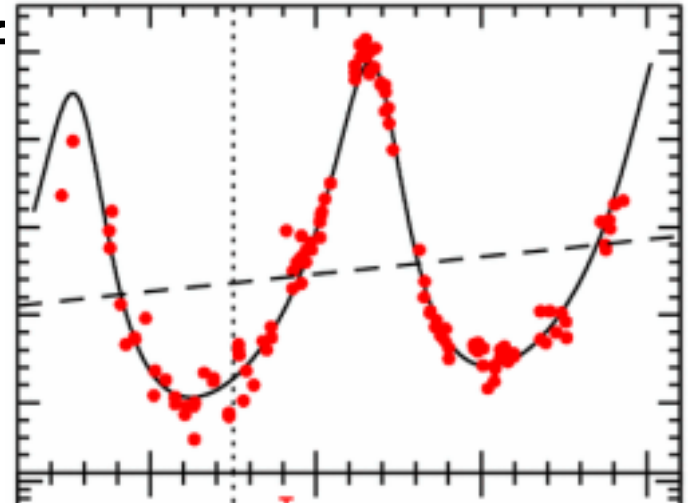
Poisson and Gaussian

The arrival of Photons follows discrete Poisson process; when large number of photons arrive, the distribution pattern is a continuous Gaussian distribution.

Thermally generated electron-hole pairs (Dark current) generation essentially follows the same principle.
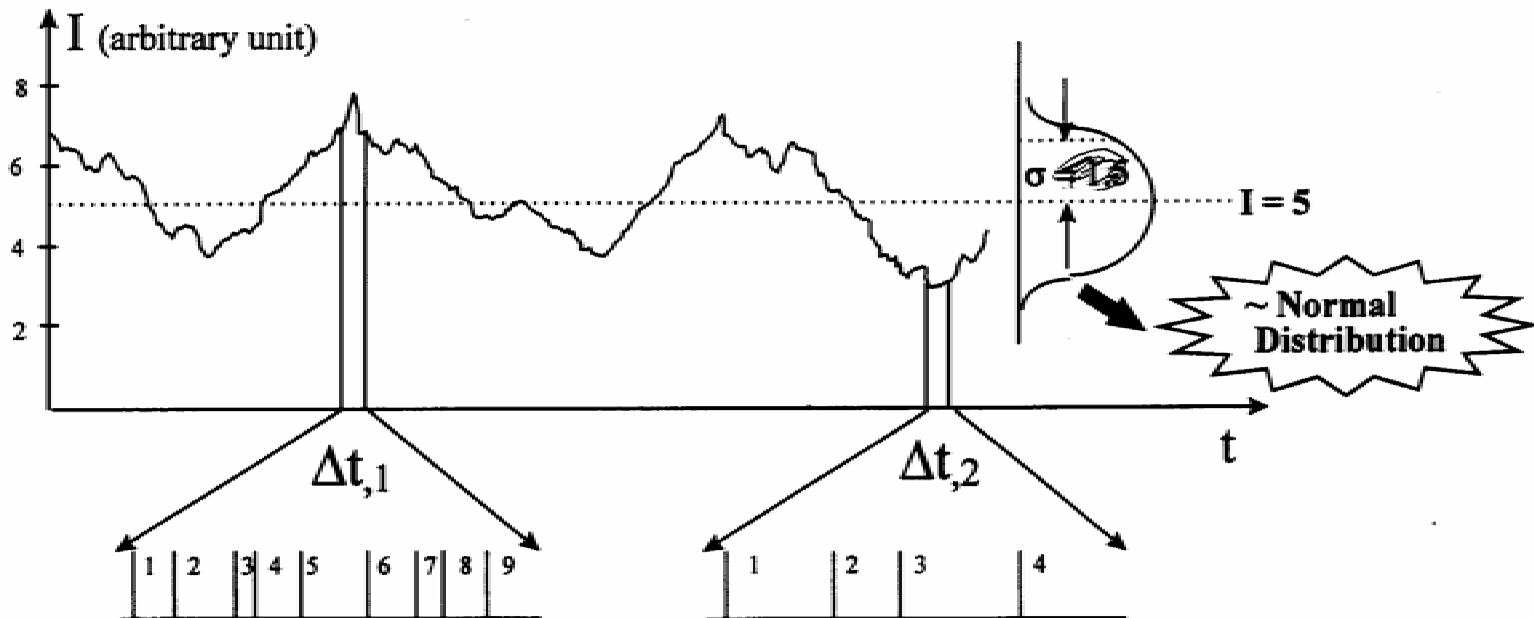
Shot Noise Current Density (Photon Noise)

Photon arrival is a "Poisson Distribution".$=N^k e^{-N}/k!$; k=0,1,2,3 (photon arrival sequence). If N is the average no. of photons, then the variance of a Poisson distribution is the same as the mean **N** .

$$I = \bar{i} = Nq/\Delta t$$

$$\overline{i_n^2} = \overline{(i-I)^2} = (q/\Delta t)^2 \overline{(n-N)^2} = (q/\Delta t)^2 \bullet N$$

$$Shot\_Noise$$

$$\overline{i^2_n} = qI/\Delta t = 2 \bullet q \bullet I \bullet \Delta f$$

Shot Current Noise is thus: $[2qI]^{1/2} /\sqrt{\Delta f}$

So Shot Noise Output Voltage in a TIA circuit is:

$e_{shot} = [2\ q\ I\ \Delta f\ ]^{1/2} R_f$

An ideal IT system is a Background Limited Infrared Photo-detector (BLIP) system.

Nyquist Frequency

- The minimum Digitization interval needed to represent a periodical signal is ½ of its maximum frequency, or

  $\Delta t = 1/(2\ f_{max})$

So the noise bandwidth Δf is defined as:

$\Delta f = 1/(2\Delta t)$

Total Noise $e_{n,total}$

$e^2_{n,total} = e^2_{det} + e^2_{dark} + e^2_{amp} + e^2_{Rf} + e^2_{photon}$

Or

$e_{n,total} = \{e^2_{det} + e^2_{dark} + e^2_{amp} + e^2_{Rf} + e^2_{photon}\}^{1/2}$

$e^2_{det} = \int_{\Delta f} kf^{-\alpha} \, df$

$e^2_{dark} = 2qI_{dark}R_f\Delta f$

$e^2_{amp} = \int_{\Delta f} [e_{input} \, (1 + \omega^2 R_f^2 \, C^2_{in})] \, df$

$e^2_{Rf} = 4kR_fT \, \Delta f$

$e^2_{photon} = 2qI_{photon} \, R_f\Delta f$

Two ways to Present "noises"

1. Input Referred: Noise current
2. Output Referred: Noise voltage

NEP, D, and D*

- NEP=I $_{noise}$/Resp [W]
- D=1/NEP [W^{-1}]
- D*=(a $_{det}$ • Δf) • D [cm • $\sqrt{Hz}$ • W^{-1}]

Planar Back-side Illuminated InSb SCA (System Chip Assembly)
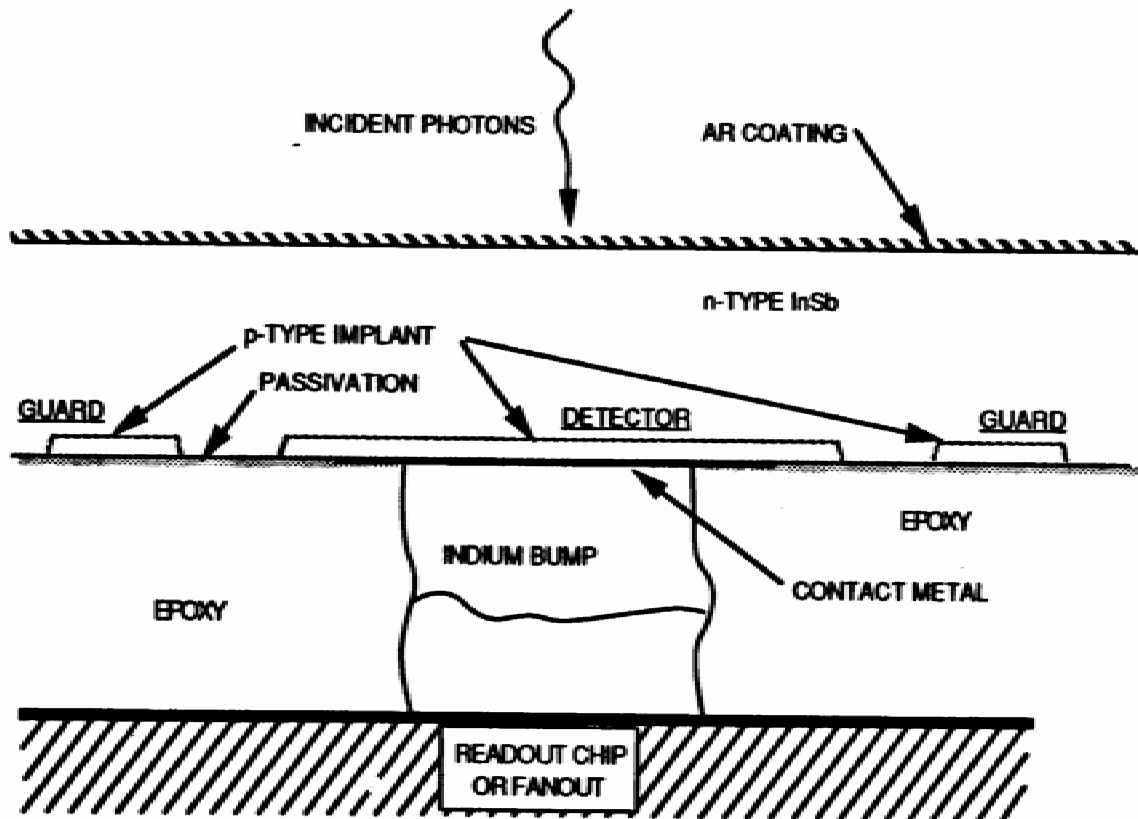
Homework (II)

System Parameters:

A_{det}: 125 μm^x 125 μm InSb PV; Q_{sig}: 10^{16} Ph/cm^2 @ 5.5 μm, @ 77K

η=0.85; unit area dark current I $_{dark}$: 8x10^{-5} A/cm^2; C_{in}=8pF R_f=10MΩ; C_f=2pF;
        $e_{n,input}$=6 nV/$\sqrt{}$Hz

Physical Parameters:

h: 6.63x 10^{-34}W-sec^2; c=3x10^8 m/sec; q: 1.6x10^{-19} A/sec;

 k:1.38 x10^{-23} W-sec/K

Find

1 the "break frequency f_{-3dB}" of the feedback circuit, and use f_{-3dB} for Δf

2a.Johnson noise voltage density; 2b: total Johnson noise voltage

3a. Total photon power falling on the detector 3b:detector responsibility

4a Photon Current, 4b: Signal voltage

5a. Photon Noise current density; 5b: total photon noise voltage

6a. Dark current; 6b: Dark current noise density 6c: dark current noise voltage

7a. Boosted noise voltage density; 7b: total boosted input noise voltage

8a. Total output-output referred noise voltage; 8b: SNR

9a: NEP; 9b:D; 9c: system D*

The Concept of Signal Chopping

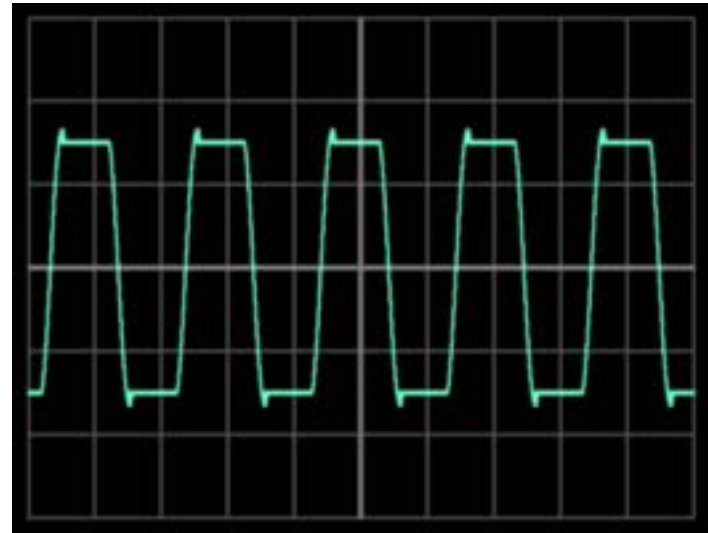- An Ideal way to "decouple" the 1/F noise is the use of a Sine Wave Chopper

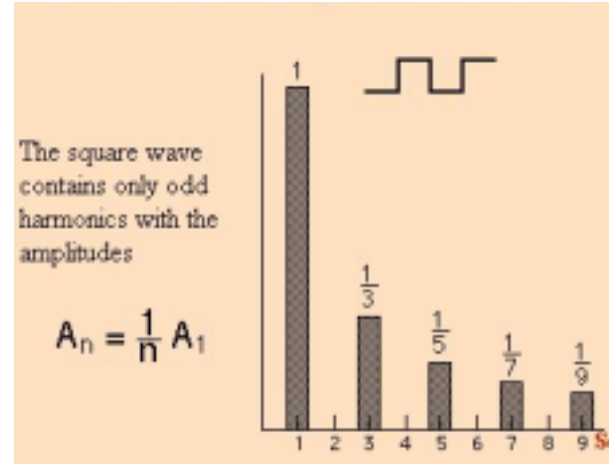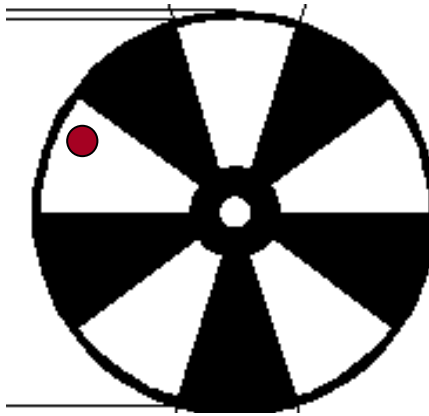That Generates Singular Frequency (Lock-In))

Signal

"1/F" noise

noise

f_0

29.4
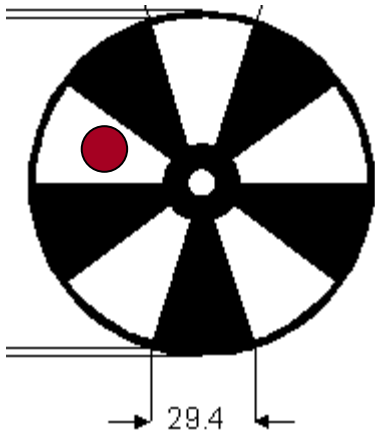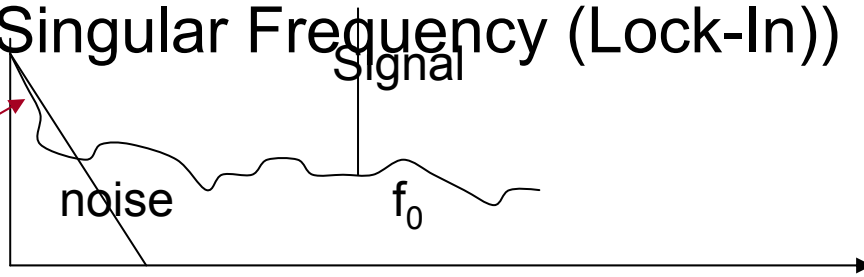
If the Aperture >> Beam Size You Have Square Waves

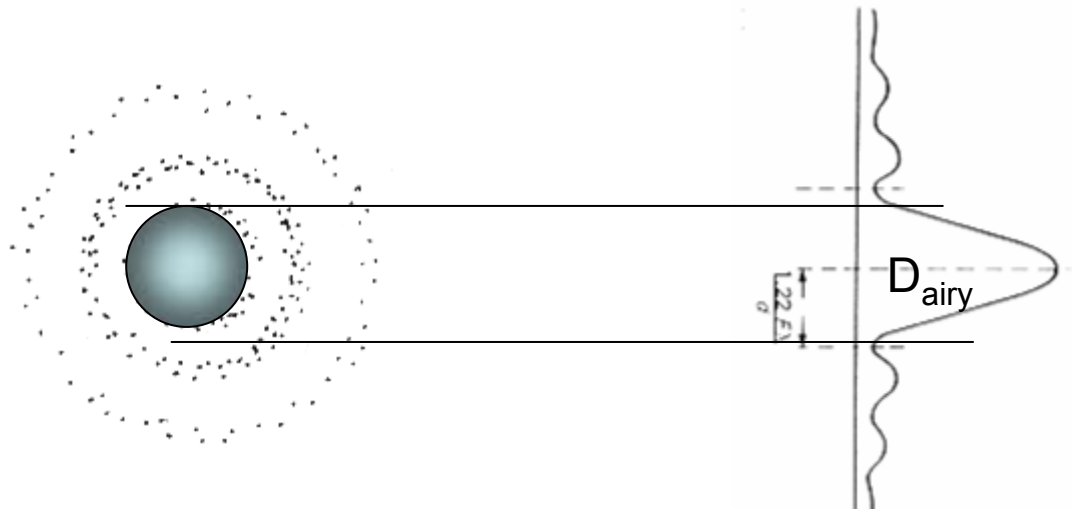- So we May Still Utilize the "Fundamental Frequency" for Signal Comparison

The square wave contains only odd harmonics with the amplitudes

$$A_n = \frac{1}{n} A_1$$

Airy Disc: Diffraction Limited Spot

$D_{airy}=2.44\ \lambda\ (F/\#)$

F/*: F-Stop of an Optical System$=f.l./D_{aperture}$

Since Numerical Aperture NA$=D_{aperture}/(2\ \cdot f.l.)=1/(2F/\#)$

So $D_{airy}=1.22\ \cdot\ \lambda\ \cdot$ NA

D_{airy}

How Many Pixels Do we need on a Digital Cameral?
The More the Better?

- Suppose a CCD Chip is 1000x1000, with each pixel dimensions of 7μm x 7μm
- The F/*=3.0;
- at 0.7 μm, the Airy disc is
- 2.44x 0.7x 3=5μm

- When λ=10μm, then the Airy disc=73 μm!
- In IR cameras, the pixels are "coarser".

Rayleigh's Spatial Resolution

- The Resolution is Half of the Spot
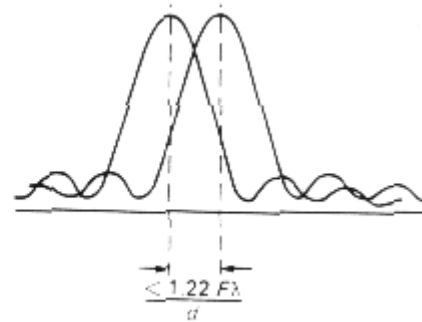
Optical MTF

An Optical MTF is the Fourier Transform of its "Optical Spot" .If the system is Diffraction limited then its Optical MTF

Can be approximated by:

MTF $_{optical}$=(2/π) (ϕ-Cosϕ sin ϕ)

Where ϕ=Cos^{-1}(λf/2NA) because the "blur circle is wavelength dependent

f: spatial frequency in "line pairs/ mm"

Practical Optical MTF Approximation

Most film MTF curves can be closely approximated by a Lorentzian function

$$MTF\ (\ f\ ) = 1/(1+(\ f/f_{50})2)$$

Where the "Nyquist MTF" f_{50} is wavelength dependent

http://www.normankoren.com/Tutorials/MTF1A.html
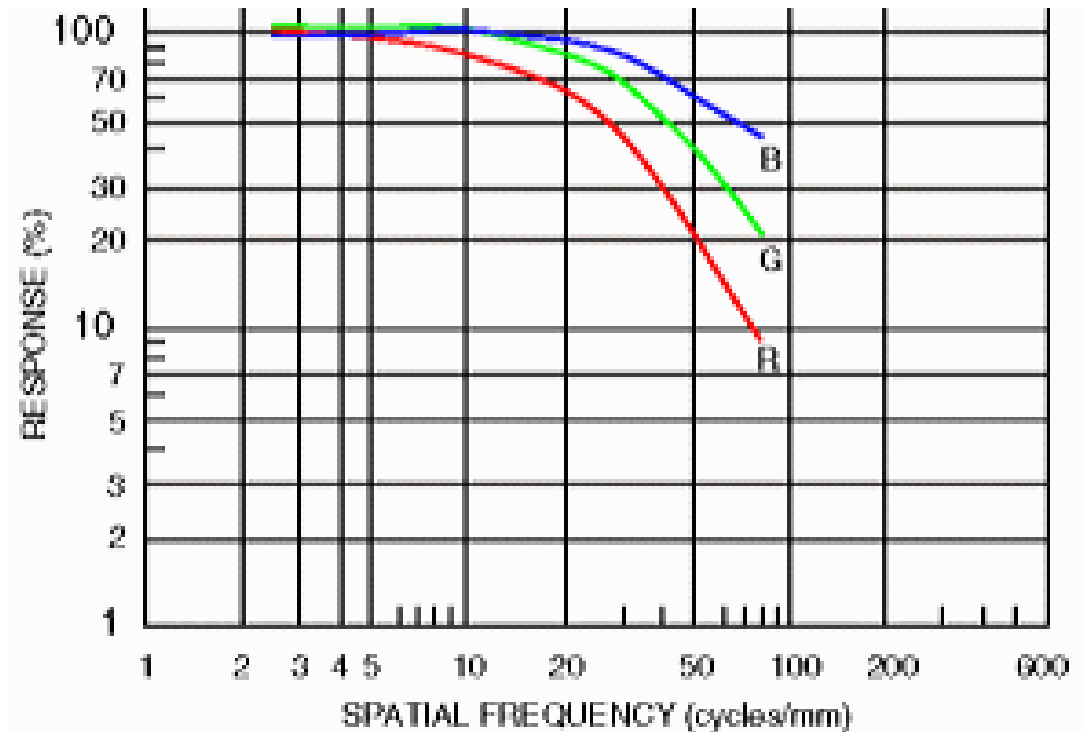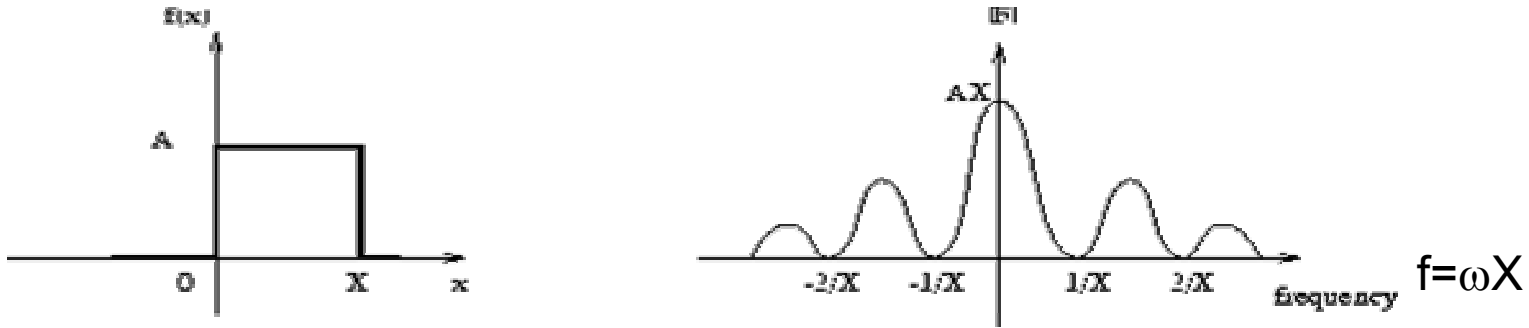
MTF Examples-1

- MTF for a "Pure Tone": sine function
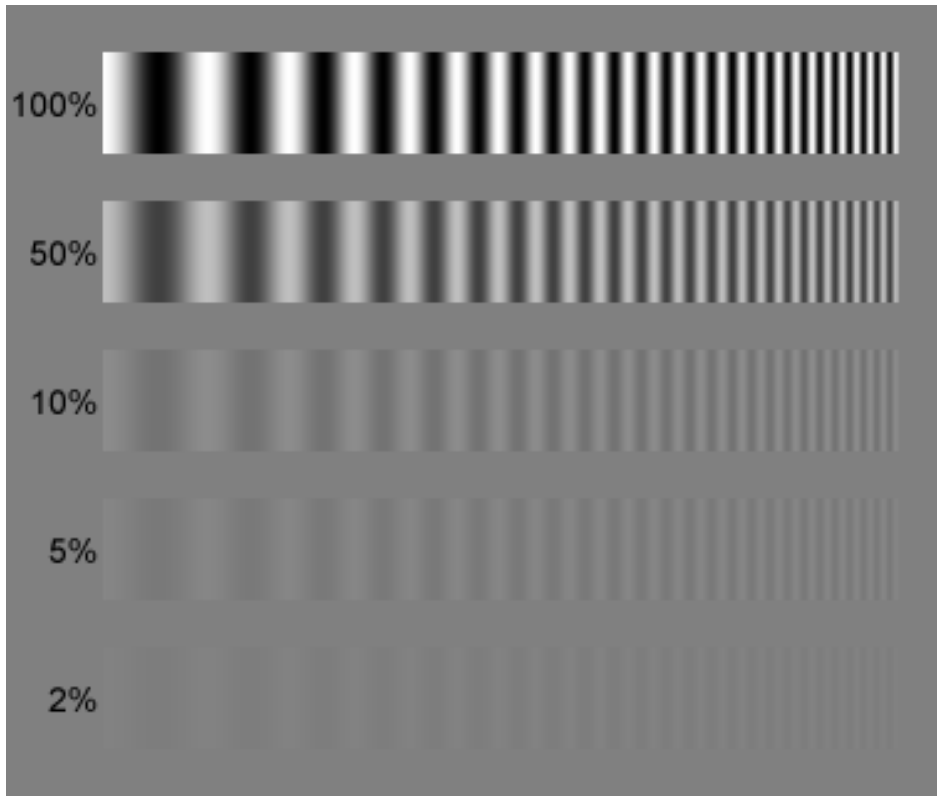
MTF Example-2
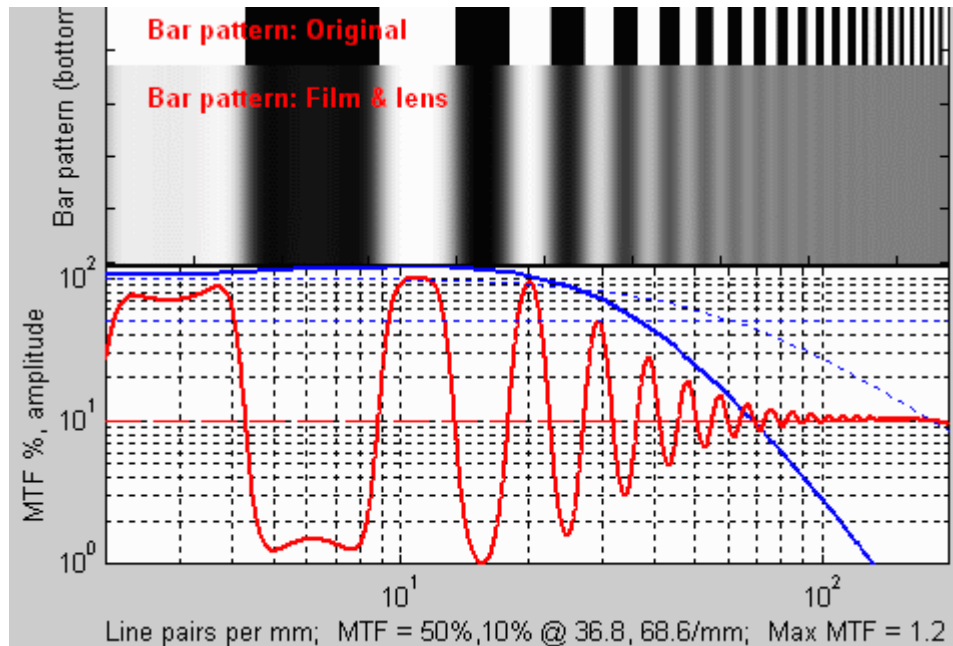
Detector MTF:Sinc Function

- Convolution of A Square Detector's and a Sine Scene is Detector's MTF

$f=\omega X$

$$MTF = AX\frac{\sin(\pi\omega X)}{\pi\omega X}$$

X: I "IFOV"

Sinc Function: sinc x=(sin π x)/ π x

MTF=| sin π x/ π x |

1

1/(0.5 π)=0.63

X=0   0.5   1

line pair/IFOV
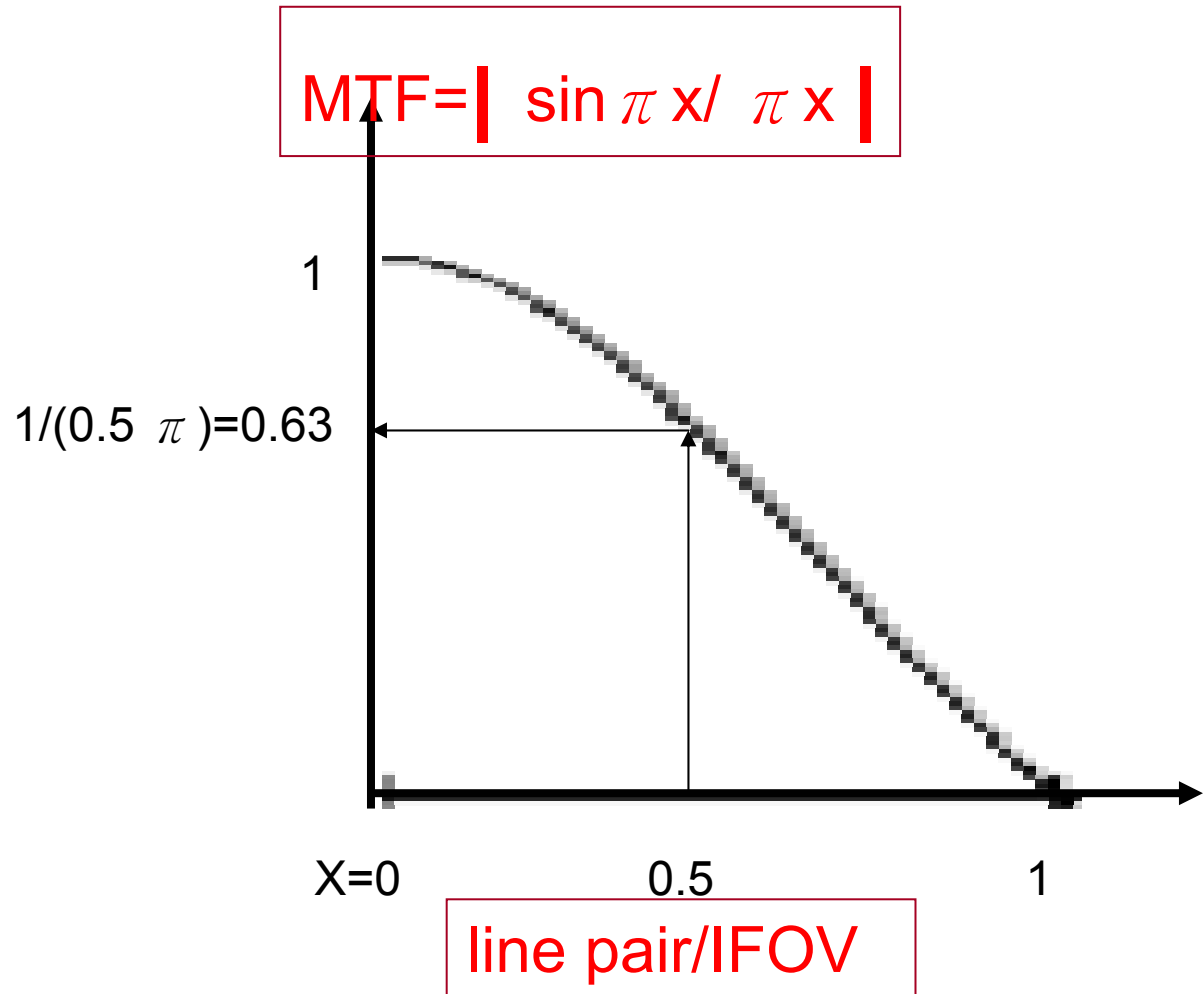
Physical Meaning of a Detector MTF

Spatial Frequency

Sinc 0=1
Sinc(0.5)=0.63

Sinc(6/10)=0.6

Sinc(5/8)=0.47

Sin(¾)=4/(3 π)=.42

Sinc(2/3)=.41

sinc 1=0

sinc 1.5=2/(3 π)=0.21

1 IFOV

1 IFOV

1

0

0.5

1

1.5
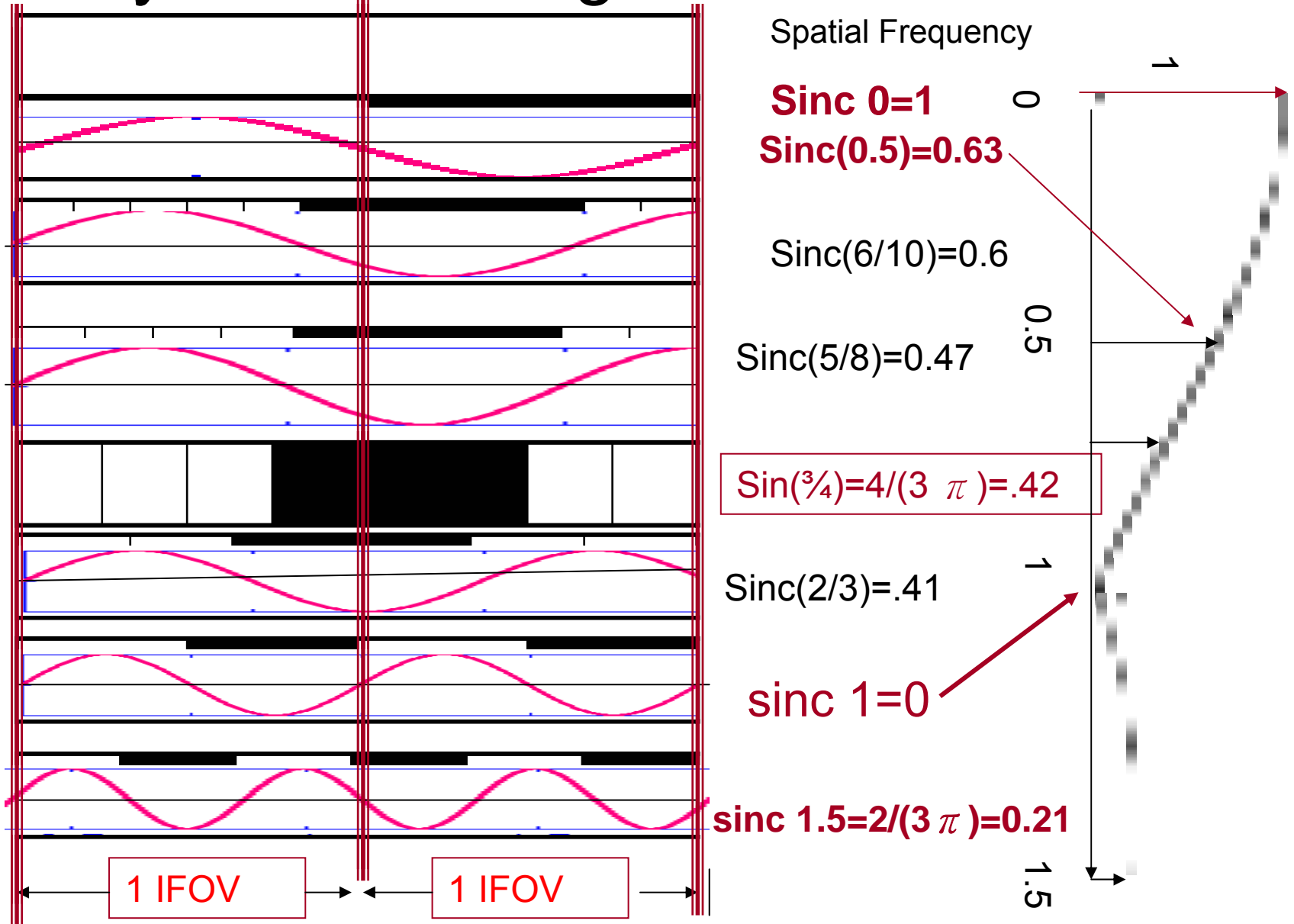
Image Convolution

Convolution of f(x) and h(x)

$$f(x) * h(x) = \int_{-\infty}^{\infty} f(u)h(x-u)du$$

Then Total MTF= MTF(f) $\cdot$ MTF(h)

Since Both Optical MTF and Detector MTF never exceed unity, the total
MTF is smaller than either MTF,
Or,
MTF only degrades as the system gets more comlicated!

Total MTF

- The Total MTF is the Product of:
- $MTF_{total} = MTF_{optical} \cdot MTF_{det}$
- (If scanning is involved, another MTF electronics would be included as well)
- In the Actual Imaging Space, it means
- "Convolution" of both Optical Blur and the Detector with a Pure Tone Sine wave

Noise Density

$V/\sqrt{Hz}$

f(Hz)
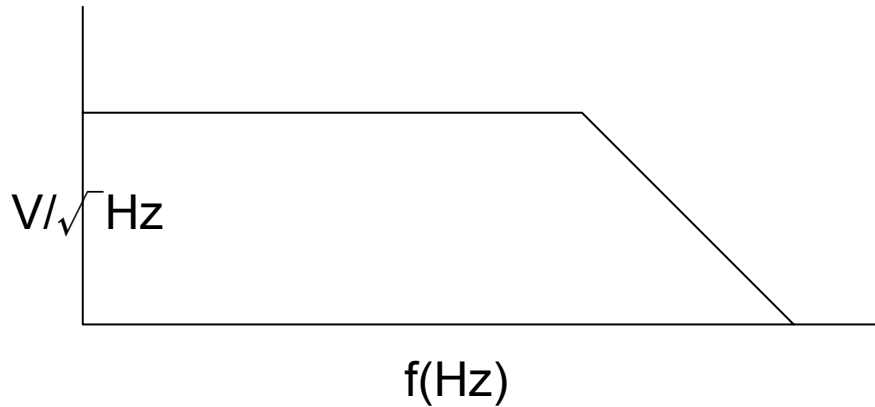
$$r.m.s.noise = \sqrt{\frac{\int_{\Delta f} v^2 df}{\Delta f}}$$

An Ideal Diode Curve

2nd Quadrant: N/A

I

1st: Quadrant

Rectifier

Short-Circuit Current

Open-circuit voltage

V breakdown V_{bias}

V

3rd Quadrant:
Detector

4th Quadrant: Solar Cell or

Power Generationg
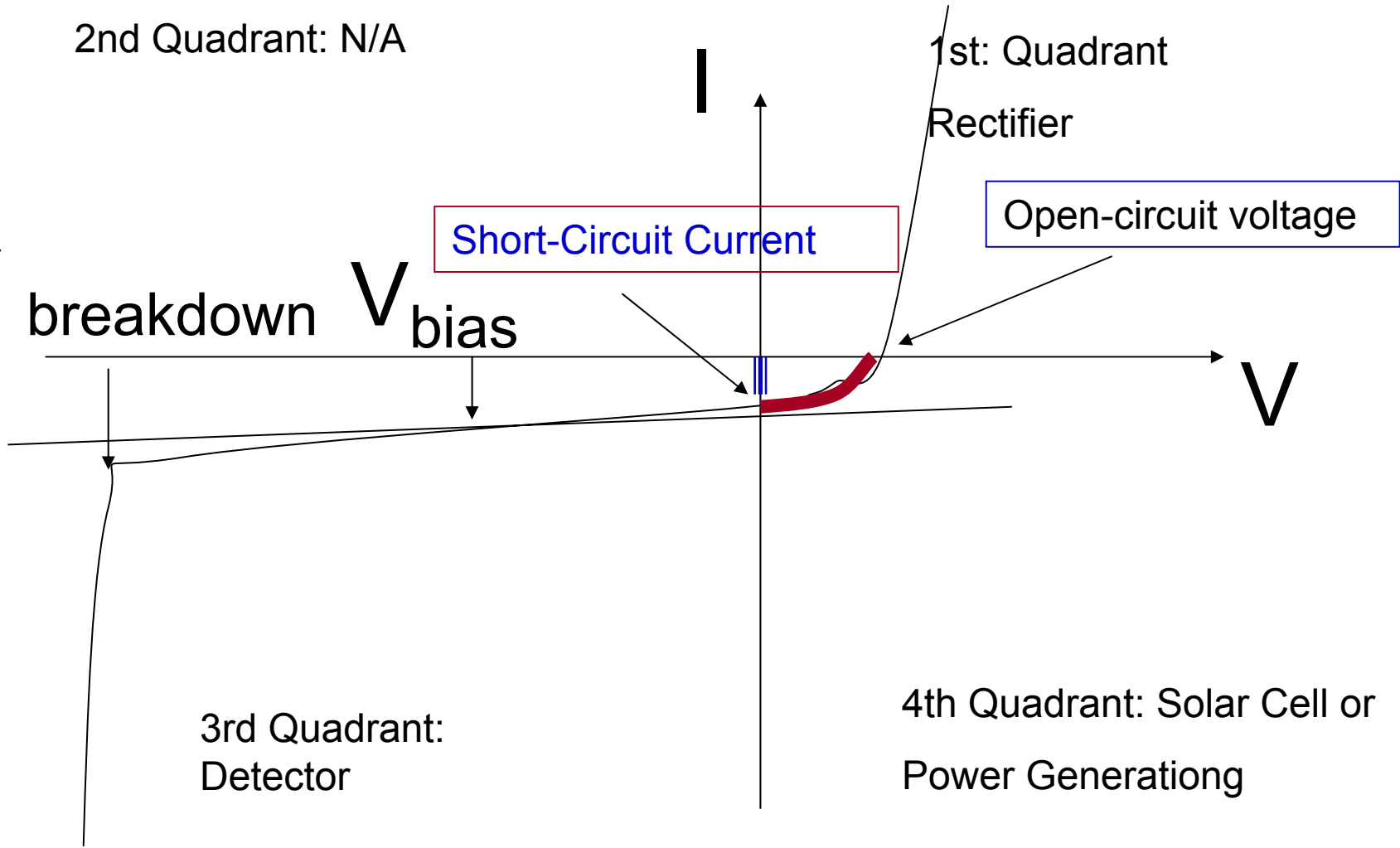
An Ideal Current Source has "Infinite Output Impedance"
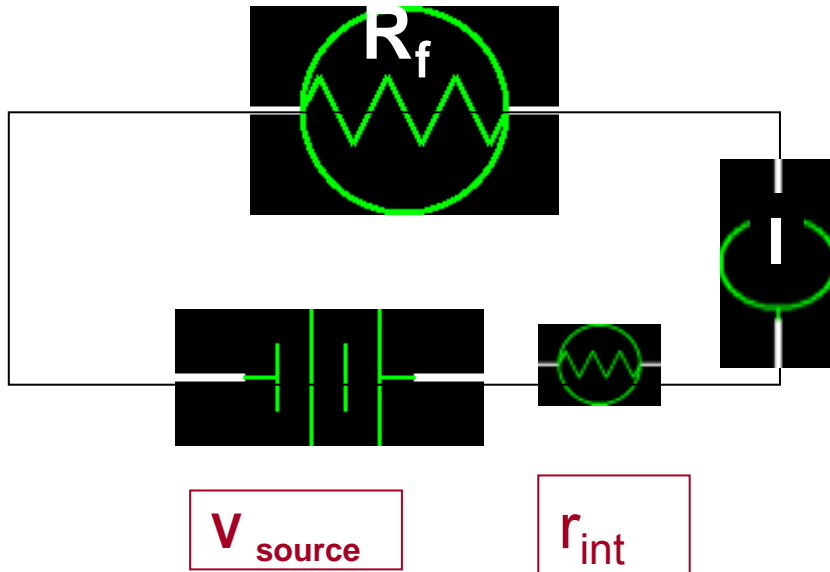
$$I = V_{source}/(R_f + r_{int})$$

When $r_{int} >> R_f$

Then

$$I = V_{source}/r_{int}$$

Photo-Diodes are a good Current Sources
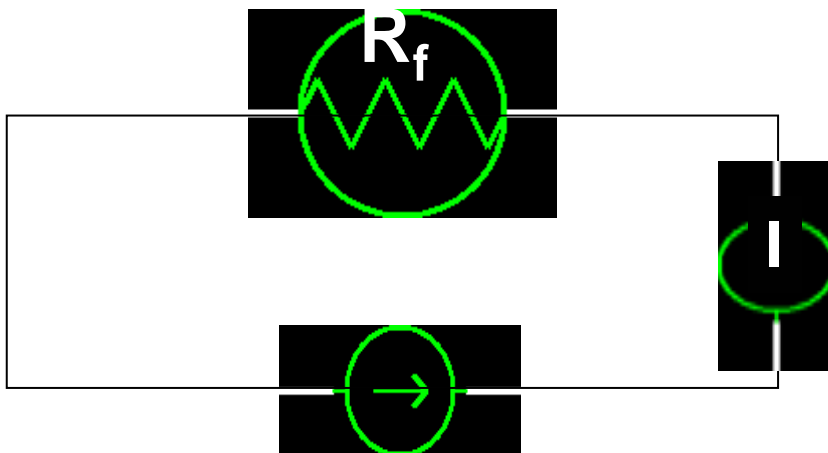
An Ideal Voltage Source has "Infinitesimal Output Impedance"
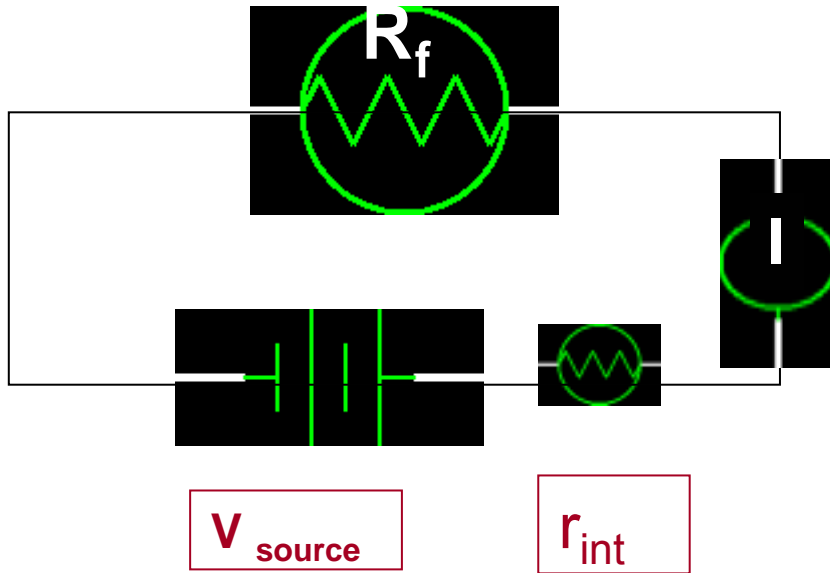
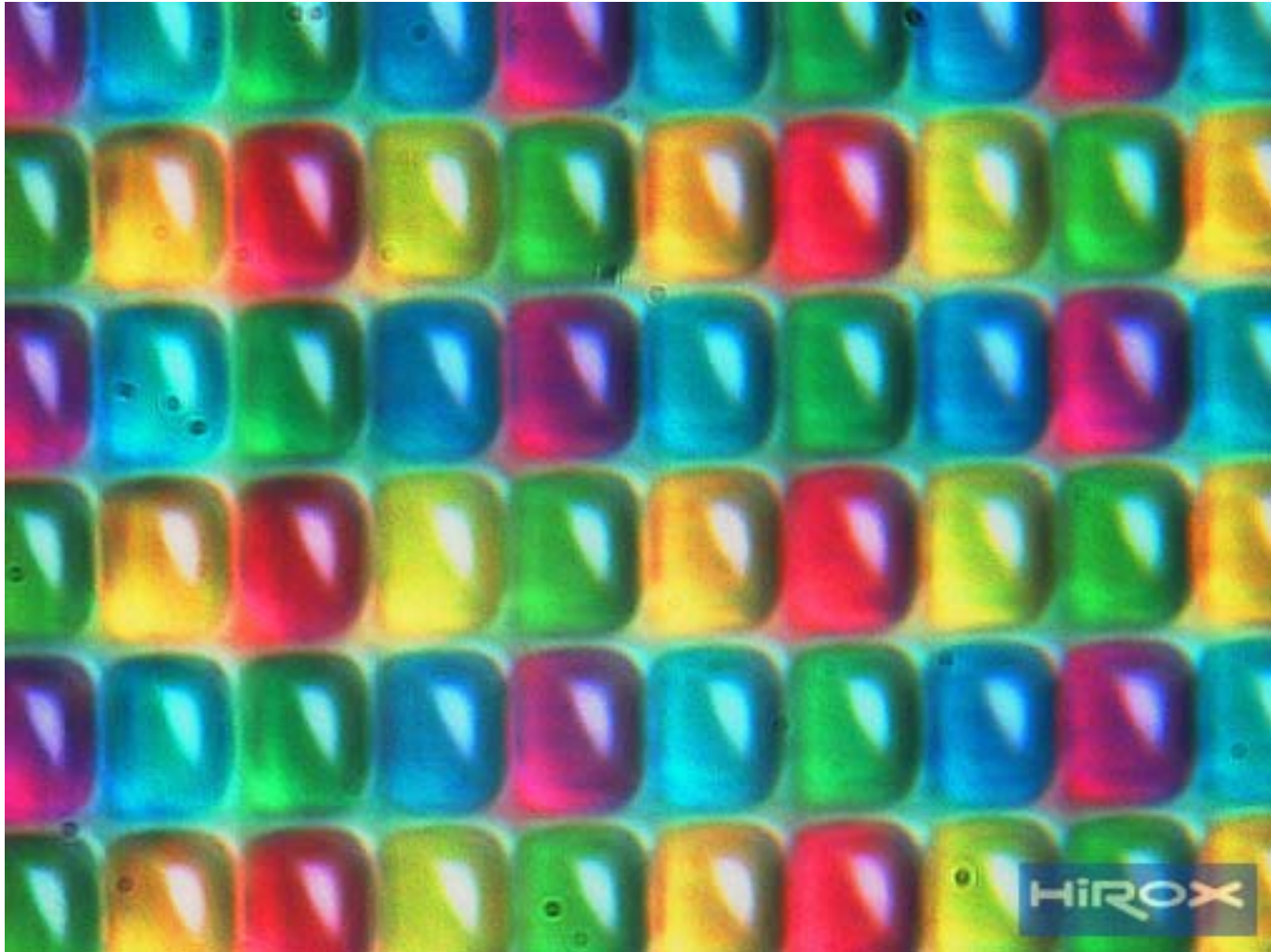$$I=V_{source}/(R_f+r_{int})$$

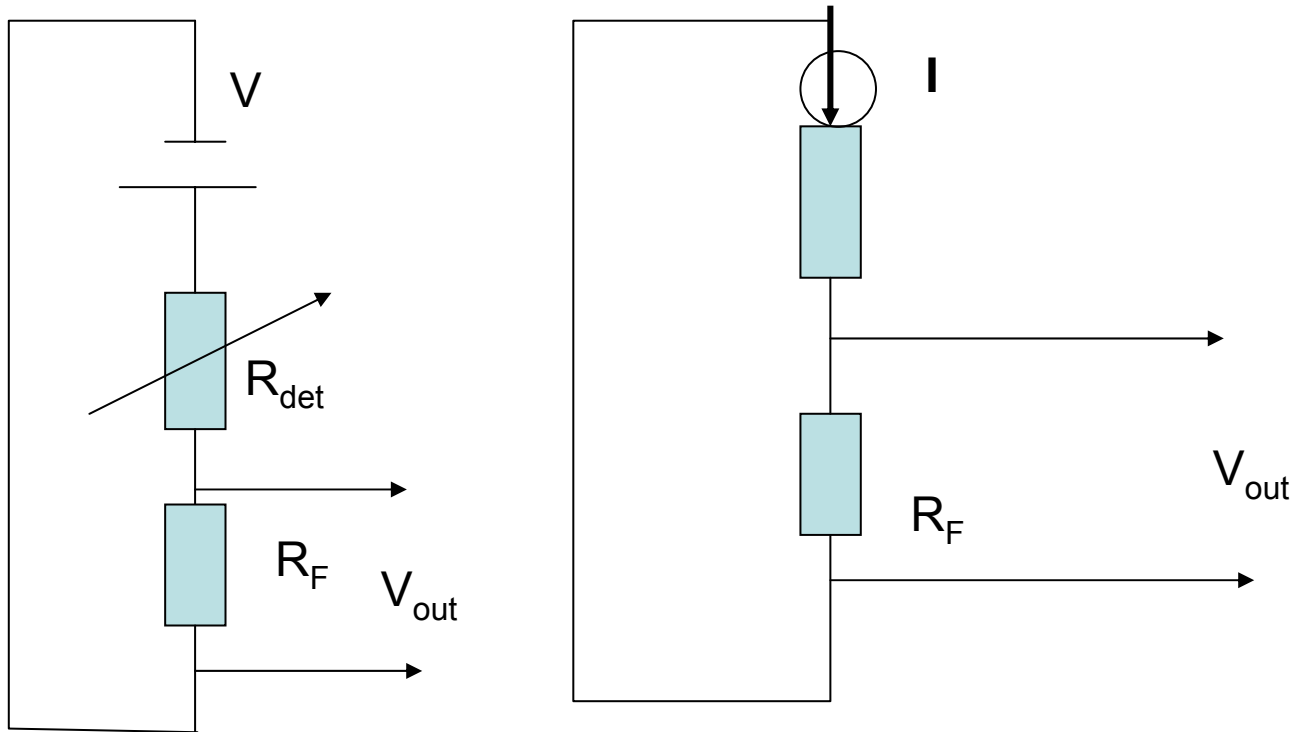**When** $r_{int}<<R_f$

Then

$$I=V_{source}/R_f$$
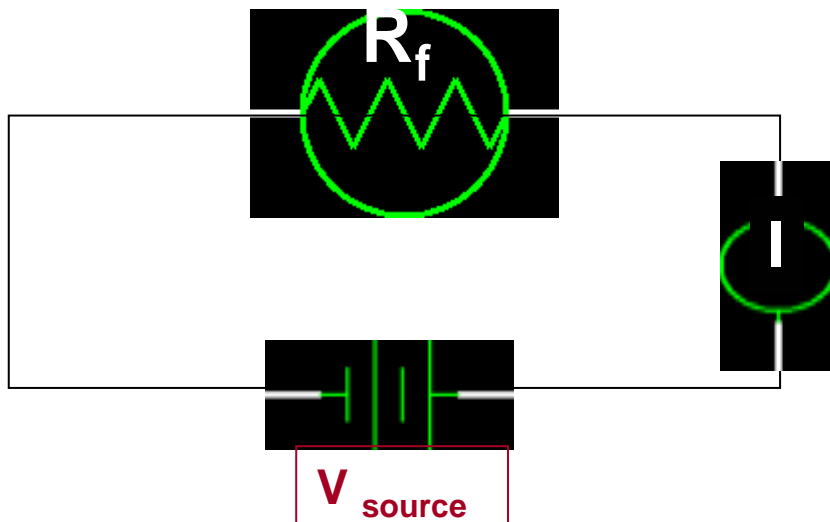
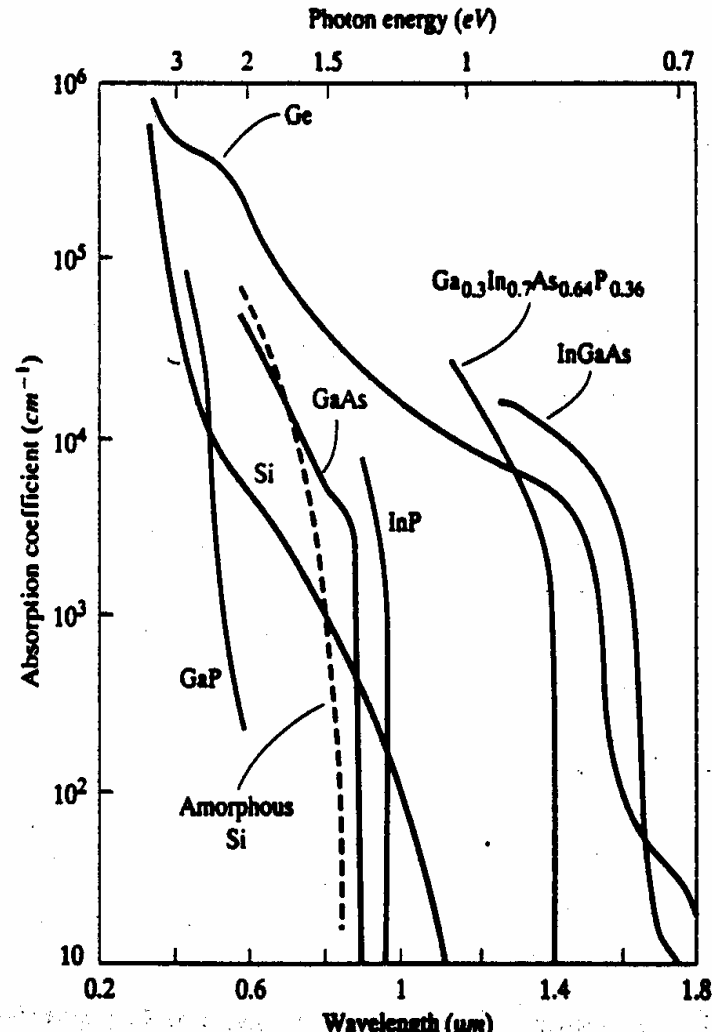**Power Supplies and Voltage Buffers** are good Current Source
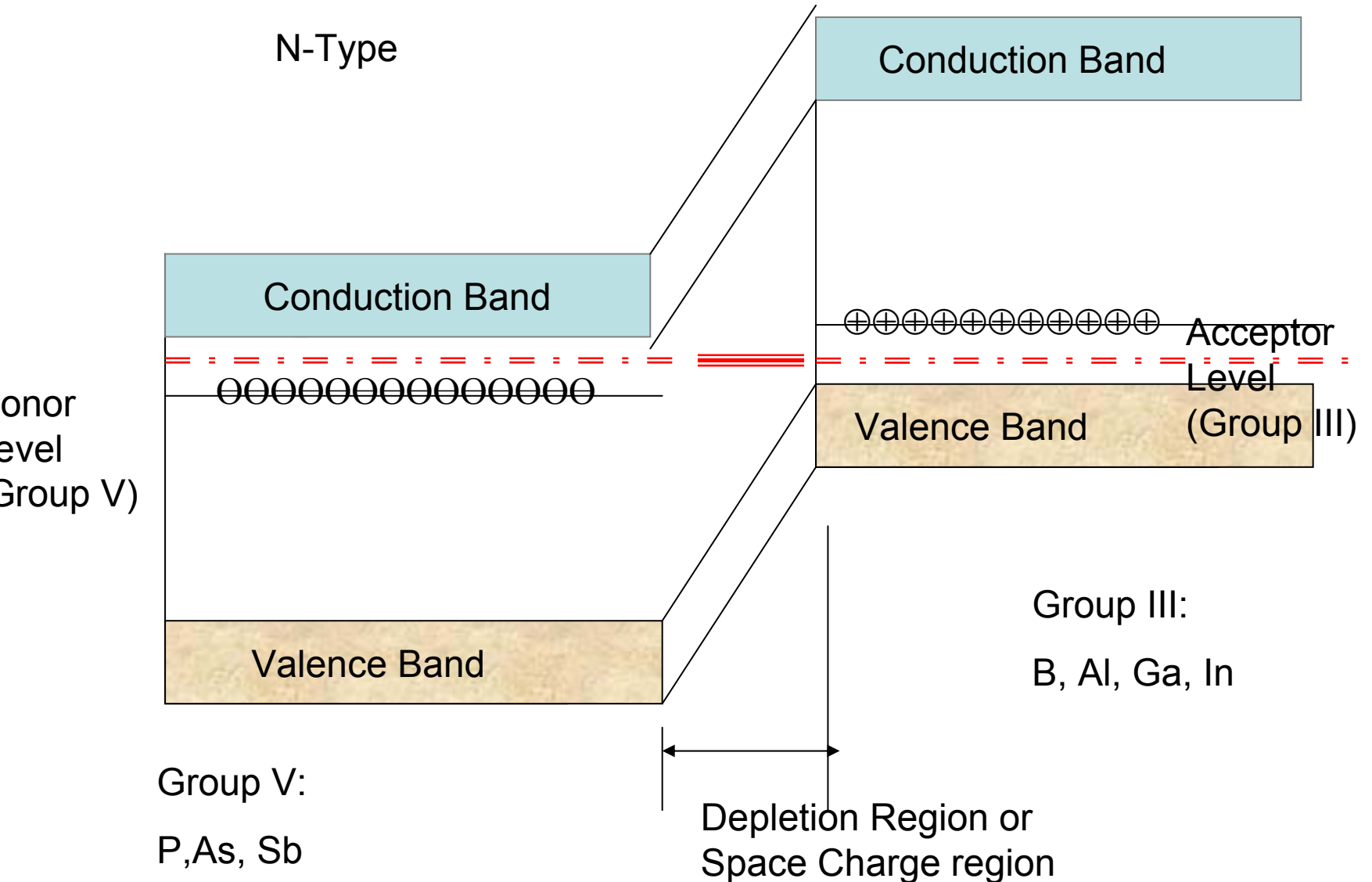
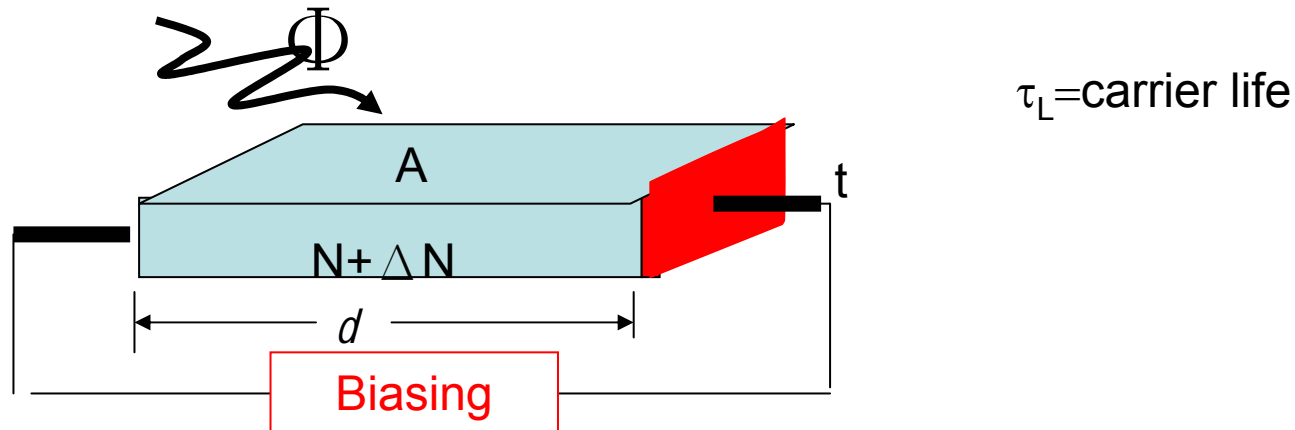# Video CCD Close-up

Simple PC Detector Biasing

Voltage Biasing

Absorption Coefficients vs. λ

Semi-Conductor P and N types

N-Type

Conduction Band

Conduction Band

⊕⊕⊕⊕⊕⊕⊕⊕⊕⊕ Acceptor

Level

OOOOOOOOOOOOOOOO

Valence Band   (Group III)

Donor
Level
(Group V)

Valence Band

Group III:

B, Al, Ga, In

Group V:

P,As, Sb

Depletion Region or
Space Charge region

PC Detector Principle

τ_L=carrier life

Photon-induced Charges $\Delta N = \eta \cdot \Phi \tau_L /(A \cdot t)$

Conductivity $\Delta \sigma = q \cdot \Delta N \cdot (\mu_e + \mu_h) \sim \Delta N \sim \Phi$

$R_{det} = 1/(\sigma \cdot A)$

$\Delta R_{det} = -1/(\sigma^2 \cdot A) \cdot \Delta \sigma = -(R_{det}/\sigma) \cdot \Delta \sigma \sim \sim \Phi$

$R_{PC}(A/W_) = \eta (q/h\nu)G$

PC Detector Responsibility

RPC(A/W)= η (q/hν)G=0.8η · λ · G

G: photo-conductive gain =τ · μ · E/d

Where μ= (μ_e + μ_h)

 d=inter-electrode spacing

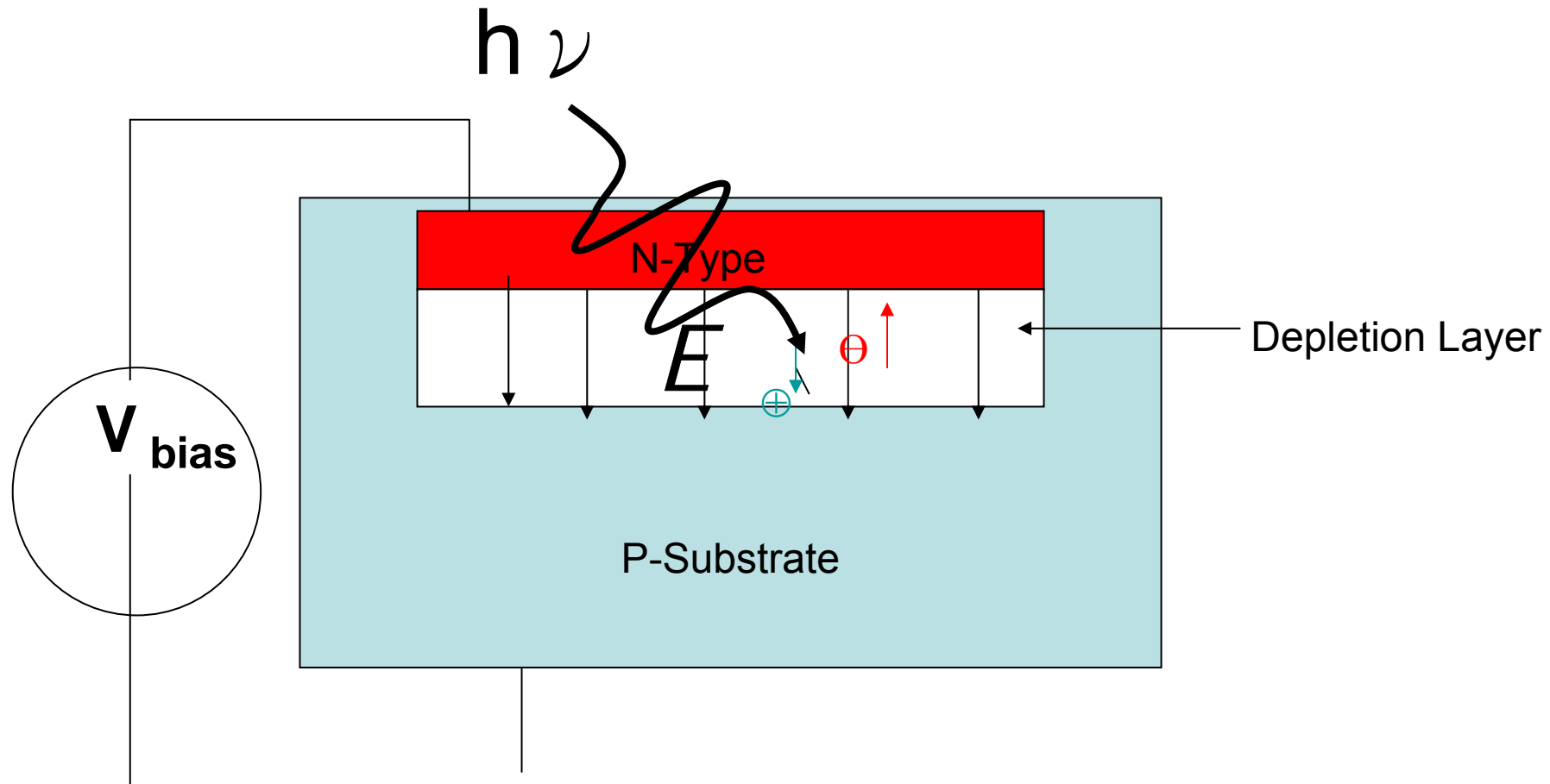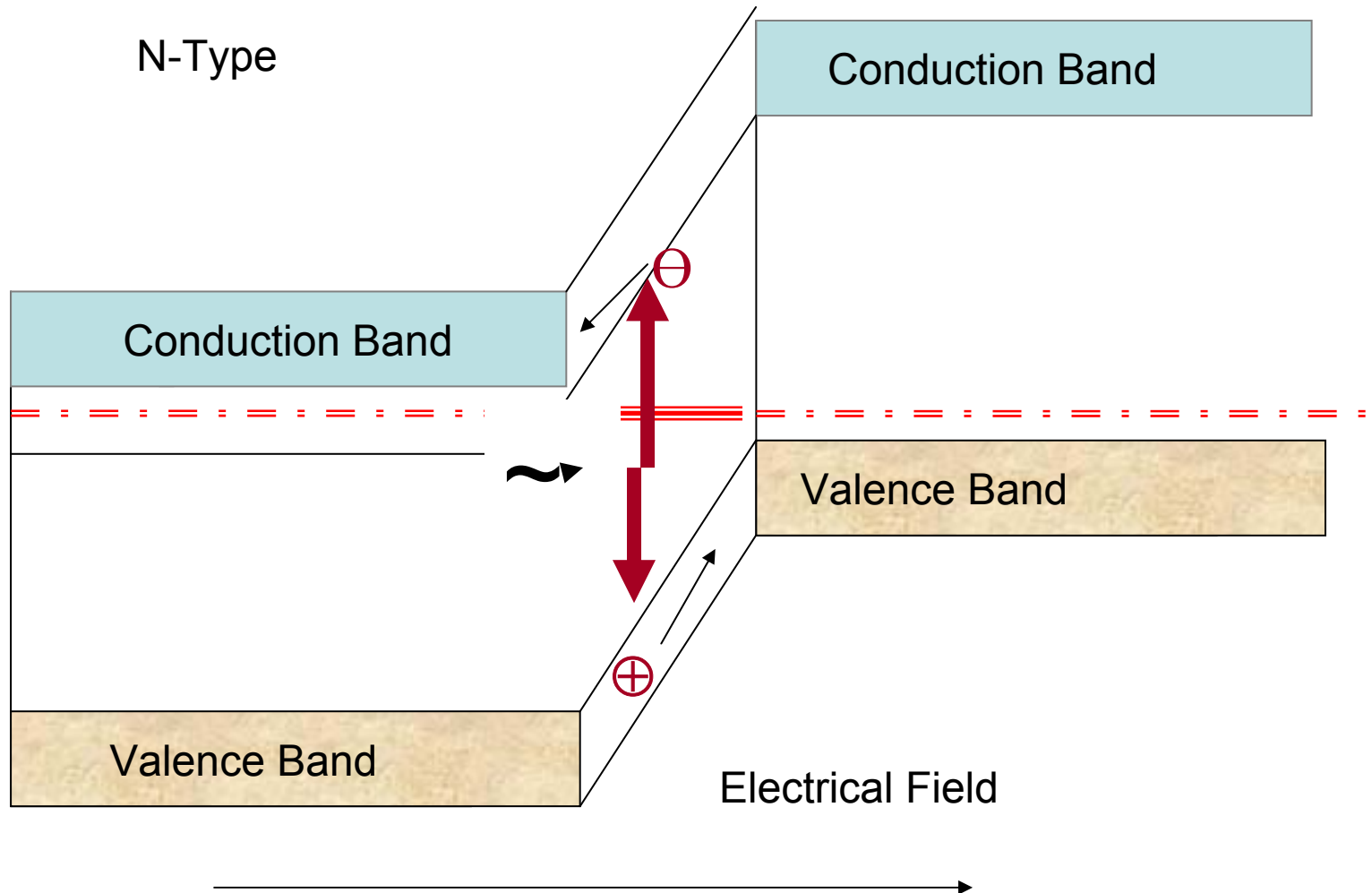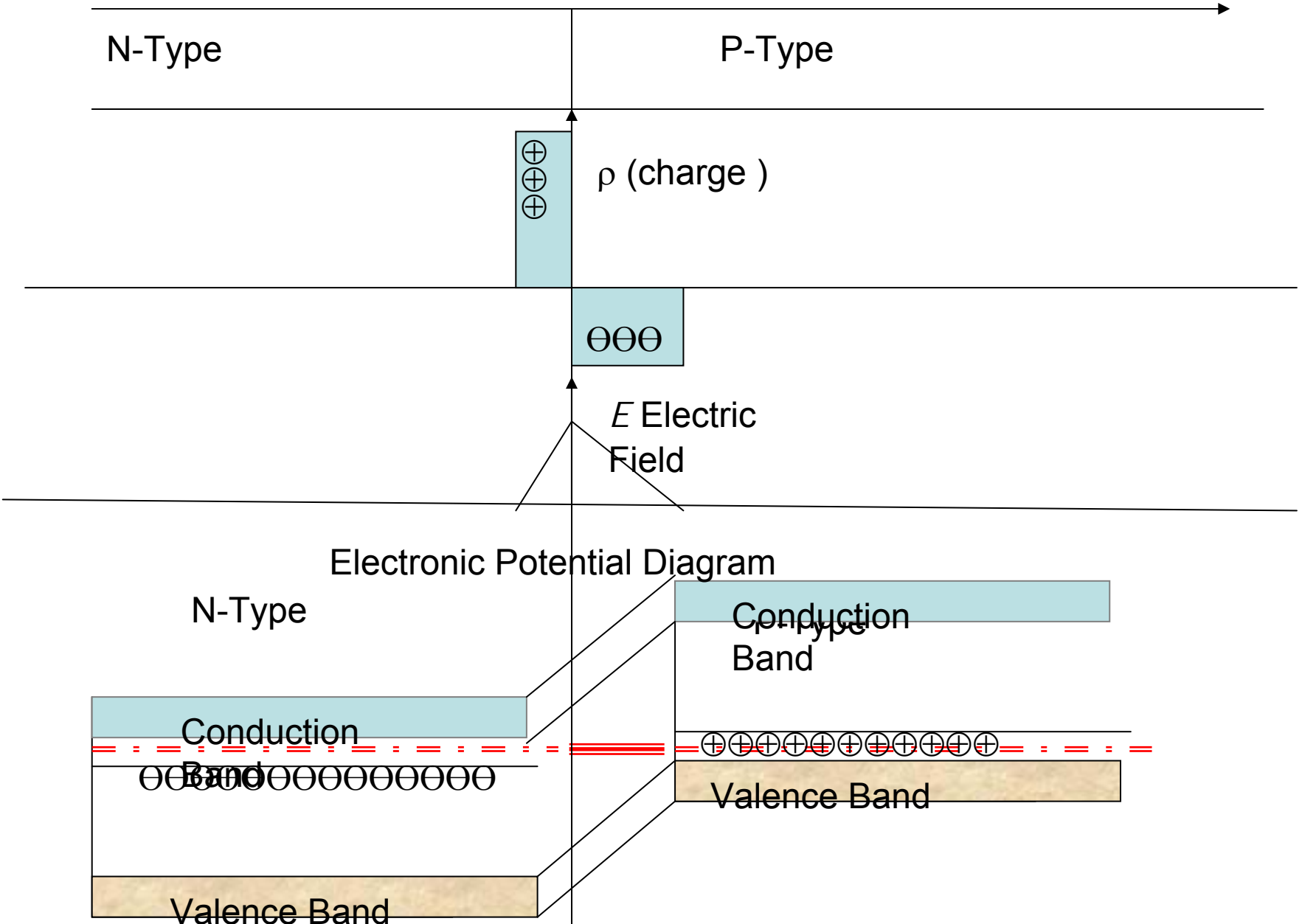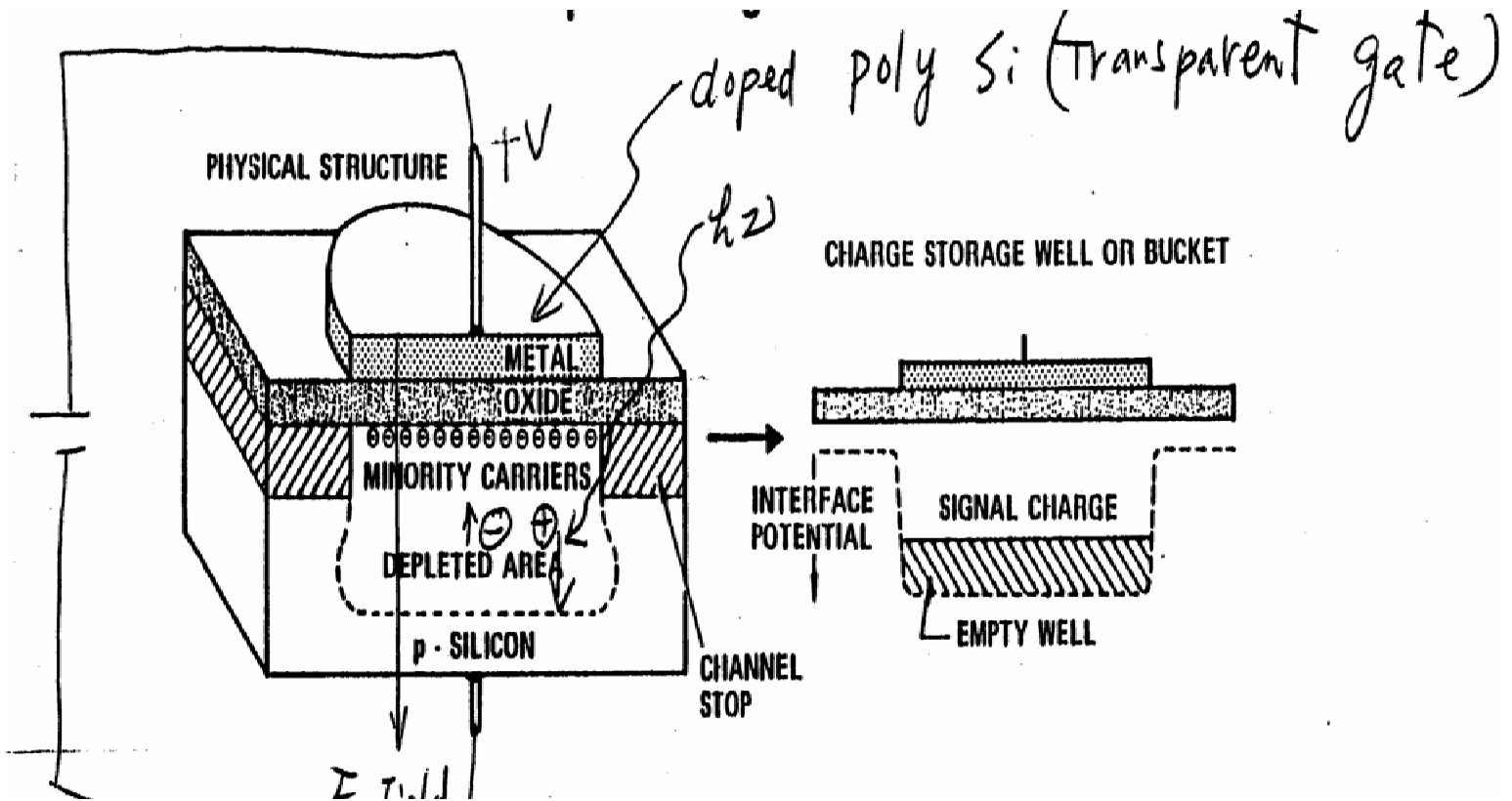G can be greater than unity; a blessing and a curse!

PV Detector Principle

Photo-Voltaic Operation

N-Type

Conduction Band

Conduction Band

Θ

Valence Band

$\sim$

$\oplus$

Valence Band

Electrical Field

Diode Schematics

N-Type

P-Type

$\oplus$
$\oplus$
$\oplus$

ρ (charge)

$\ominus\ominus\ominus$

E Electric
Field

Electronic Potential Diagram

N-Type

P-Type

Conduction
Band

Conduction
Band

$\ominus\ominus$Band$\ominus\ominus\ominus\ominus\ominus\ominus\ominus\ominus\ominus\ominus$

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Valence Band

Valence Band

CCD Storage "Well"

MOS and CCD Representations
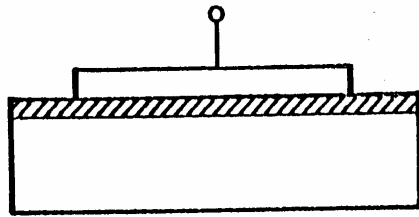
M O S STRUCTURE
(metal oxide semiconductor, silicon)

GATE

SOURCE
DIFFUSION
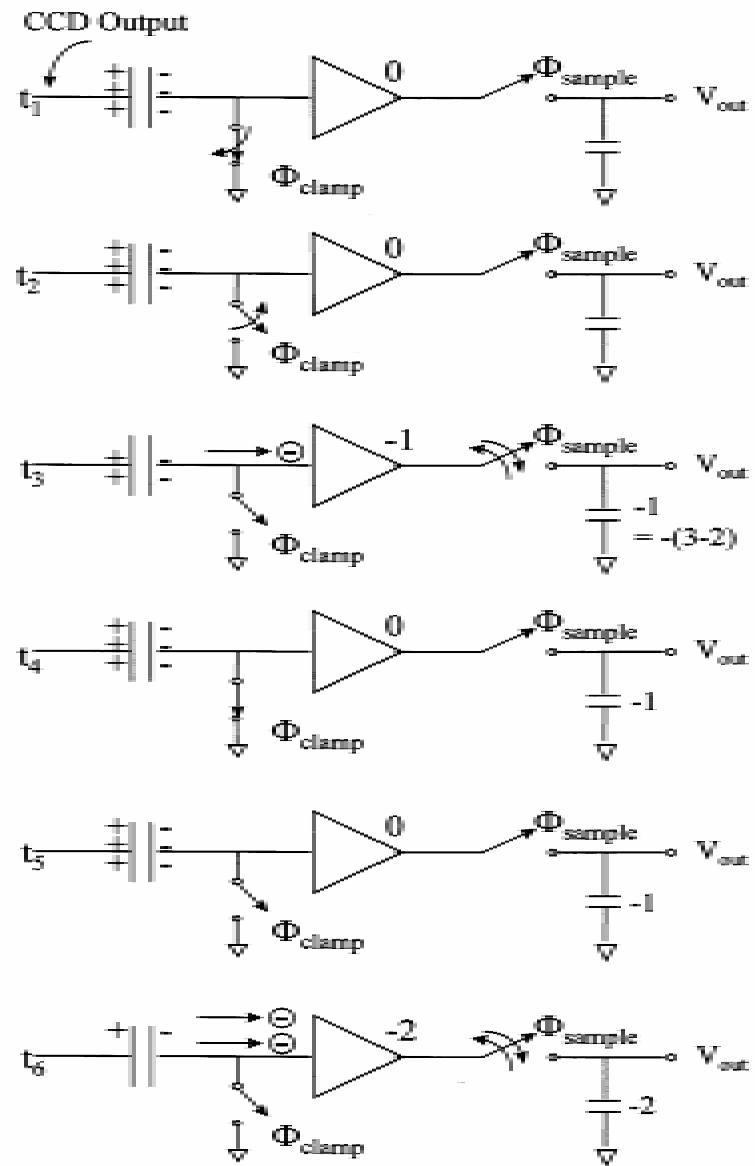
DRAIN
DIFFUSION
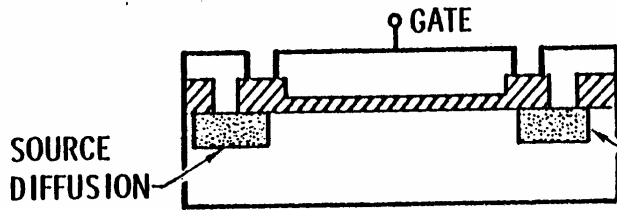
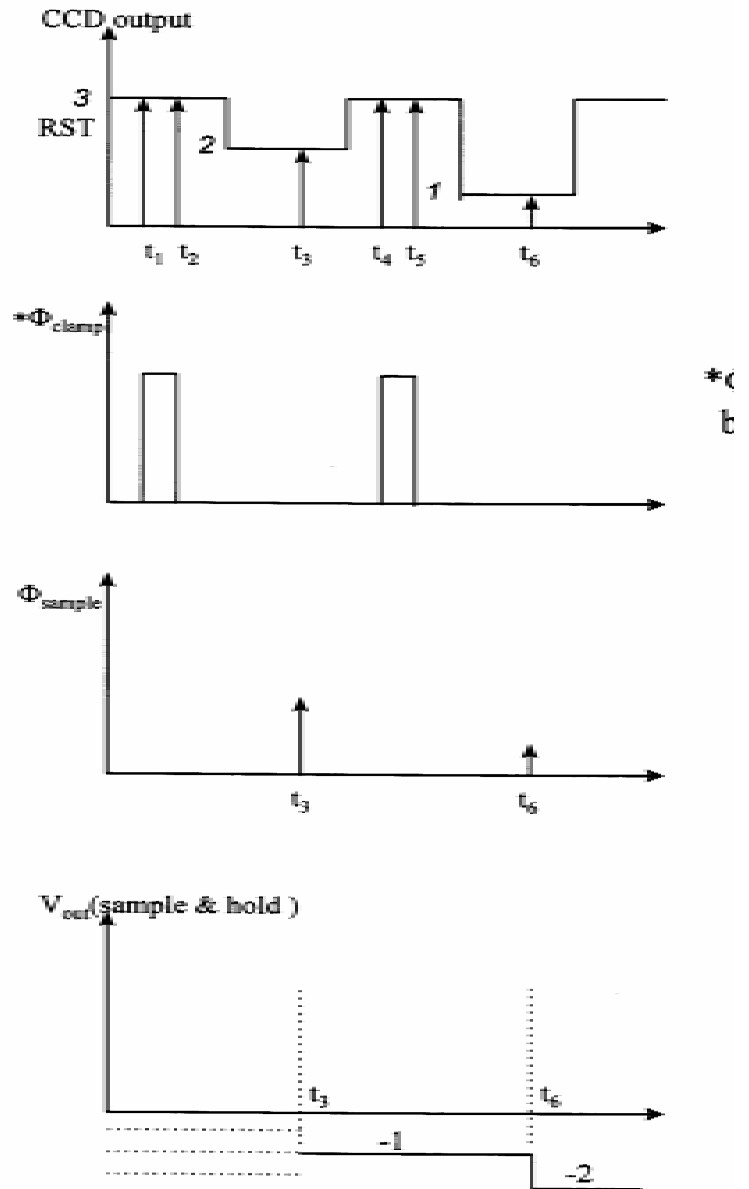BASIC MOST (transistor)
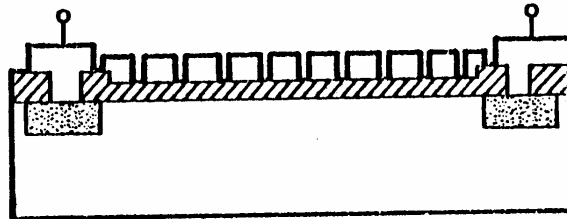
BASIC CCD STRUCTURE
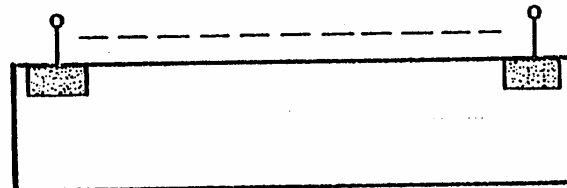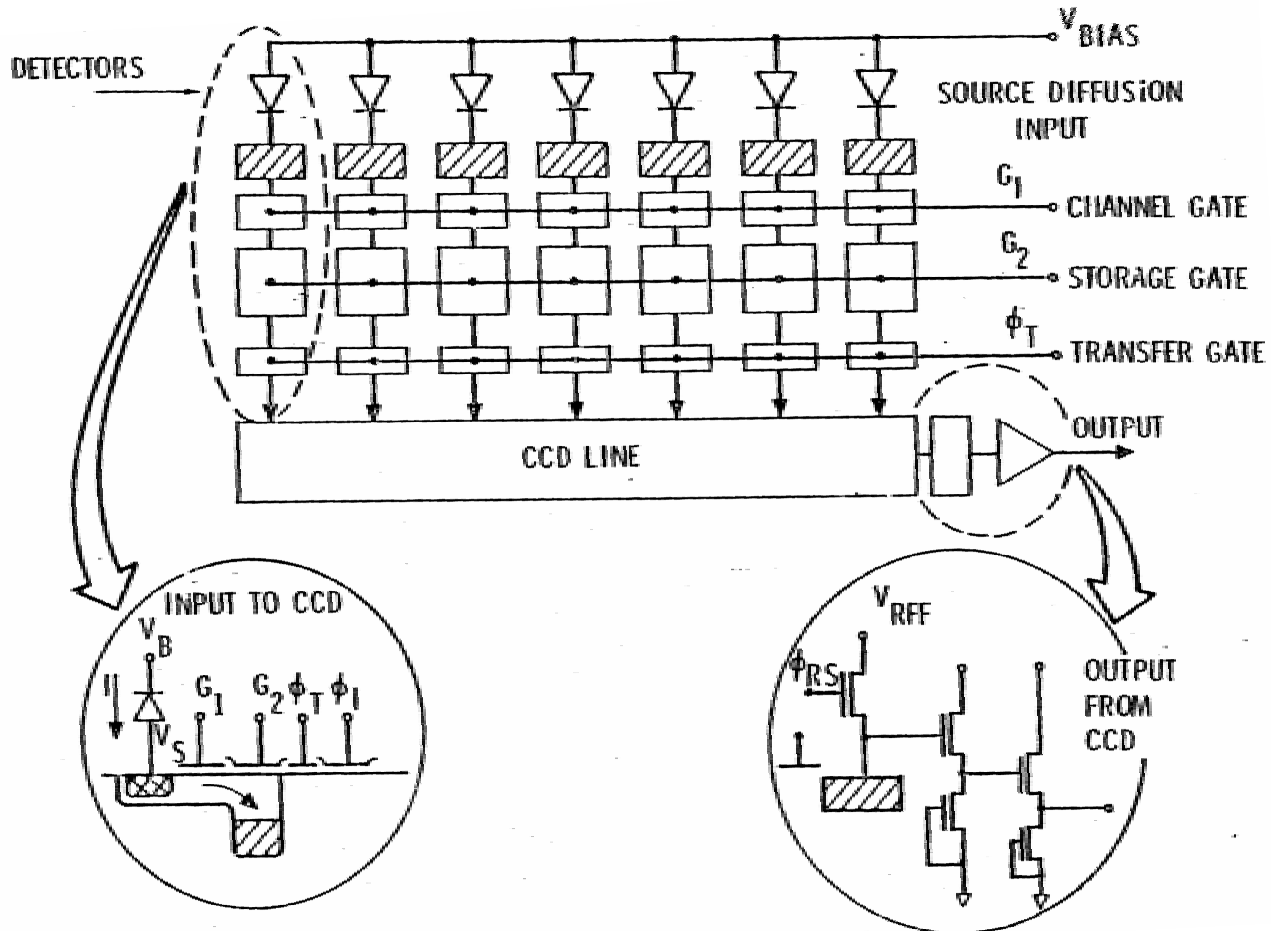
REPRESENTATION OF CCD STRUCTURE

Correlated Double Sampling Sequence

Sample and Hold Timing Diagram

Linear CCD Array

Homework 3

- An IR system has an optical blur function of exp(-ax/2), where a=125 μm, and the detector dimension of 200 μm square.

- 1. Plot both blur functions and the convolution function

- Compute and plot the system MTF. What is the Nyquist MTF?

Hint: MTF of exp(-ax/2) is $[1+(af/f_0)^2]^{-1/2}$