# Sub-millimeter and Millimeter Detection

$0.2\,\text{mm} \lesssim \lambda \lesssim 3\,\text{mm}$

photon detector - nonthermal distribution of excited electrons

thermal detector - excitations from photons have relaxed to a thermal distribution before detection

photon energies $\sim 10\,\text{meV} - 10\,\mu\text{eV}$

Use thermal detectors

Still incoherently measuring incident power

Associated instrumentation is similar to CCD's for (UV, optical, IR), but some material properties make optical elements different (same design principles)

E.g. mirror surface accuracy requirements

scale w/ $\lambda$, so finish can be $\sim \frac{1e^{-3}}{500e^{-9}} \sim 1000\times$ rougher

finely polished, plated glass vs. machined surface

Atmospheric absorption lines are extremely important for ground-based observations

Atmospheric "windows" define commonly used bands

Water, oxygen absorb in these wavelengths

Scale height of atmospheric gases $\sim 8$ km $(1/e)$

Scale height of water $\sim 2$ km

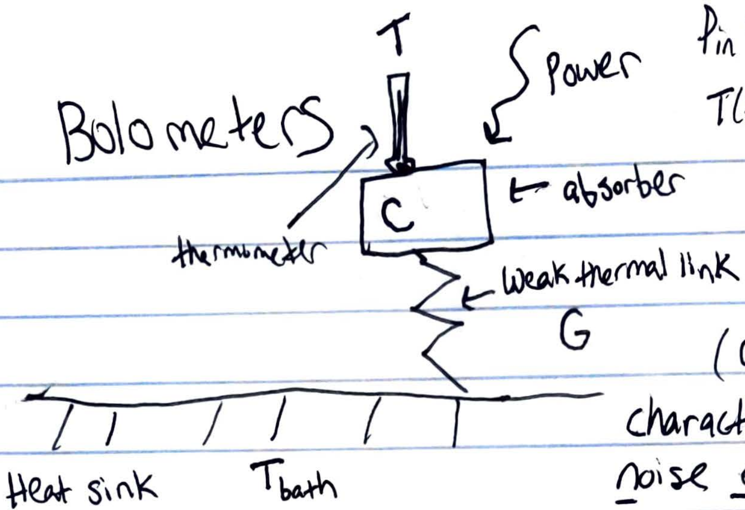
Residual water effects efficiency and noise (sort of like light pollutio

Atmospheric "seeing" is also important

Water is "bright", but sun and moon are dim in mm-wav

Can observe any time weather is good (daytime, full moo

# Bolometers



$G = \frac{dP}{dT}$

$$P_{in} = P_0 + \eta P_1(t) = GT + C\frac{dT}{dt}$$

$$T(t) = \begin{cases} P_0/G, & t<0 \\ P_0/G + \frac{\eta P_1}{G}\left(1-e^{-t/(C/G)}\right) & t \geq 0 \end{cases}$$

Temperature rise $\propto$ incoming power

read out thermometer

(CCDs had signal proportional to # of photons

characterize noise with NEP

noise equivalent power

speed of bolometer response $\tau_{thermal} = \frac{C}{G}$

fundamental noise source $NEP_{\substack{phonon \\ thermal}} = \frac{\sqrt{4KT^2G}}{\eta}$

(fluctuations on thermal link)

NEP: power on detector with S/N of 1 (in 1 Hz bandwidth)

how small of a power can you detect (lower is good)

$NEP_{thermal} \propto T, \sqrt{G}$ want it to be cold, with a very weak thermal link

little G slows down detector, and can cause it to "saturate," so need to carefully tune parameters

also $NEP_{photon} = \frac{hc}{\lambda}\left(\frac{2\phi}{\eta}\right)^{1/2}$ ($\phi$ = photons/s) (noise $\propto \sqrt{N}$)

Detector is sensitive to all incident power, including atmosphere, optics, etc, so have to carefully filter for desired signal, and keep instrument as cold as possible (blackbody radia

Want photon-noise limited performance ($NEP_{photon} > NEP_{phonon}$)

(ideally almost all signal-photons contributing to $NEP_{photon}$)

From best ground sites, need T ~ 300 mK

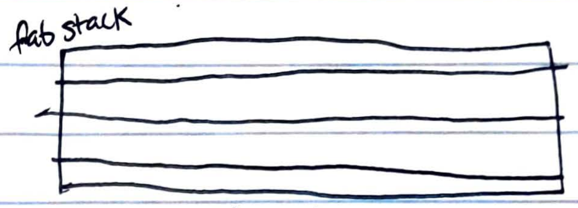
From balloons and space, need T ~ 100 mK

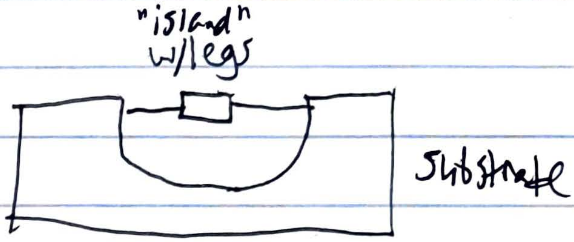
Bolometer structure is created w/ "silicon micromachining"

~ < 1 mm pixel dimension

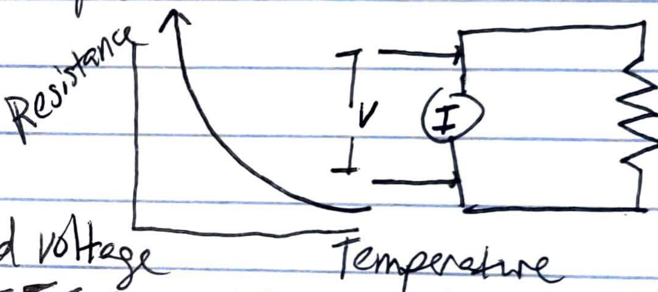
"nano microfabrication"

<u>photolithography</u>





How to read out temperature?



use doped silicon

- strong R vs T
- bias w/ current and read voltage
- use a JFET or MOSFET amplifier, to amplify voltages
- make resistance high (high-impedance amplifiers)

used on Herschel / PACS (2048-pixel array)

$P_{bias}$ electrical power to measure resistance

current bias: constant current

$P_{bias} = I_{bias}^2 R$, $V = I_{bias} \cdot R$

dR/dT is <u>negative</u>

incoming Power ⟹ T ↑, R ↓, and $P_{bias}$ ↓

$P_{opt}$ ↑, $P_{bias}$ ↓ <u>negative</u> feedback

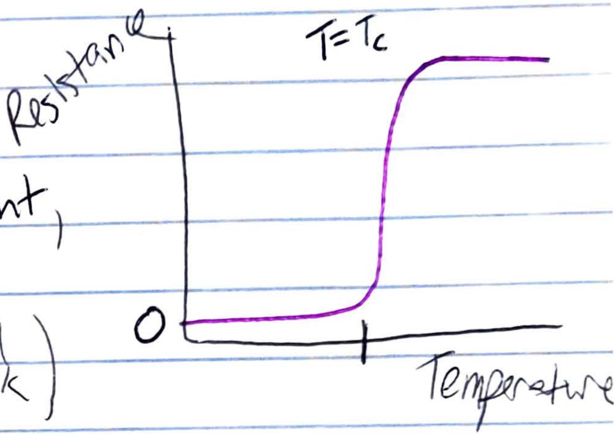
<u>electrothermal feedback</u>

dR/dT sets <u>strength</u> of feedback

want high dR/dT for strong feedback

strongest known temperature dependence is in superconducting transition

$dR/dT > 0$



If biased with constant current, feedback is positive, unstable (w/o external feedback)

Need to cool to superconductor's critical temp, but already driven to low temp by fundamental noise sources

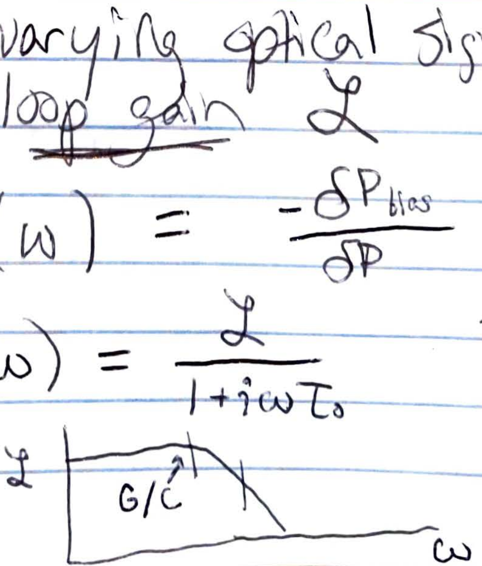
To get negative electrothermal feedback, need to voltage bias (easier said than done)

$$P_b = \frac{V_b^2}{R} \qquad \frac{dP_b}{dT} = -\frac{V_b^2}{R^2}\frac{dR}{dT} < 0$$

With time-varying optical signal $\delta P_{opt} e^{i\omega t}$ define loop gain $\mathcal{L}$

$$\mathcal{L}(\omega) = \frac{-\delta P_{bias}}{\delta P}$$

$$\mathcal{L}(\omega) = \frac{\mathcal{L}}{1+i\omega\tau_0} \qquad \tau_0 = C/G$$



Actually measuring current I
responsivity is $S_I = \frac{dI}{dP_{opt}}$

$$S_I = -\frac{1}{V_{bias}} \frac{\mathcal{L}}{\mathcal{L}+1} \frac{1}{1+i\omega\tau} \Rightarrow -\frac{1}{V_b} \quad (\mathcal{L} \gg 1)$$

$$\tau = -\frac{\tau_0}{\mathcal{L}+1}$$

Achievable $\mathcal{L}$ set by $\frac{dR}{dT}$

$\mathcal{L} \gg 1$ only possible w/ superconducting transition (TES)
negative electrothermal feedback w/ $\mathcal{L} \gg 1$
only possible w/ voltage-biased superconducting transition

want linear responsivity, independent of
$P_{opt}$, $T_{bath}$

How to read out current? R ~ few ohms, at most
- need a low impedence amplifier

breakthrough in TES usability w/ use of SQUIDS
Superconducting Quantum Interference Devices
extrememely sensitive magnetometers
Josephson junction: insulator separating two superconductors
superconducting Cooper pairs of electrons tunnel through
SQUID: two JJ's in superconducting loop
amount of flux in loop is quantized
develops a voltage proportional to flux (induced by I)
read out voltage w/ good amplifier