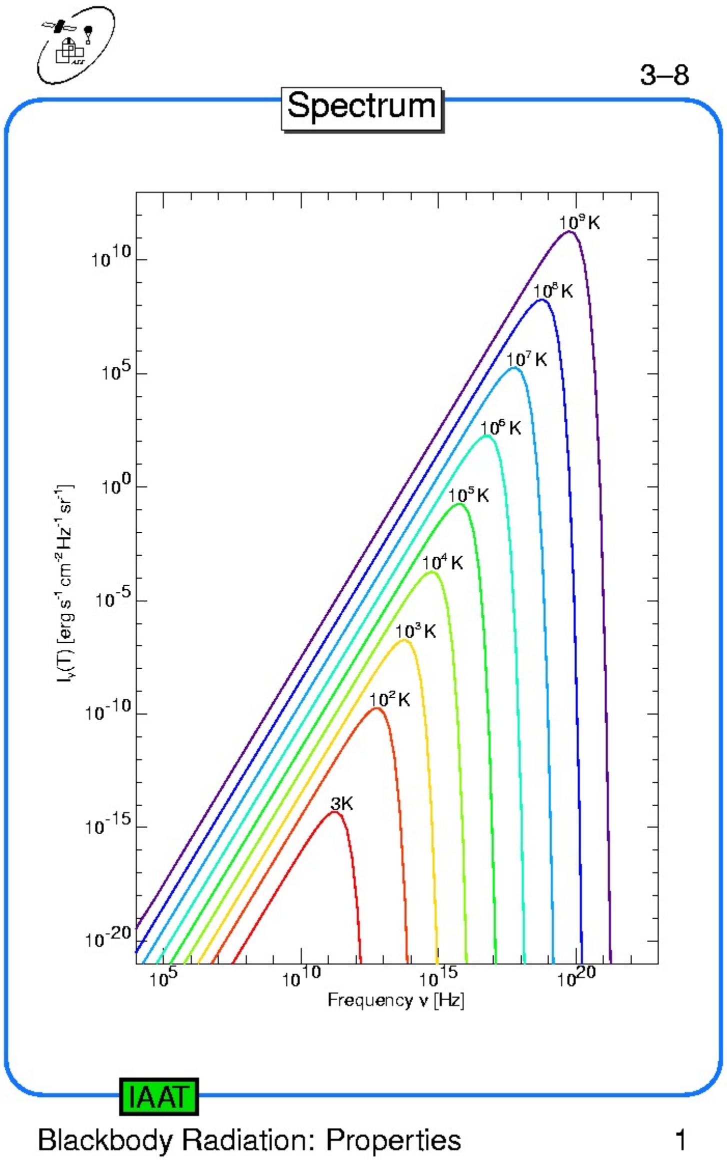
MAS836 – Sensor Technologies for Interactive Environments

Lecture 11 – Temperature and Acoustic Sensing

Temperature Measurements

- Read Fraden, Ch. 11, Ch. 16, Ch. 13 (II Ed.)
- Most materials exhibit a temperature effect
  - Mechanical or electrical or radiative
- Contact and noncontact (remote) temperature measurements

Blackbody Radiation

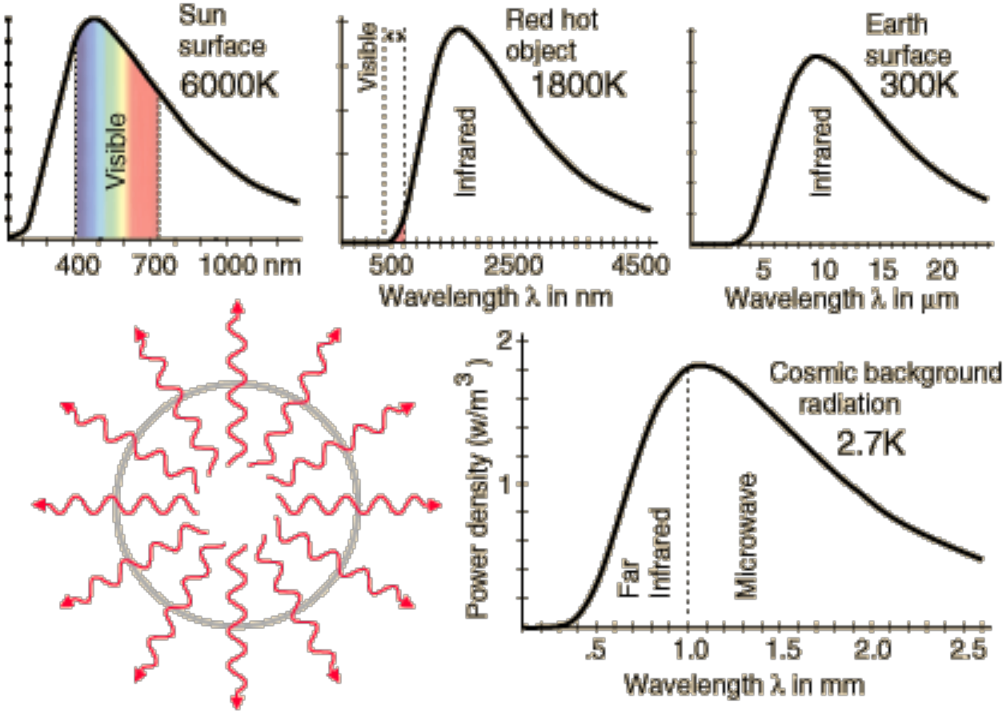


3–8

Spectrum

IAAT

Blackbody Radiation: Properties 1



From Planck – sum of oscillators

Pyroelectricity

Some piezoelectric materials are pyroelectric

Heat flux deforms crystal & creates charge

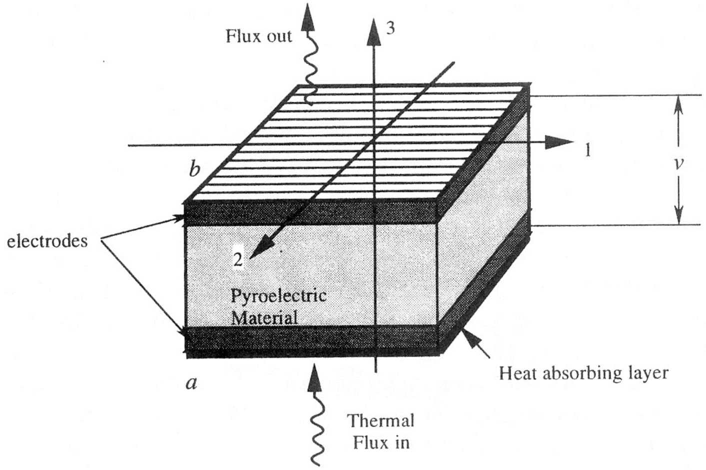
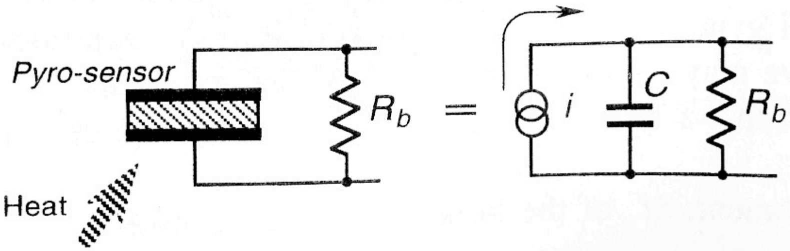


FIGURE 3.26. Pyroelectric sensor has two electrodes at the opposite sides of the crystal. Thermal radiation is applied along axis 3.

$$P_Q = \frac{dP_s}{dT} \quad \text{Pyroelectric charge coefficient,}$$

$$P_V = \frac{dE}{dT} \quad \text{Pyroelectric voltage coefficient,}$$

$$\Delta V = P_Q \frac{A}{C_e} \Delta T = P_Q \frac{\epsilon_r \cdot \epsilon_0}{h} \Delta T.$$



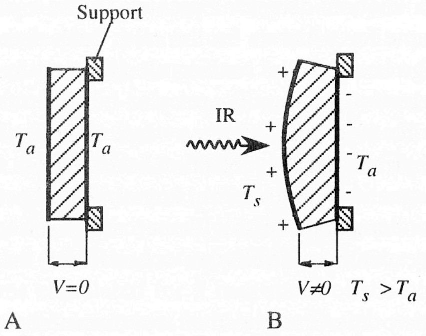


FIGURE 6.14. A simplified model of a pyroelectric effect as a secondary effect of piezoelectricity. Initially, the element has a uniform temperature (A); upon exposure to thermal radiation, its front side expands, causing a stress induced charge (B).

Differential Sensors

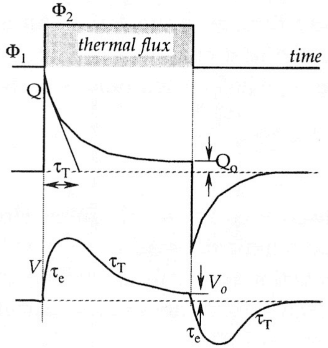


FIGURE 3.29. Response of a pyroelectric sensor to a thermal step function. The magnitudes of charge Q_0 and voltage v_0 are exaggerated for clarity.

$$i = i_0 e^{-t/\tau_T}$$

$$\tau_T = CR = cAhR$$

C = Thermal Capacitance
= cV (heat capacity * volume)
R = Thermal Resistance
= heat loss to environment

9 um PVDF, Lithium Tantalate, etc.

PVDF is pyroelectric in 7-20 um (0-50° C)

Pyroelectric Motion Detectors

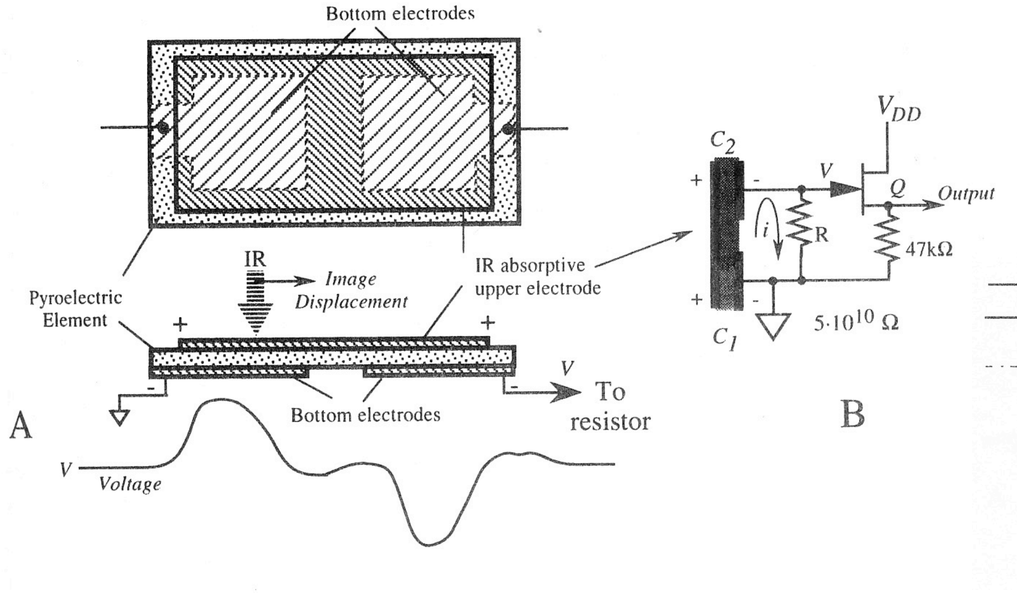


FIGURE 6.15. Dual pyroelectric sensor. A sensing element with a front (upper) electrode and two bottom electrodes deposited on a common crystalline substrate (A). A moving thermal image travels from left part of the sensor to the right generating an alternate voltage across bias resistor, *R* (B).

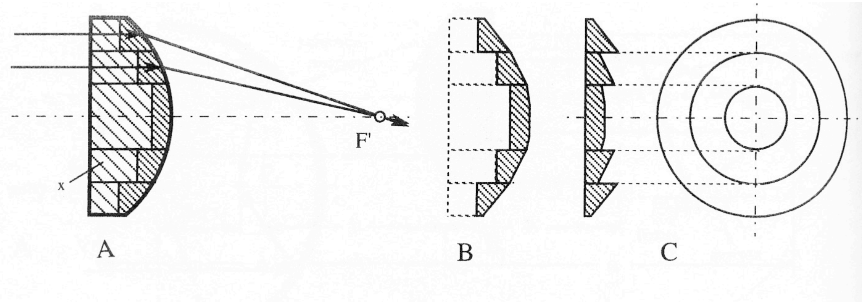


FIGURE 3.61. Concept of a Fresnel lens.

Fresnel lens collapses lens to planar structure
- Index of refraction steps discretized

Lens is thinner - less absorption of deep IR
- Polystyrine, etc.

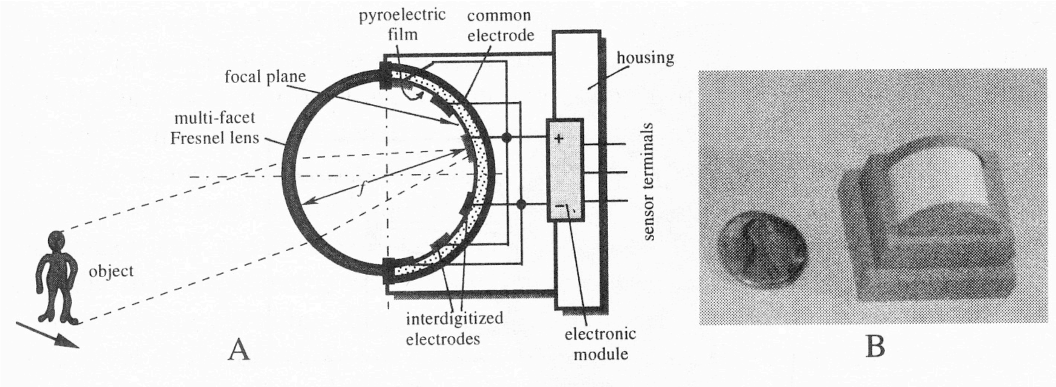
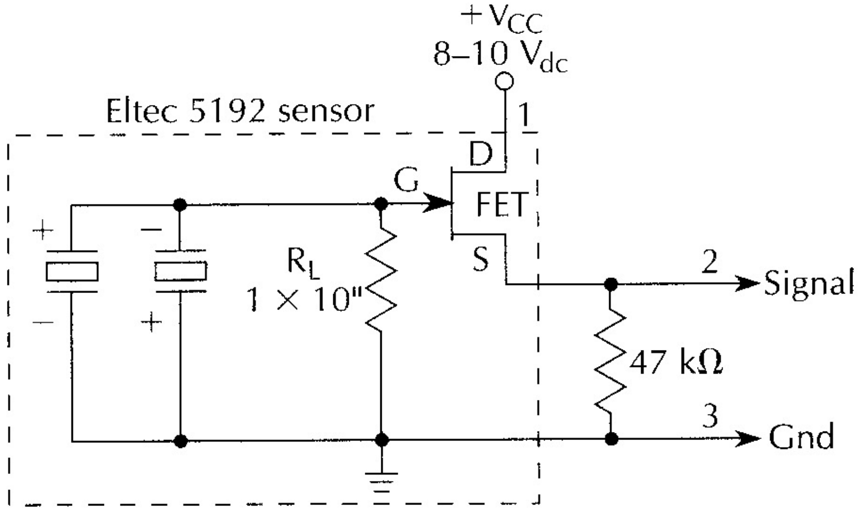


FIGURE 6.16. Far infrared motion detector with a curved Fresnel lens and a pyroelectric PVDF film. A: Internal structure of the sensor; B: external appearance of the sensor.

Pyroelectric Motion Detectors



Another is:
442-3 IR-EYE
or:
PYD 1998

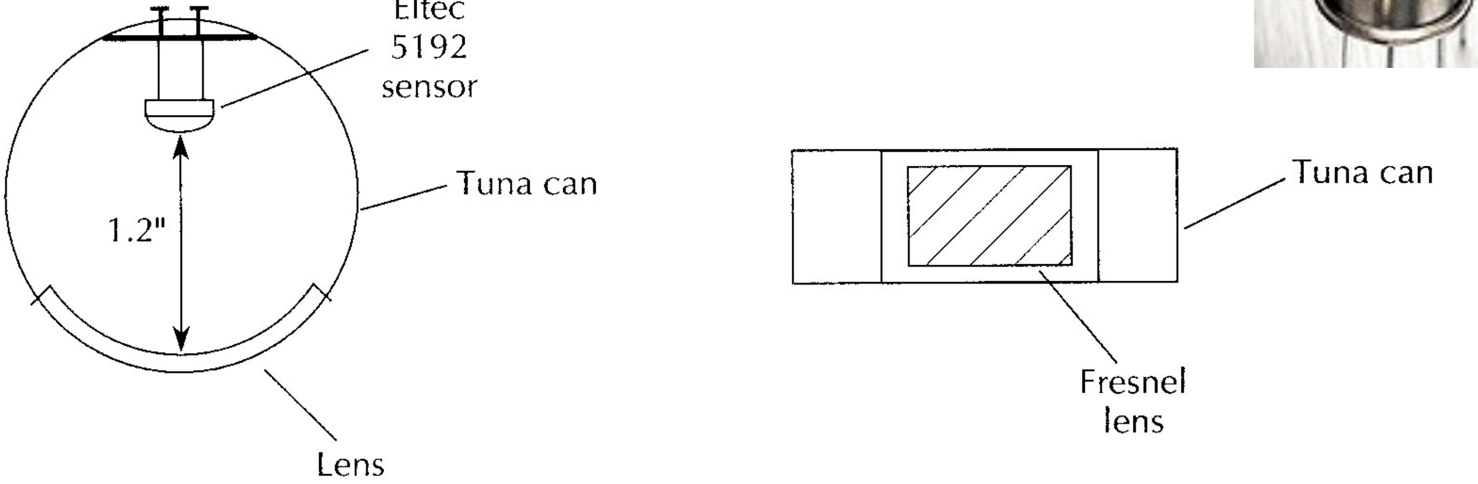


Fig. 8-10 *Pyroelectric sensor tuna-can mount.* (from Petruzelis)

PIR Lens Configurations

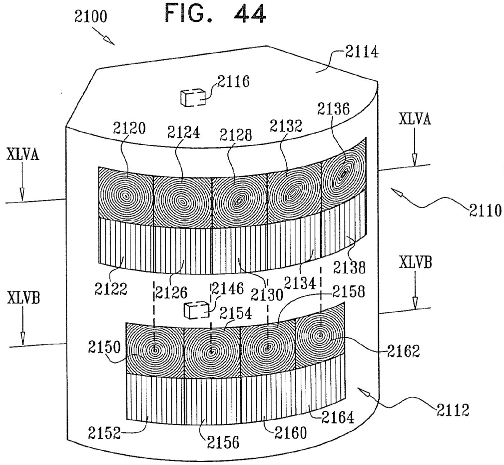


FIG. 44

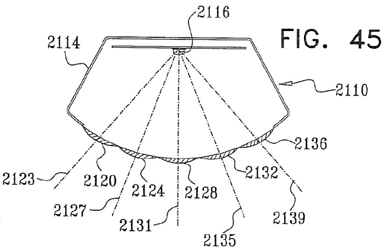


FIG. 45A

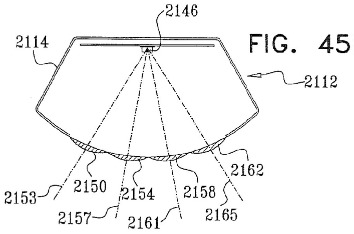


FIG. 45B

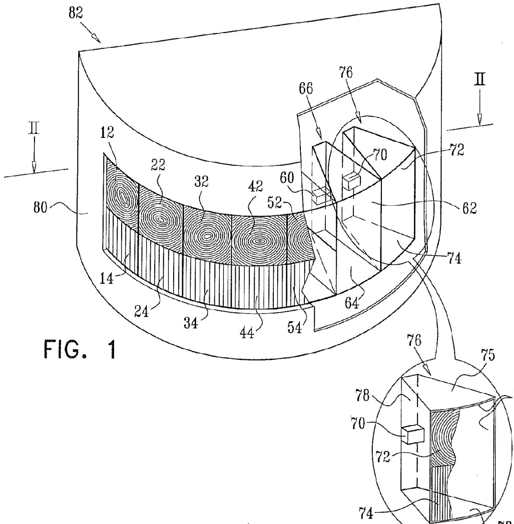


FIG. 1

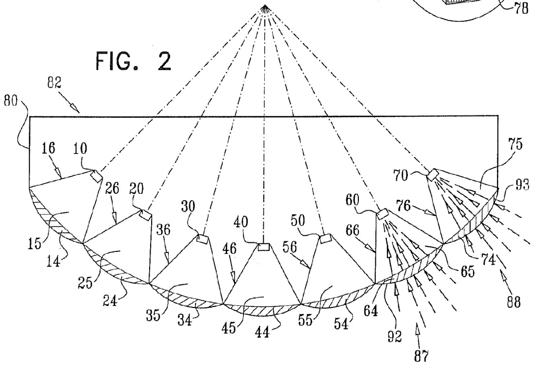


FIG. 2

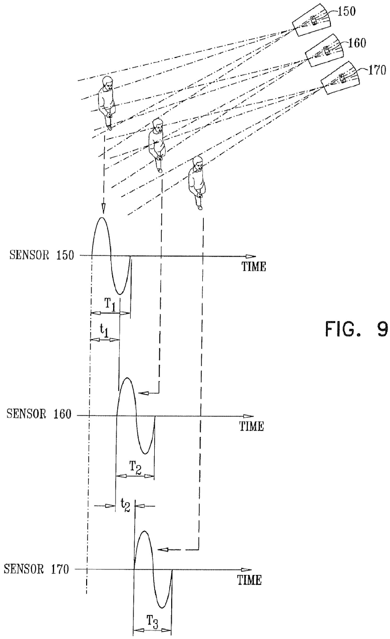


FIG. 9A

Many ‘sweeps’ across adjacent views

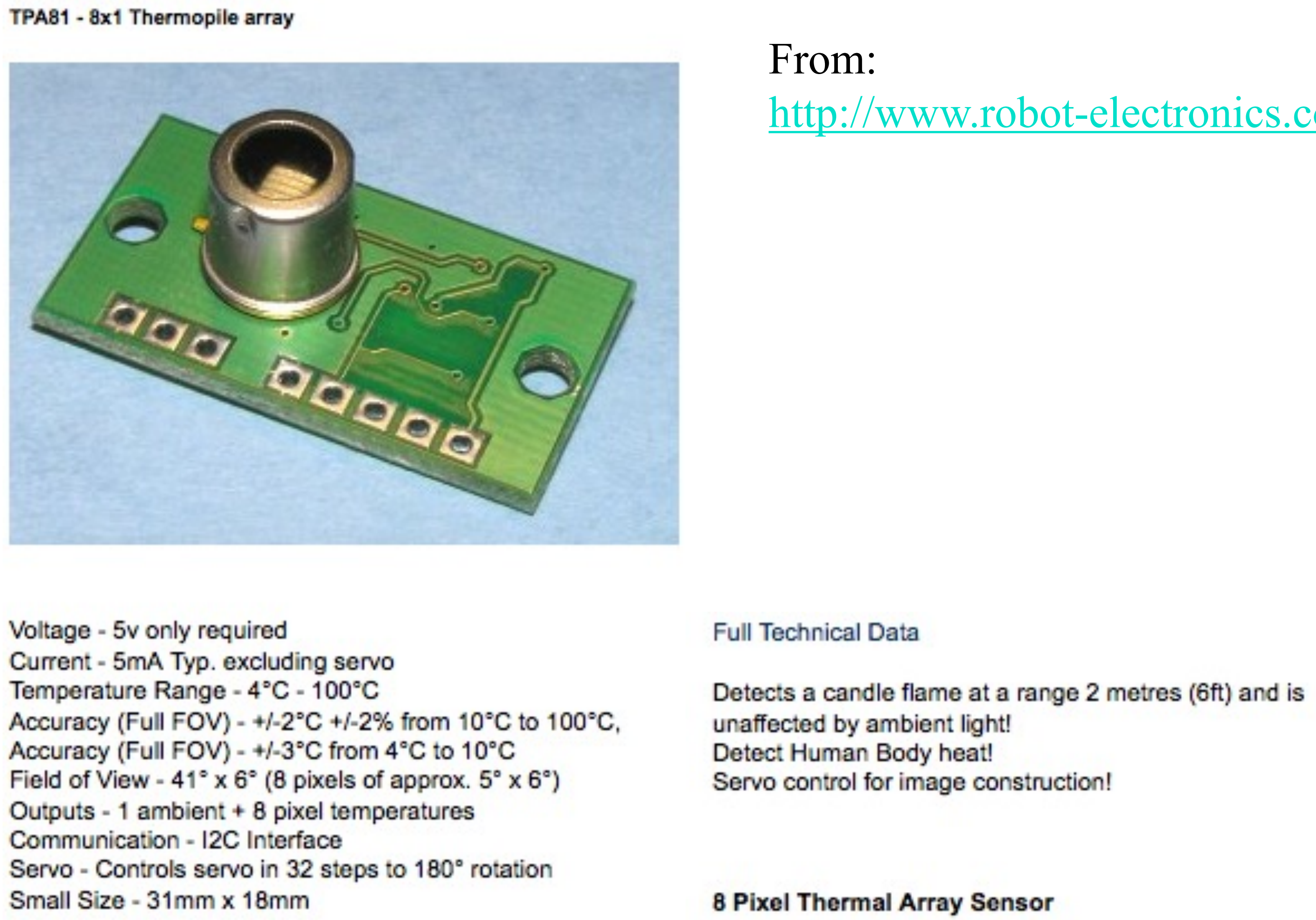
US Patent Application No.: US 2007/0029486A1 Zhevelev et al.

AFIR Detectors

- Project heat source through thermal lens
- Measure current required to keep temperature of heat source stable
- Current will vary with radiation absorption of objects in lens field-of-view
- Impervious to extraneous heat sources...

Pyroelectric Line Array

From:
http://www.robot-electronics.co.uk



TPA81 - 8x1 Thermopile array

Voltage - 5v only required
Current - 5mA Typ. excluding servo
Temperature Range - 4°C - 100°C
Accuracy (Full FOV) - +/-2°C +/-2% from 10°C to 100°C,
Accuracy (Full FOV) - +/-3°C from 4°C to 10°C
Field of View - 41° x 6° (8 pixels of approx. 5° x 6°)
Outputs - 1 ambient + 8 pixel temperatures
Communication - I2C Interface
Servo - Controls servo in 32 steps to 180° rotation
Small Size - 31mm x 18mm

Full Technical Data

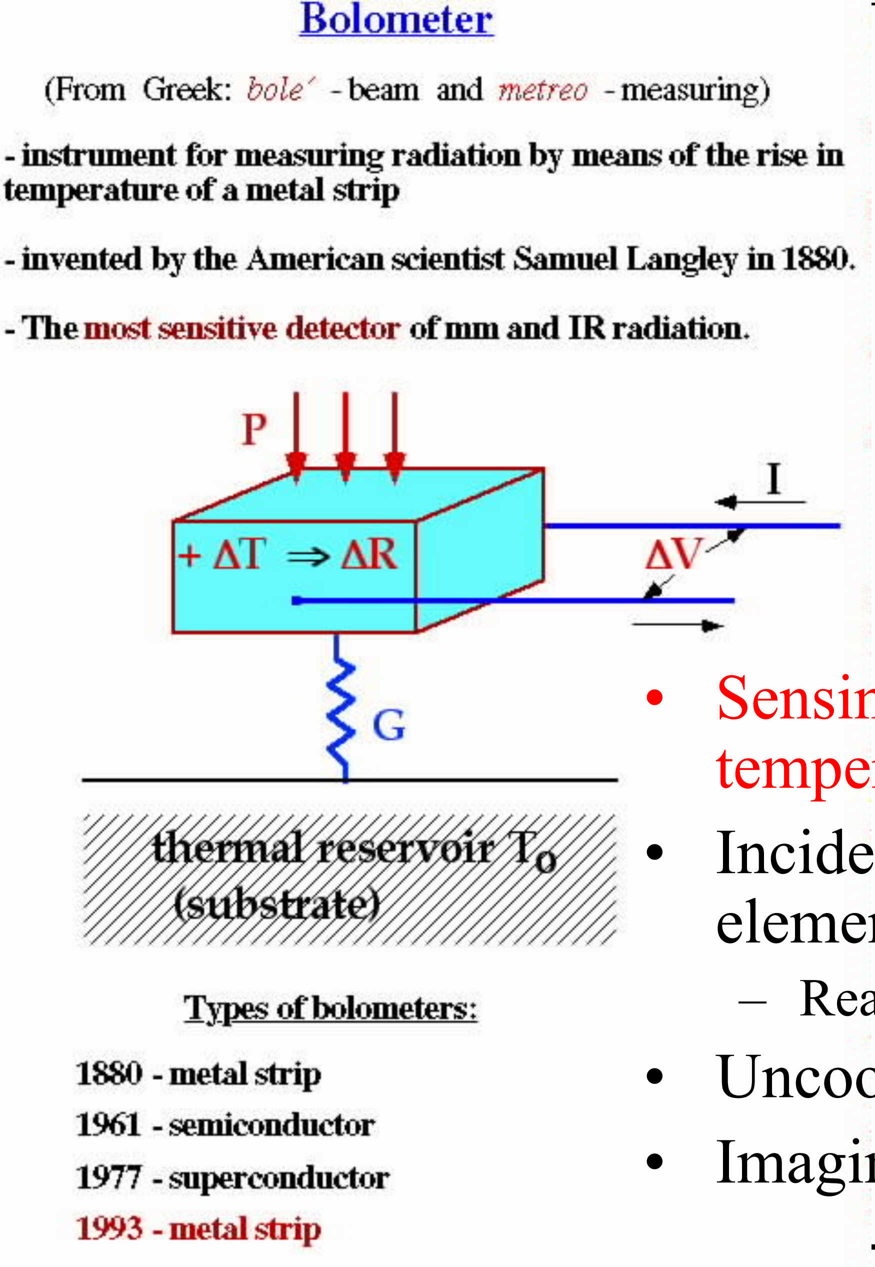
Detects a candle flame at a range 2 metres (6ft) and is unaffected by ambient light!
Detect Human Body heat!
Servo control for image construction!

8 Pixel Thermal Array Sensor

Pyroelectric Videcons

- Thermal imaging cameras
  - Arrays of pyroelectric elements
  - Generally shuttered (look at temp. reference, then look at scene) and/or periodically discharged.
  - Previously most were cooled (w. Peltier devices) to avoid background
  - Limit heat capacity, heat storage in components to increase bandwidth and sensitivity

Bolometer Arrays



Bolometer

(From Greek: *bole´* - beam and *metreo* - measuring)

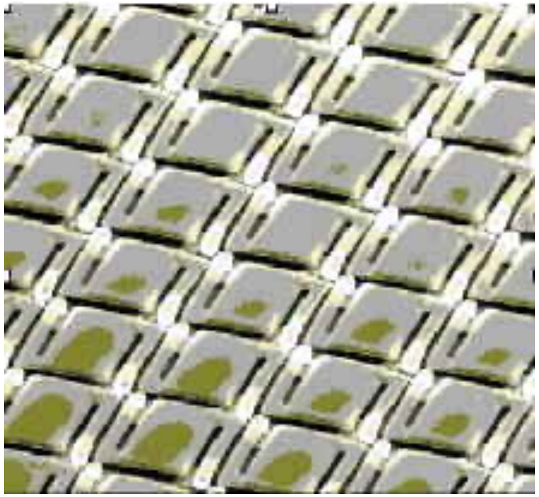
- instrument for measuring radiation by means of the rise in temperature of a metal strip

- invented by the American scientist Samuel Langley in 1880.

- The most sensitive detector of mm and IR radiation.

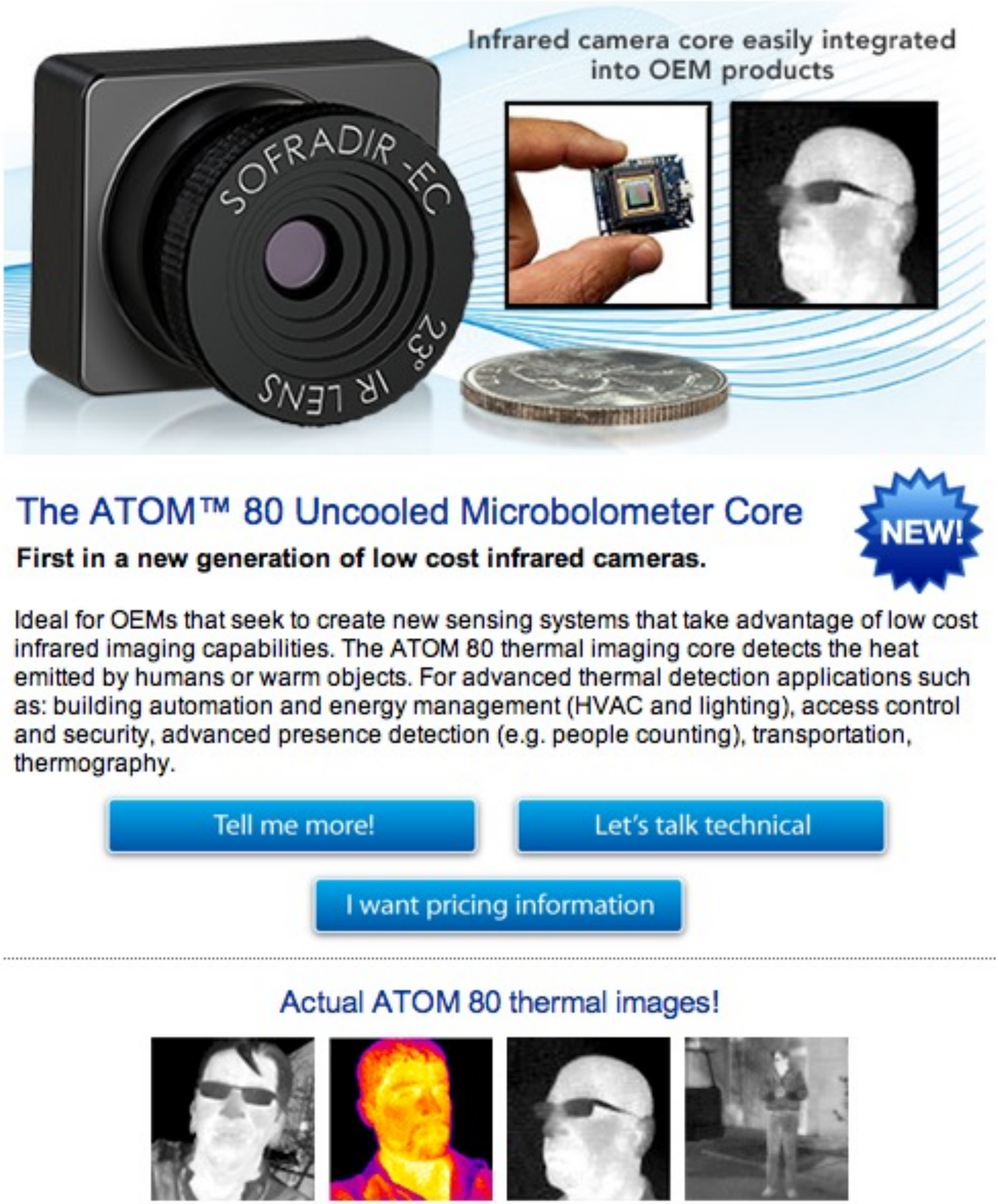
Types of bolometers:

1880 - metal strip
1961 - semiconductor
1977 - superconductor
1993 - metal strip



- Sensing elements change resistance with temperature (phase transition)
- Incident radiation (thermal, RF) heats elements
  - Read out via bridge
- Uncooled devices are now made
- Imaging arrays not too expensive (e.g., $3K)

Smaller, Hotter, Cheaper!



Infrared camera core easily integrated into OEM products

The ATOM™ 80 Uncooled Microbolometer Core

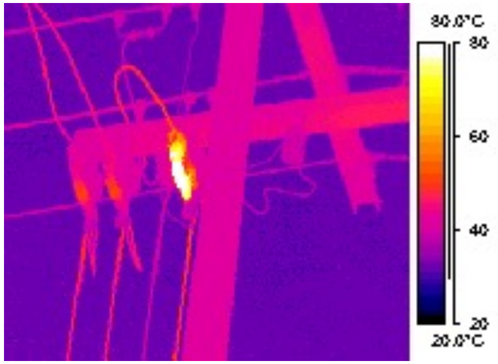
First in a new generation of low cost infrared cameras.

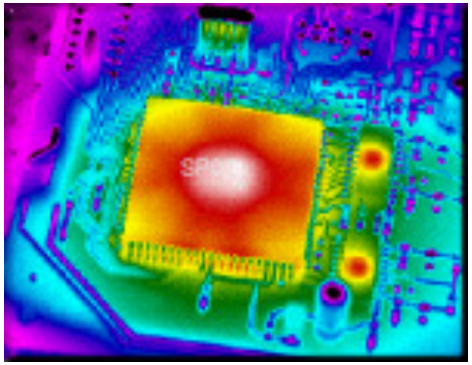
Ideal for OEMs that seek to create new sensing systems that take advantage of low cost infrared imaging capabilities. The ATOM 80 thermal imaging core detects the heat emitted by humans or warm objects. For advanced thermal detection applications such as: building automation and energy management (HVAC and lighting), access control and security, advanced presence detection (e.g. people counting), transportation, thermography.

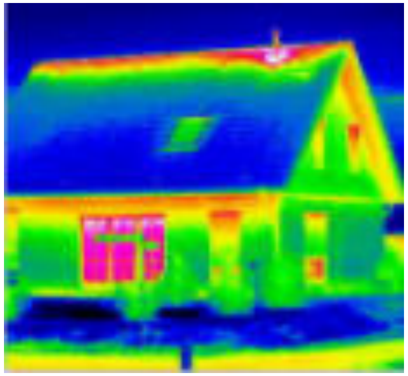
Actual ATOM 80 thermal images!

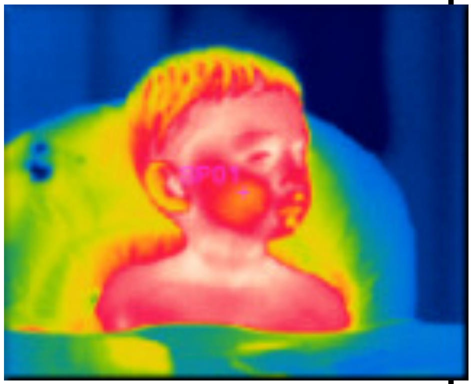
See also FLIR, etc.

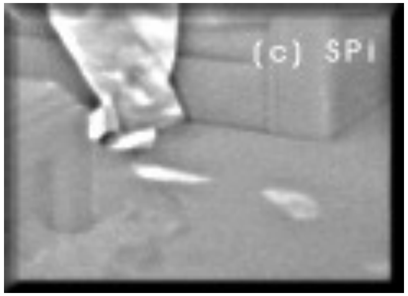
Thermal Imaging



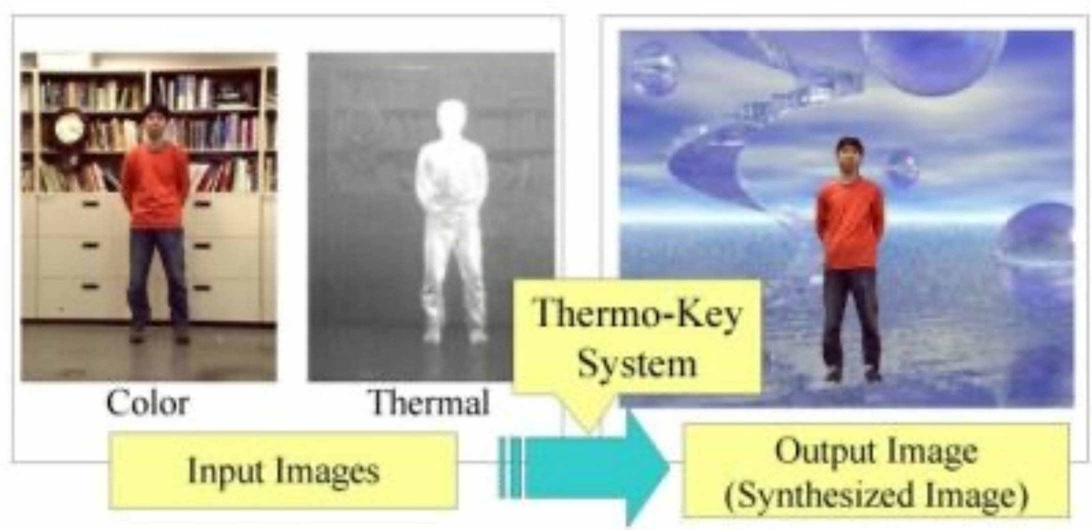








www.x20.org/thermal/

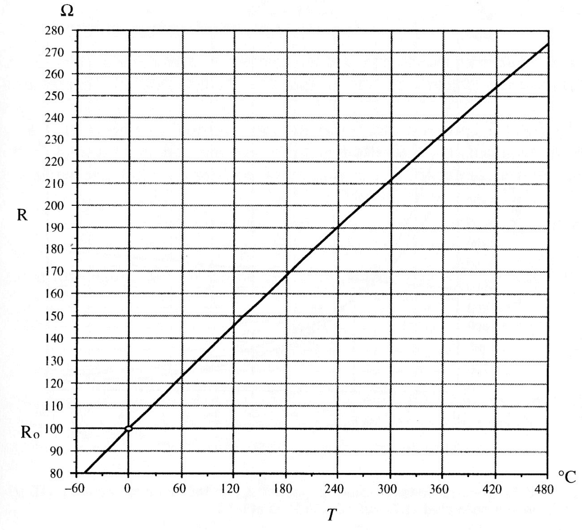


Thermo-Key (U. Tokyo)

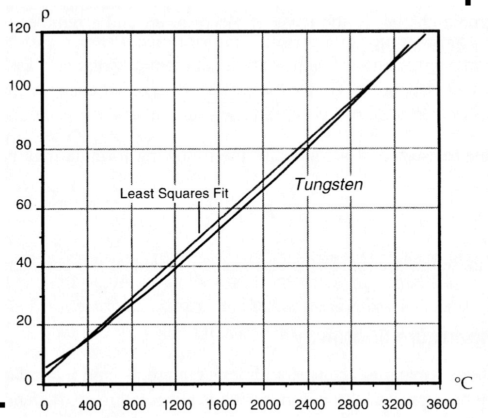
Thermo Resistive Sensors

- Resistance Temperature Detectors (RTD's)
  - Measure resistance of metal wire
    - Metals have Positive temperature coefficients [PTC]
    - Effective over extremes of temperature
  - Platinum most common
    - Nicely linear from -200° C - 630° C
    - $R = R_0(1.0036 + 36.79 \cdot 10^{-4}\, T)$
  - Tungsten is used over 600° C
- Linearized around reference point
- Wirewound devices
  - Tolerances within ± 10 mΩ → ±0.025 ° C
  - Read with constant current (measure voltage)

Platinum



Tungsten



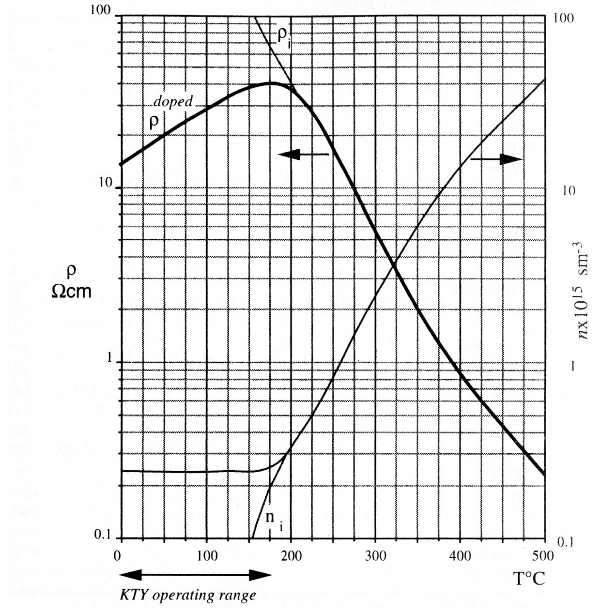


FIGURE 16.3. Resistivity and number of free charge carriers for *n*-doped silicon.

Silicon RTD's

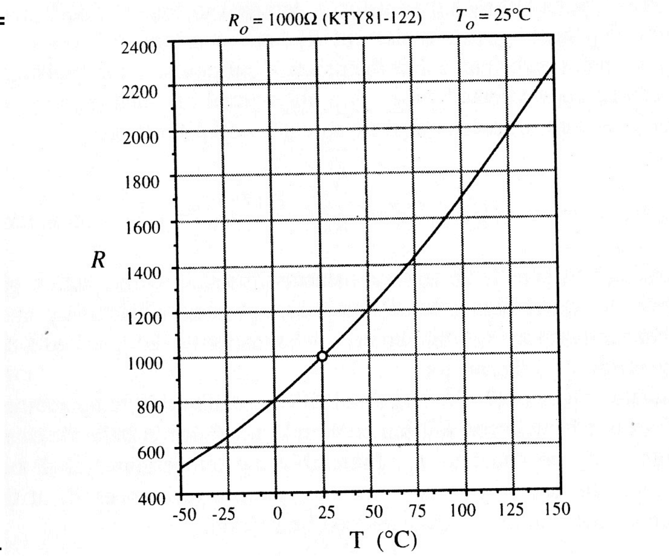


FIGURE 16.4. Transfer function of a KTY silicon temperature sensor.

- Much cheaper, more sensitive than Pt
- Bulk silicon has a negative TC (NTC)
  - Thermal runaway possible with home heating apps
    - Silicon gets hotter, lower resistance, more current, hotter, lower resistance…
  - Can be doped to have PTC in selected region (e.g., <200° C)
    - This can produce a silicon RTD that works between -50° C to 150° C that's stable and delivers 0.7% per ° C
  - Philips KTY Sensors

Thermistors

$$R = R_o e^{-\beta(1/T - 1/T_o)}$$

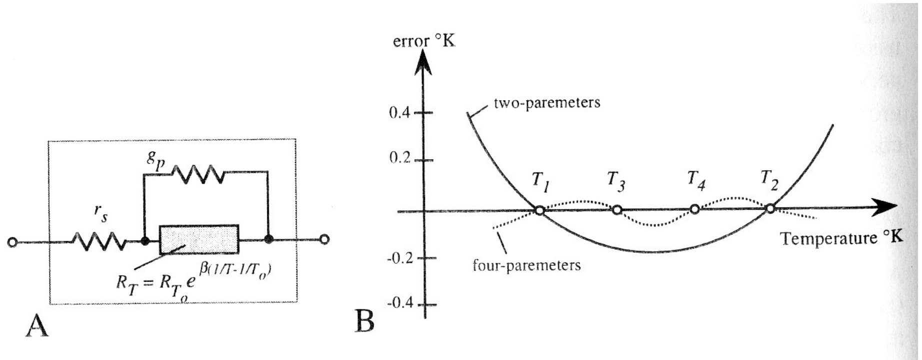


FIGURE 16.5. An equivalent circuit diagram of NTC thermistor (A) and error of a thermistor sensor resulted from use of four- and two-parameter approximations (B).

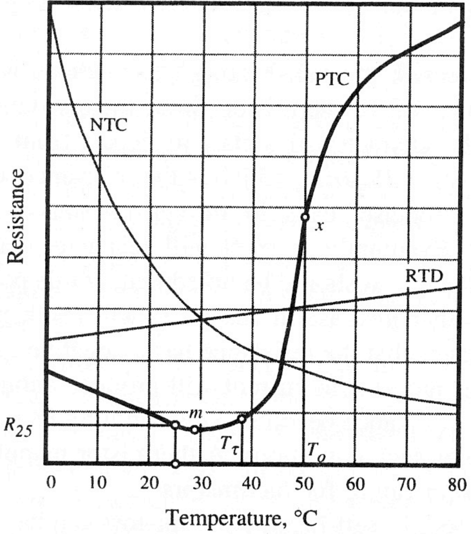


FIGURE 16.10. Transfer functions of PTC and NTC thermistors as compared with RTD.

- Thermistors are temperature-sensitive resistors
  - Compensate thermal effects in analog circuits...
- Metal Oxide Thermistors have NTC
- Much more sensitive than RTD
  - Goes from -8% to -2% per ° C
  - NTC worse for self-heating, runaway problems
    - Depends on airflow…
- Can make PTC thermistors
  - Polycrystalline ceramic (Barium or Strontium Titanate)
  - PTC sensitivity can get to 200% per ° C
    - Narrower range…

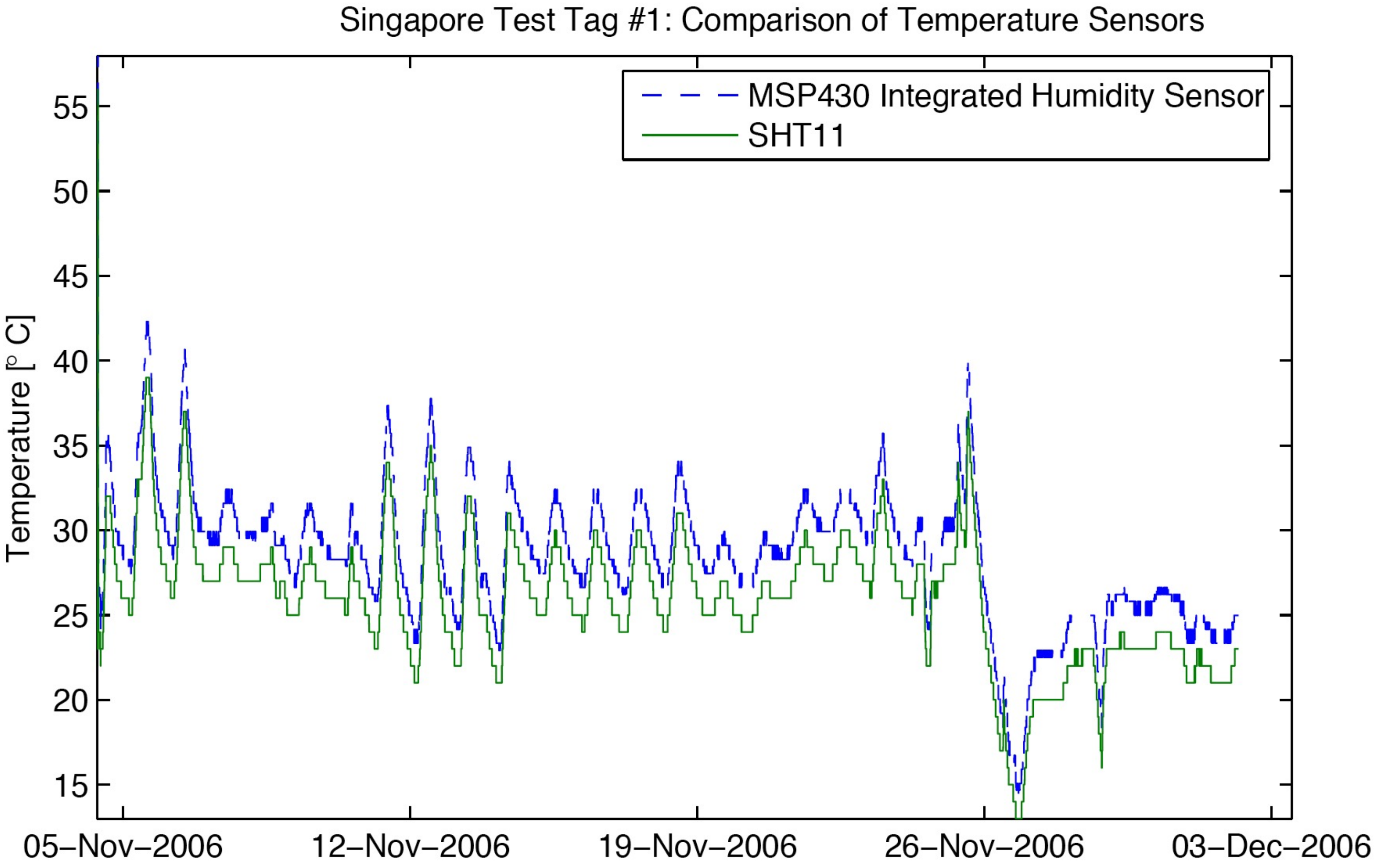
Thermistors can age (chip packaged can degrade at +1% per yr, glass beads much slower)

Semiconductor Junctions

$$I_c = I_o e^{qV_{BE}/2KT}$$

- Every transistor is a temperature sensor
- Most thermometer IC’s exploit this
- Many packages available
  - LM35Z from National
  - AD592 from Analog
  - Dallas Digital TMP series
- Often integrated into microcomputers too
  - Cygnal (Silicon Labs) devices, AD Microconverters

Internal vs. External Sensors



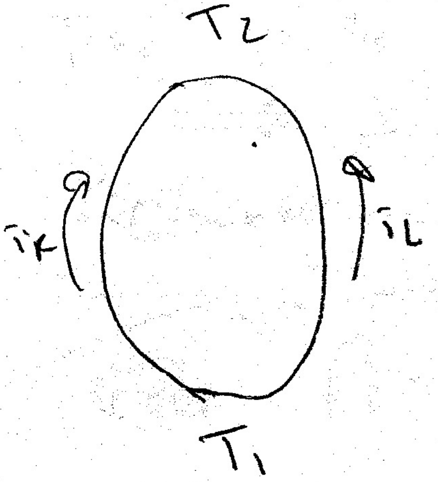
CargoNet Tag - Singapore to Taiwan - Malinowski M.Eng.

Thermocouples

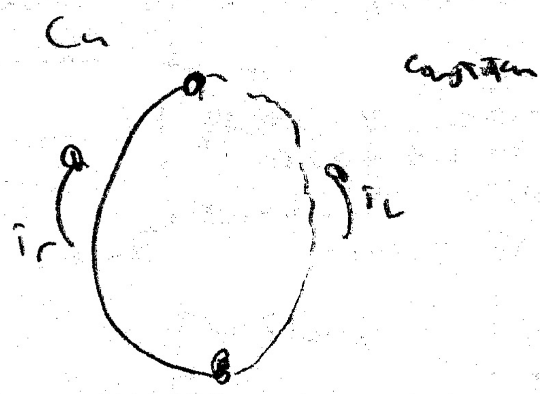
Thompson effect: Thermal gradient set up an electric field inside conductor

$\partial V_a = \alpha_a \partial T$

Seebeck coefficient (prop. of material)

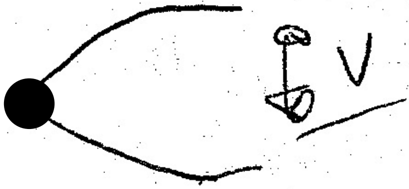


$i_L = i_r \Rightarrow i = 0$



Thermocouple

Cu



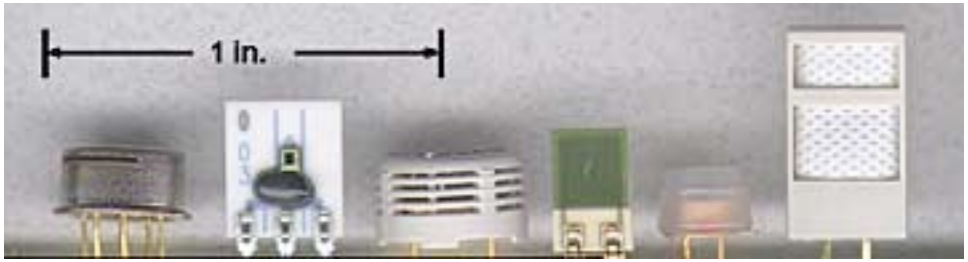
Constatan

$V_{Left} \neq V_{Right}$, $\underline{\alpha_a \text{ different}}$

$\Rightarrow i_r \neq i_L \Rightarrow i \neq 0$!!

[one metal want to give up electrons at hi T more than the other]

Humidity Sensors



Capacitive

The typical uncertainty of capacitive sensors is ±2% RH from 5% to 95% RH with two-point calibration

Resistive

Many varieties of capacitive humidity sensors
Exponential resistance-to-RH characteristic
Often coat board substrate with polymer.
Temperature compensation needed.
Interdigitated fingers - need AC source

Thermal

For measuring absolute humidity at high temperatures, thermal conductivity sensors are often used. They differ in operating principle from resistive and capacitive sensors. Absolute humidity sensors are left and center; thermistor chambers are on the right.

Other types: Chilled Mirror optical humidity sensor, etc.

http://www.sensorsmag.com/sensors/article/articleDetail.jsp?id=322590

Denes K. Roveti, July 2001

"Inexpensive" Surface-Mount Humidity Sensor

Sensirion SHT11

2 sensors for relative humidity & temperature
Precise dewpoint calculation possible
Measurement range: 0-100% RH
Absolute RH accuracy: +/- 3% RH
Temp. accuracy: +/- 0.4° C @ 25 ° C
Calibrated & digital output (2-wire interface)
Fast response time < 4 sec.
Low power consumption (typ. 30 μW)

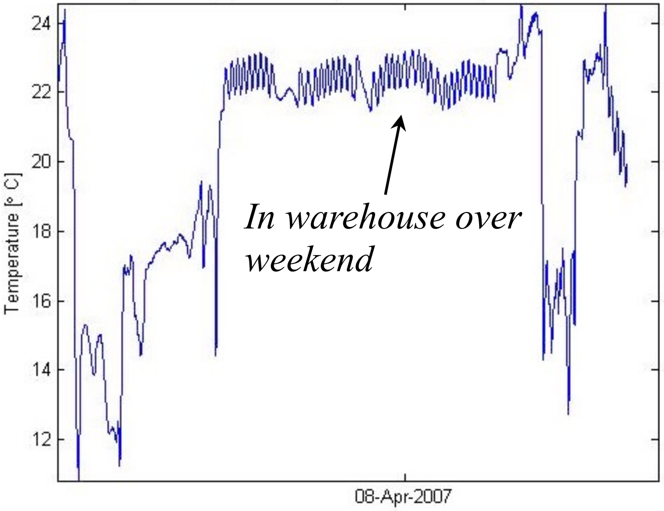
5 day test:

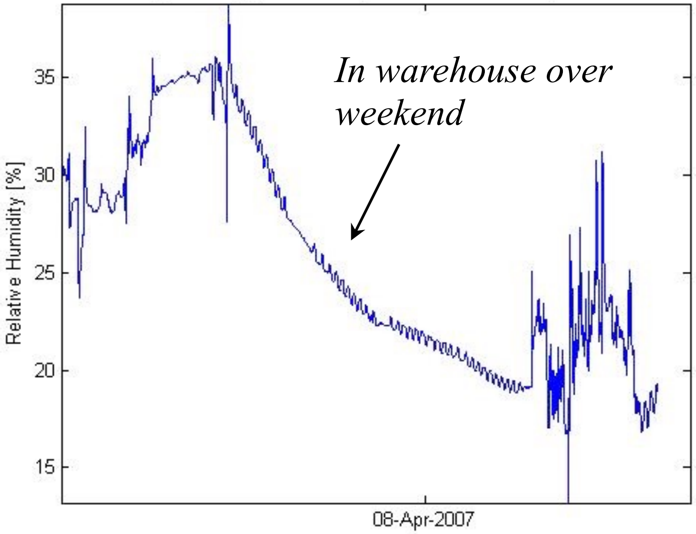
-Ship to Pepsi

-Weekend in warehouse

- On delivery truck

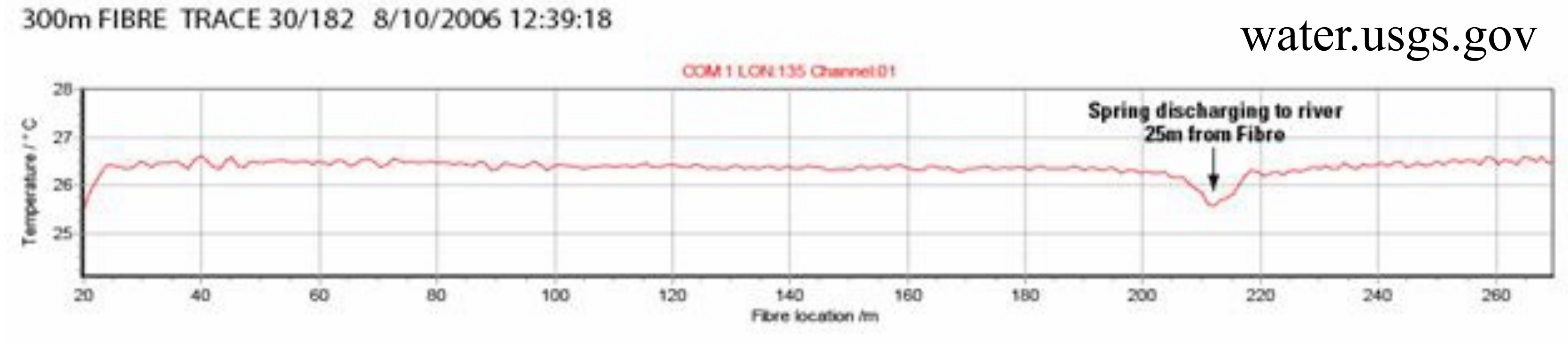
-Ship back to MIT





- Surface mount - precise temperature & humidity measured
- Digital connection - readings are compensated

Fiber Optic Temperature Sensors



water.usgs.gov

www.micronor.com

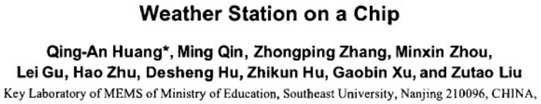
- Temperature affects index of refraction (hence reflected/transmitted signal) across fiber
- Use Time-Domain Reflectometry to get circa 1 meter T resolution across km’s of optical fiber

Anemometer

Rotating cups…
Fan blades
On shaft encoder

- Measures wind speed
  - Heat source and temperature sensors exposed to airflow (Hot Wire Anemometer)
    - ΔQ → ΔT
    - Use Thermistors, Transistors, Tungsten Bulb!

Can do it all on a silicon chip!



Weather Station on a Chip

Qing-An Huang*, Ming Qin, Zhongping Zhang, Minxin Zhou,
Lei Gu, Hao Zhu, Desheng Hu, Zhikun Hu, Gaobin Xu, and Zutao Liu
Key Laboratory of MEMS of Ministry of Education, Southeast University, Nanjing 210096, CHINA,

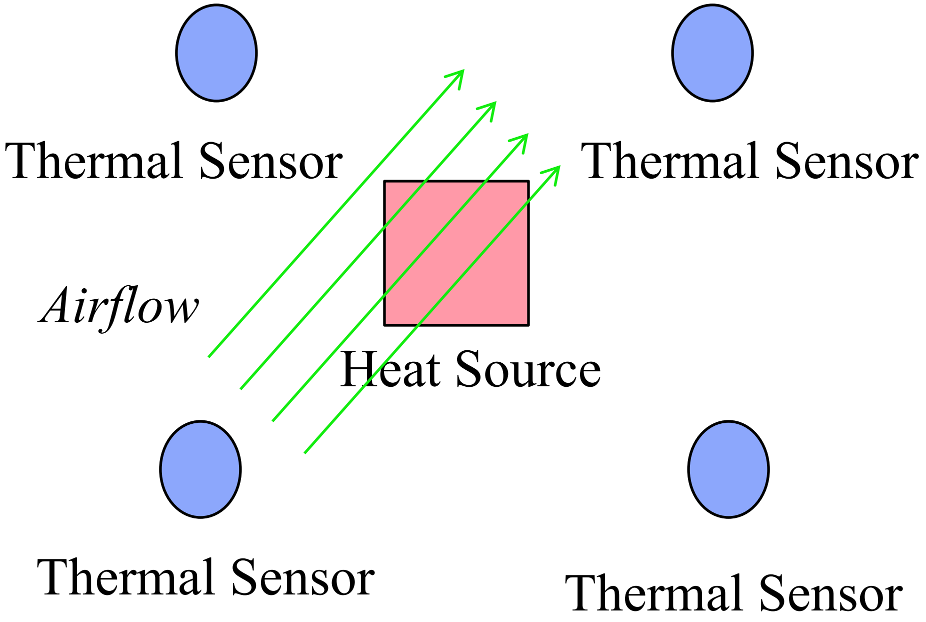
- Ultrasonic Anemometers
  - Measure the change in velocity with wind
    - Can break into components

$$\boxed{t = D/(c \pm v)}$$

Sonic propagation time = distance over (soundspeed ± wind velocity)

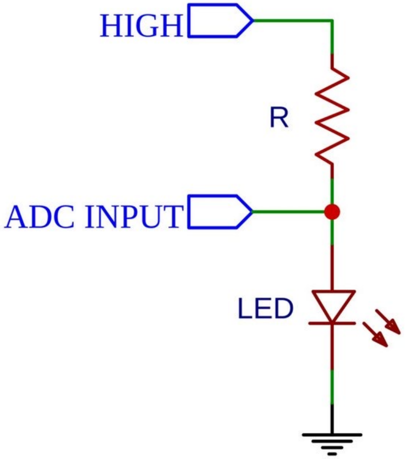
- Microphone in tube, bendy sensor, accel. or piezo blowing in wind, etc…

Planar Thermal Anemometer



Like a MEMSIC accelerometer with the cover off

Paul Dietz’s LED Anemometer

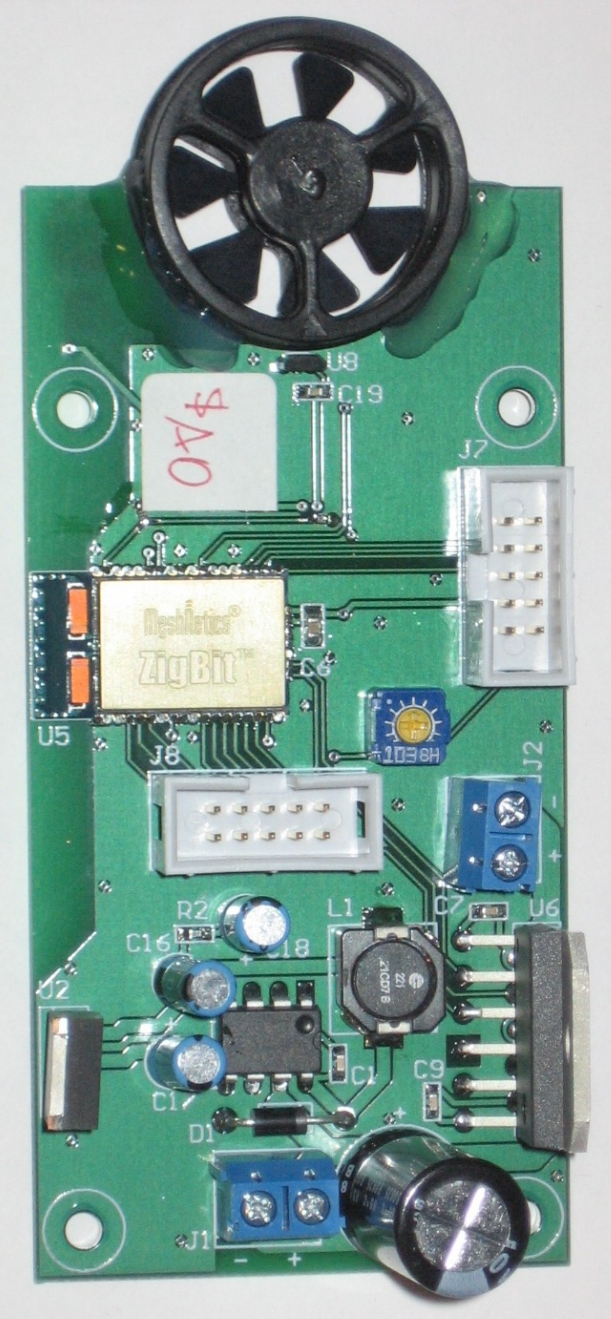


https://youtu.be/TD6A_tvbKT0

Mark Feldmeier PhD Thesis (2009)

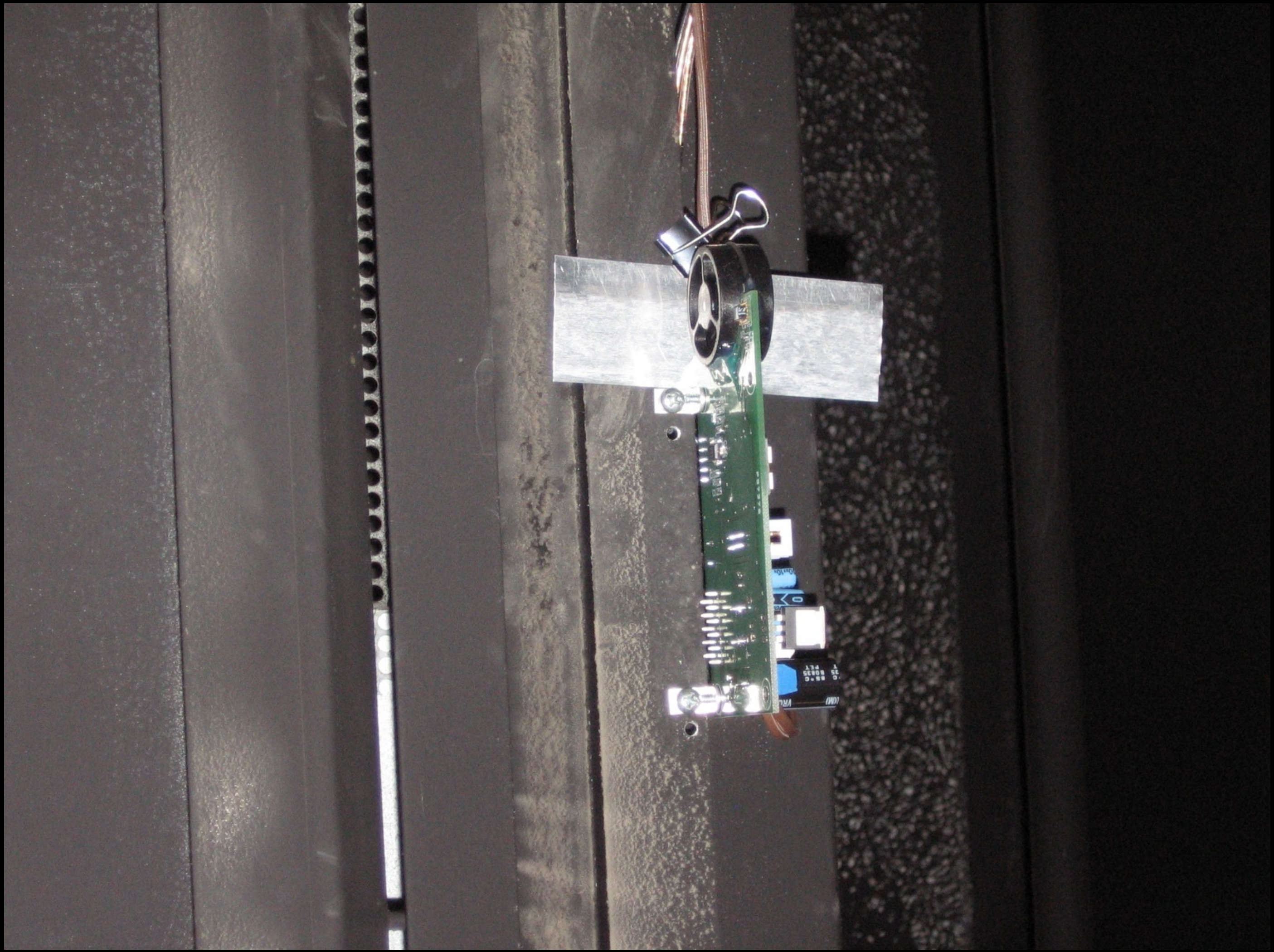
CONTROL NODE

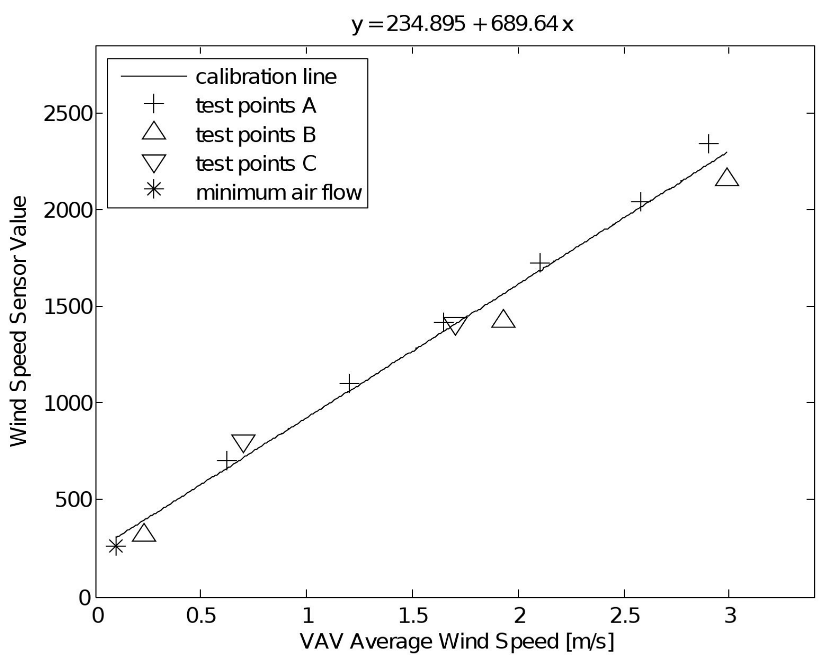
- Wind speed sensor
- Temperature sensor
- Humidity sensor
- Light sensor
- Motor driver
- Wireless transceiver
- 8MHz microcontroller
- 24Vdc power supply
- Expansion port

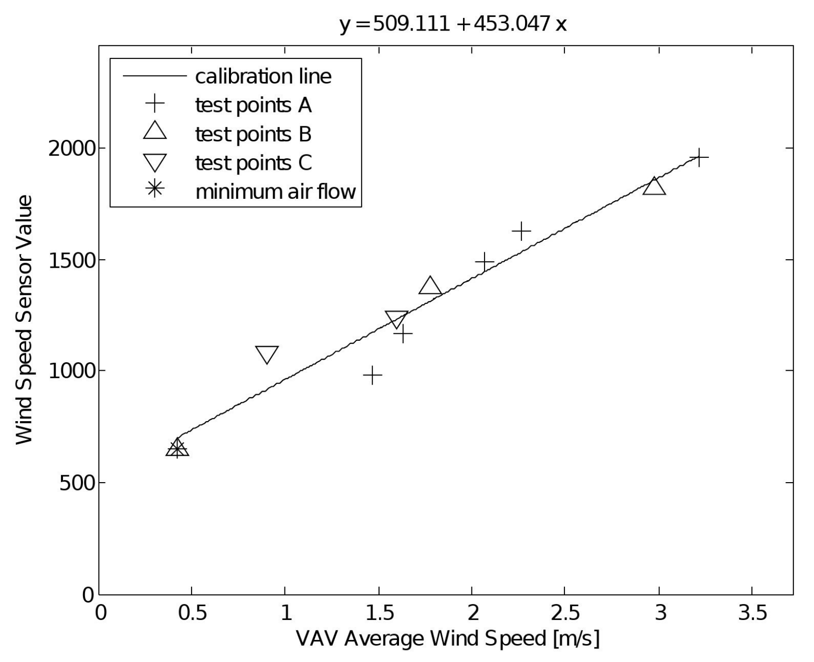


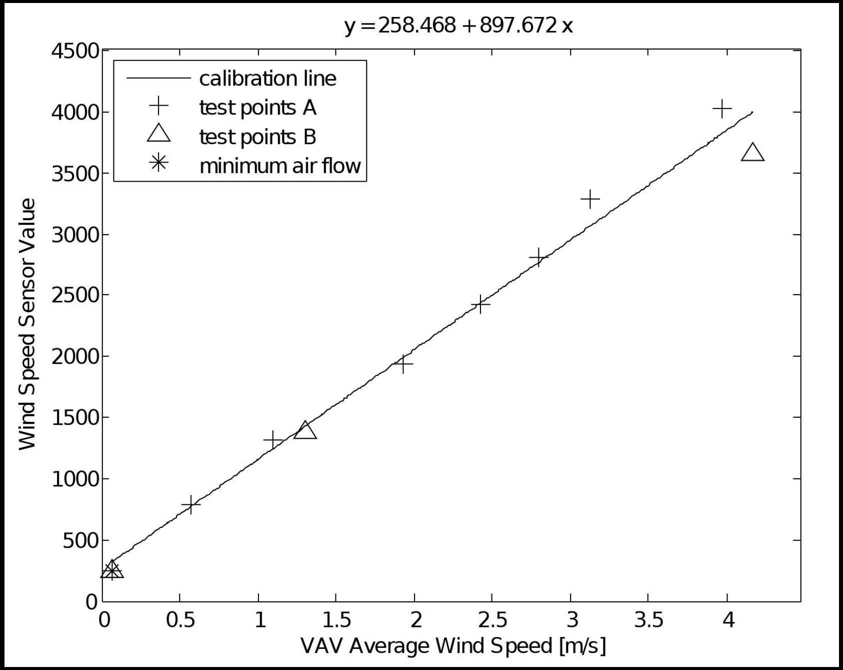
WIND SPEED SENSOR

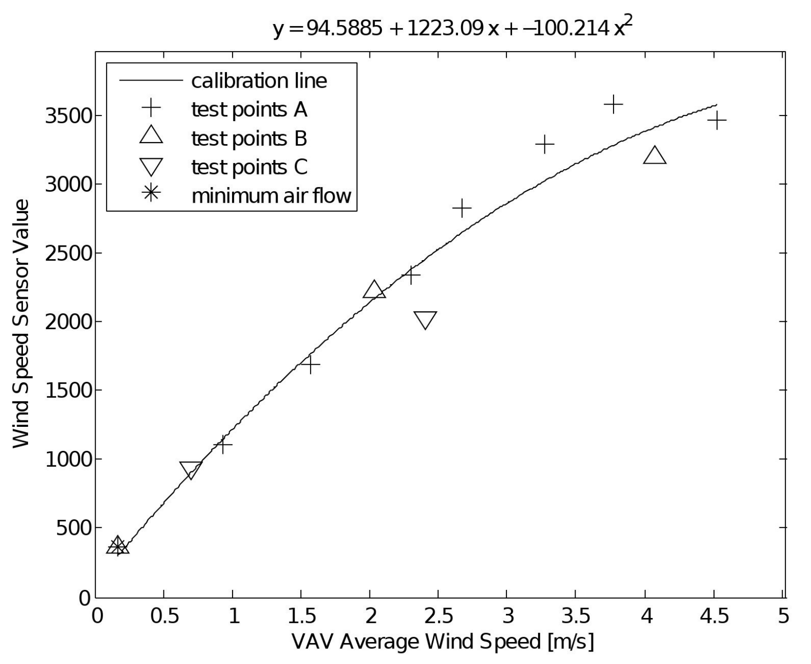
- Noise
- Sensitivity
- Calibration
- Energy metrics

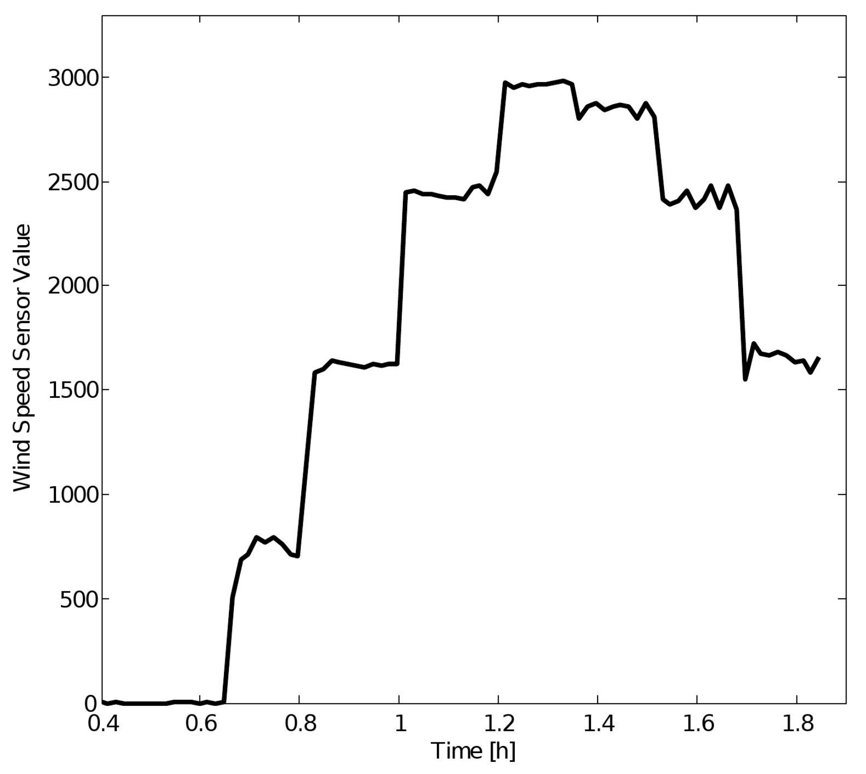



y = 234.895 + 689.64 x
calibration line
test points A
test points B
test points C
minimum air flow
Wind Speed Sensor Value
0
500
1000
1500
2000
2500
0
0.5
1
1.5
2
2.5
3
VAV Average Wind Speed [m/s]

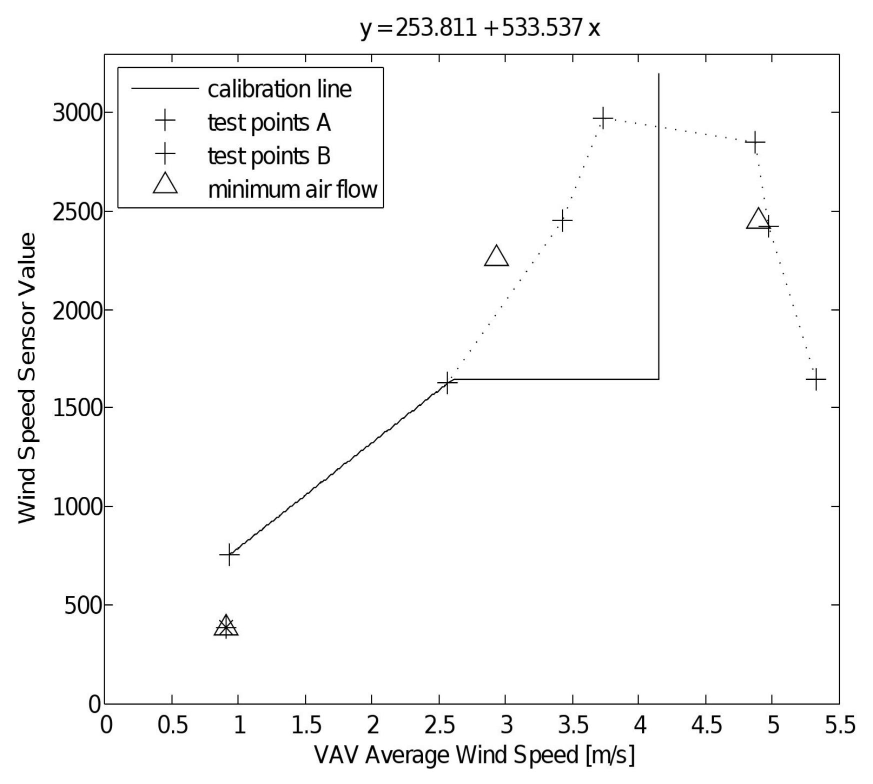

y = 509.111 + 453.047 x
calibration line
test points A
test points B
test points C
minimum air flow
Wind Speed Sensor Value
0
500
1000
1500
2000
0
0.5
1
1.5
2
2.5
3
3.5
VAV Average Wind Speed [m/s]


y = 258.468 + 897.672 x
calibration line
test points A
test points B
minimum air flow
Wind Speed Sensor Value
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
0.5
1
1.5
2
2.5
3
3.5
4
VAV Average Wind Speed [m/s]


y = 94.5885 + 1223.09 x + −100.214 x²
calibration line
test points A
test points B
test points C
minimum air flow
Wind Speed Sensor Value
0
500
1000
1500
2000
2500
3000
3500
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
VAV Average Wind Speed [m/s]



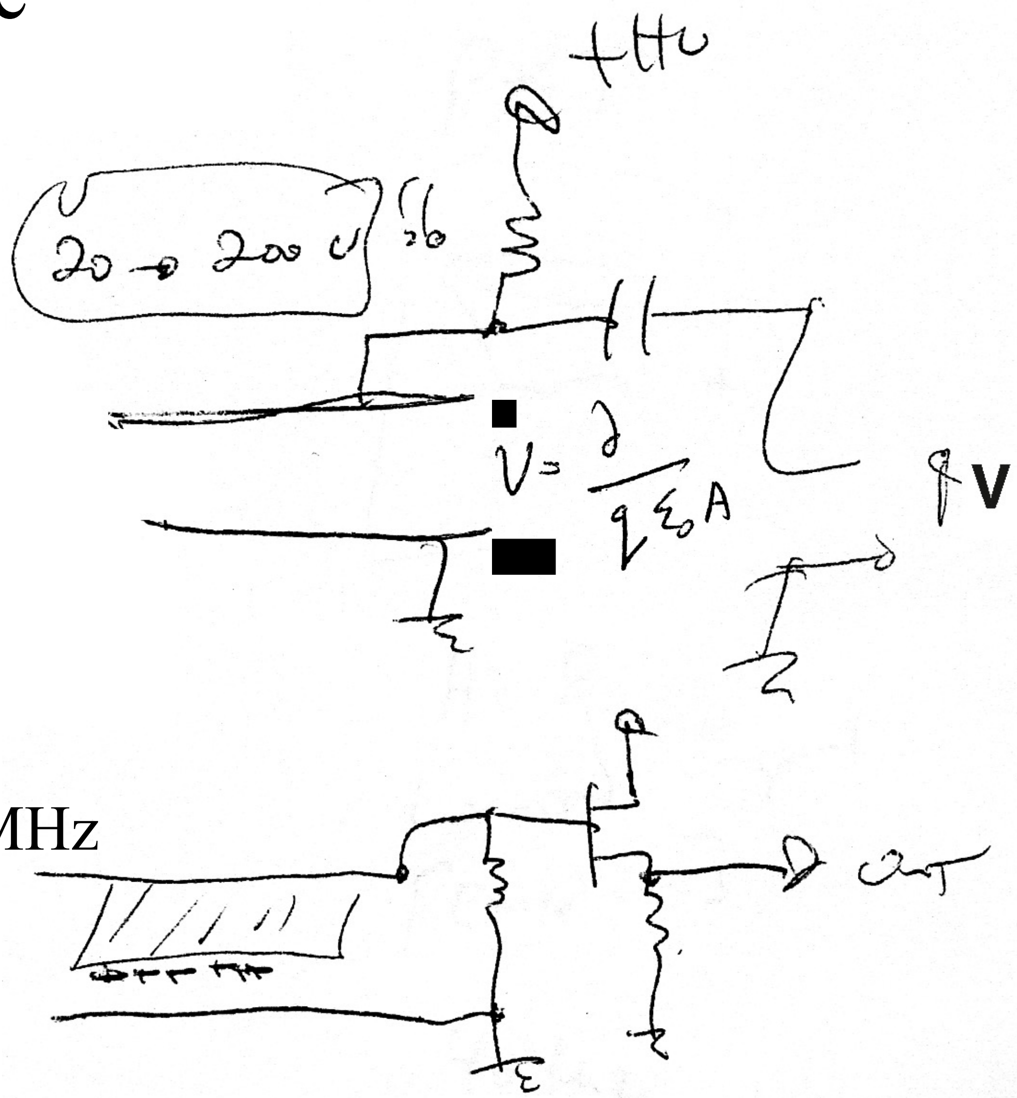
Wind Speed Sensor Value
3000
2500
2000
1500
1000
500
0
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Time [h]



y = 253.811 + 533.537 x
calibration line
test points A
test points B
minimum air flow
Wind Speed Sensor Value
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
VAV Average Wind Speed [m/s]

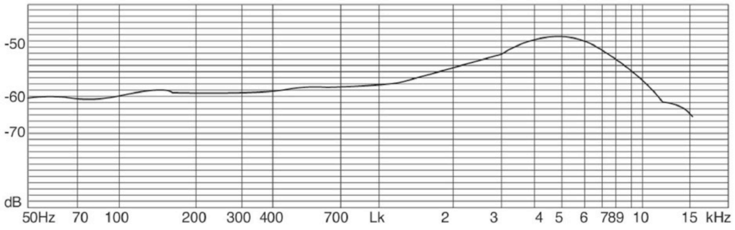
Acoustic Transducers

- Measure dynamic range to moving diaphragm
- Carbon mic
- Condensor mic
- Electret mic
  - Foil electret mic
  - FEP material polarized with corona discharge
  - Wideband
    - 10^{-3} Hz to hundreds of MHz
  - Usually have integrated FET



http://www.openmusiclabs.com/learning/sensors/electret-microphones

More Acoustic Transducers



→ Piezo Mic

~ Peaky (Passive Acoustic Filters)?

→ PZT

PVDF Diaphragm

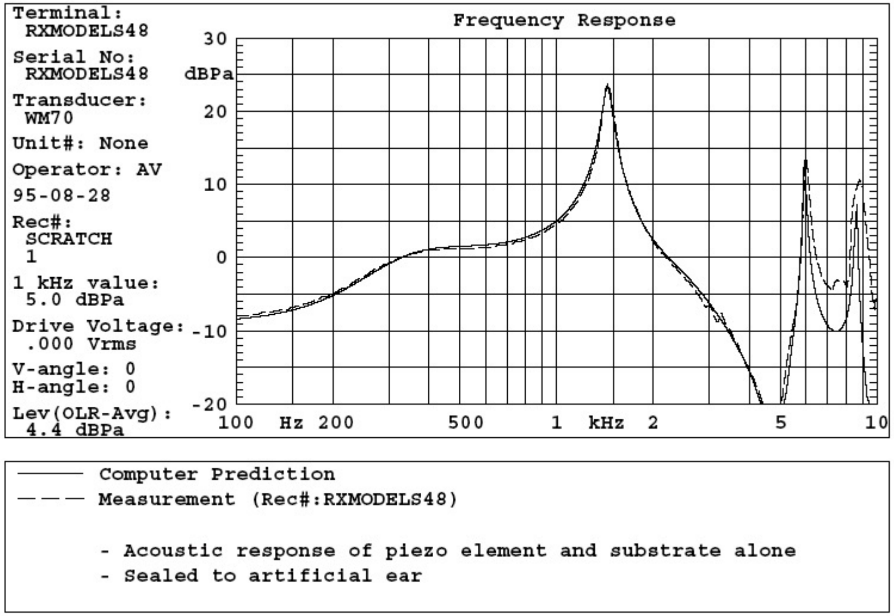
→ Electrodynamic mic ~ moving coil

→ Speaker or mic

→ dB re. 1 V/mPA

→ Optical Techniques (spy devices)

PZT Cellphone Receiver

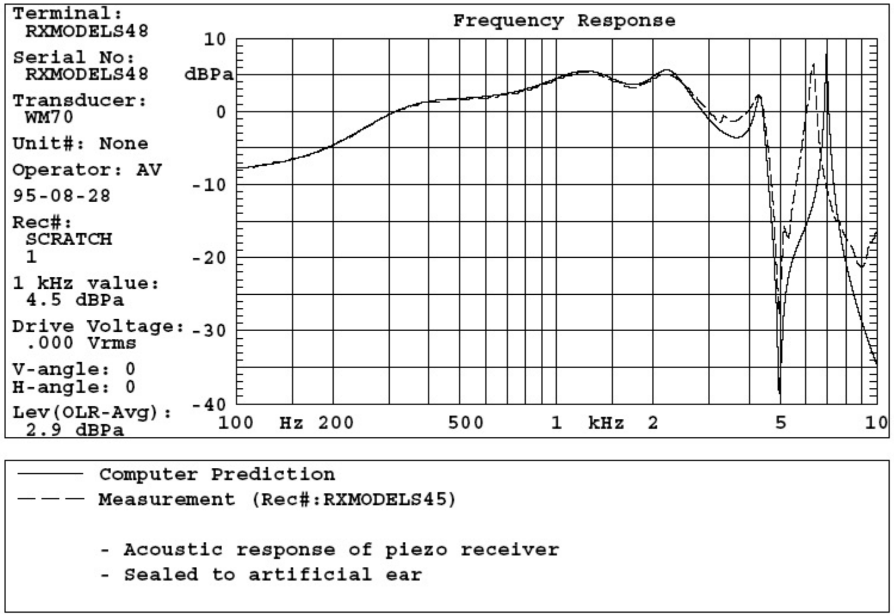


Terminal:
RXMODELS48
Serial No:
RXMODELS48
Transducer:
WM70
Unit#: None
Operator: AV
95-08-28
Rec#:
SCRATCH
1
1 kHz value:
5.0 dBPa
Drive Voltage:
.000 Vrms
V-angle: 0
H-angle: 0
Lev(OLR-Avg):
4.4 dBPa

——— Computer Prediction
— — — Measurement (Rec#:RXMODELS48)

- Acoustic response of piezo element and substrate alone
- Sealed to artificial ear

Just PZT plate



Terminal:
RXMODELS48
Serial No:
RXMODELS48
Transducer:
WM70
Unit#: None
Operator: AV
95-08-28
Rec#:
SCRATCH
1
1 kHz value:
4.5 dBPa
Drive Voltage:
.000 Vrms
V-angle: 0
H-angle: 0
Lev(OLR-Avg):
2.9 dBPa

——— Computer Prediction
— — — Measurement (Rec#:RXMODELS45)

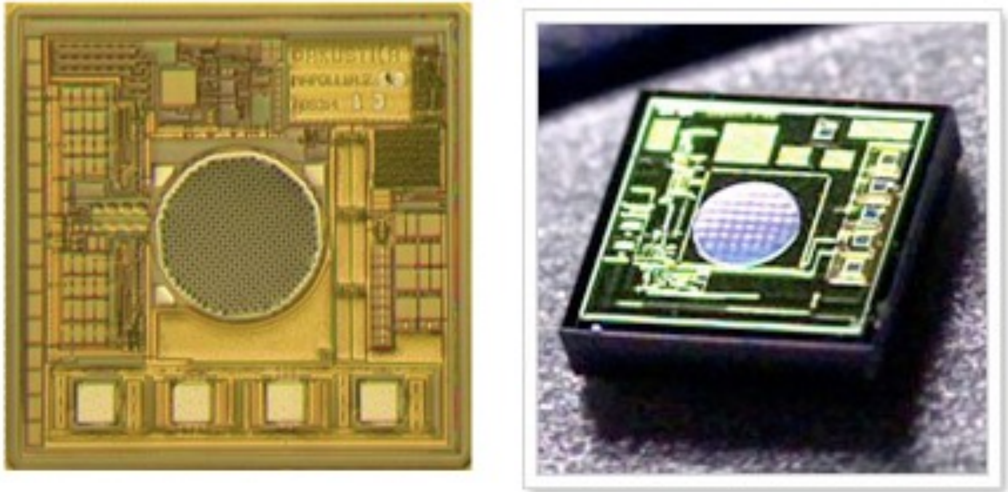
- Acoustic response of piezo receiver
- Sealed to artificial ear

After mechanical compensation in receiver

Nortel Measurements

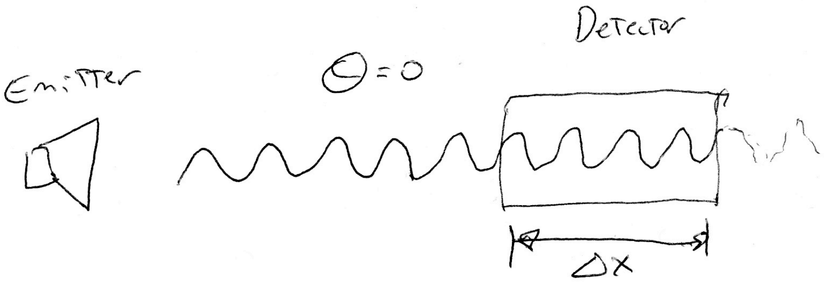
MEMs Microphones

The World's Smallest Microphone!



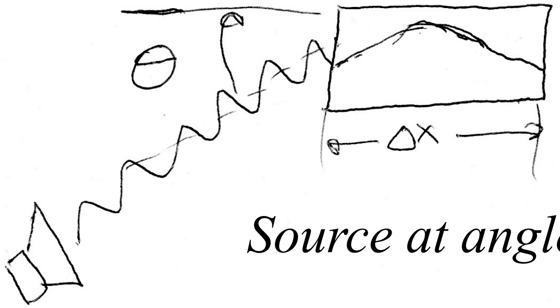
- Many Manufacturers
  - Akustica (direct digital output), Infineon, Panasonic, etc.
- Very small - surface-mount chip
- Have integrated amplifier and sometimes ADC

Where Beamwidth Comes From



$$\int_{\Delta X} V_{T_N}\,dx = V(T)\big|_N \Rightarrow 0$$

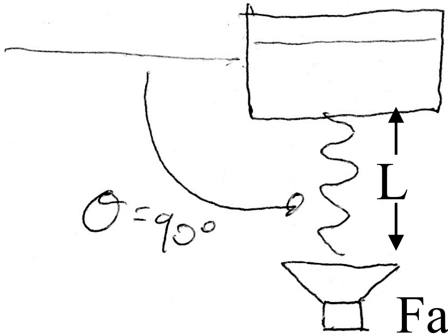
Source on edge



$$\int_{\Delta X} V_{T_N}\,dx = \alpha V(T)_N \Rightarrow \alpha V(T)_N$$

$(\alpha < 1)$

Source at angle



$$\int_{\Delta X} V_{T_N}\,dx = V(T)_N$$

(In far field, waveform at T_N is constant across aperture ΔX)

Source broadside

Far-field (L >> ΔX)

Beamwidth as Fourier Transform

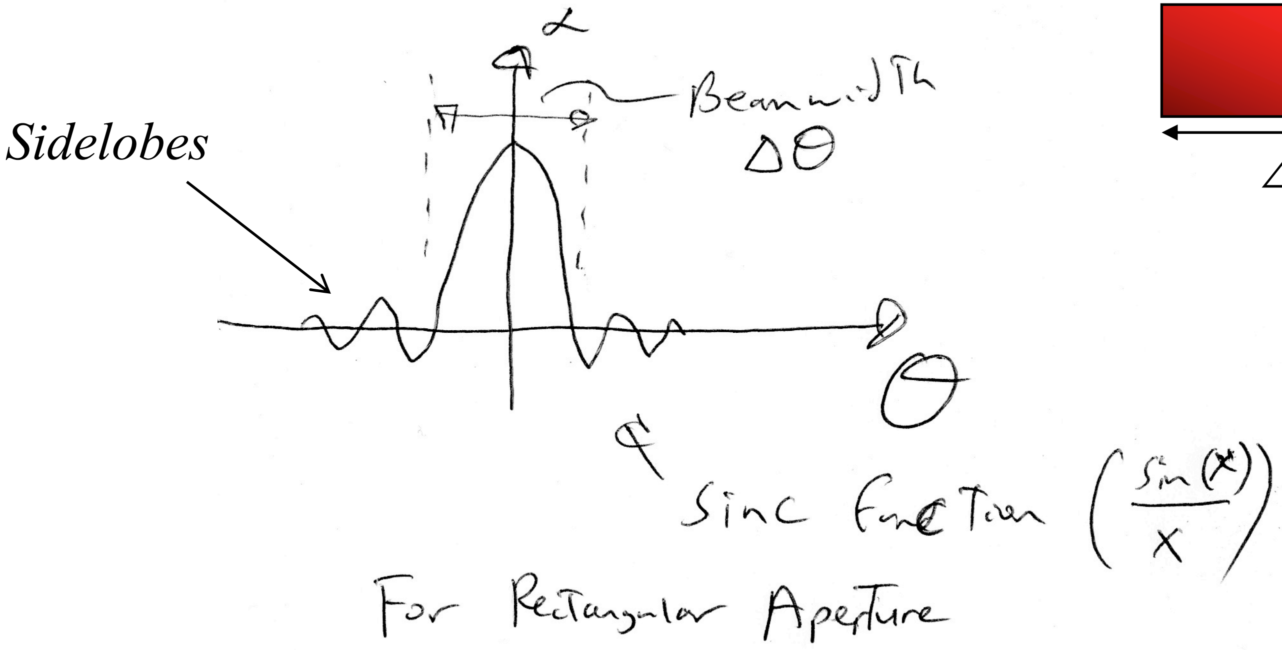
$$V(T) = \underset{\text{Gain}}{G} \int_{x=-\infty}^{x=+\infty} \underset{\substack{\text{Aperture}\\ \text{Shading}\\ \text{Function}\\ \text{(Shape)}}}{A(x)} \cdot \sin(\omega T + \underset{\substack{\uparrow\\ \text{"Wavenumber"}\\ "\\ \cos(\Theta)\,2\pi/\lambda}}{Kx})\, dx$$

$$V(T) = G e^{i\omega T} \int_{\Delta x} A(x)\, e^{i \frac{2\pi\cos\theta}{\lambda} x}\, dx$$

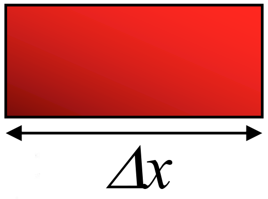
$$|V(x)| \underset{\substack{\text{Fourier}\\ \text{Xform}}}{\Longleftrightarrow} |\bar{V}(\underset{\substack{\downarrow\\ (k)}}{\cos\theta})|$$

K is the trace *wavenumber*

Beamwidth of Rectangular Aperture



Sidelobes

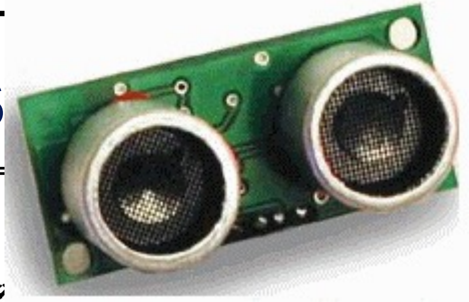


$$\Delta\theta_{3dB} = 50^\circ \quad \lambda/\Delta x$$

$$\lambda << \Delta x$$

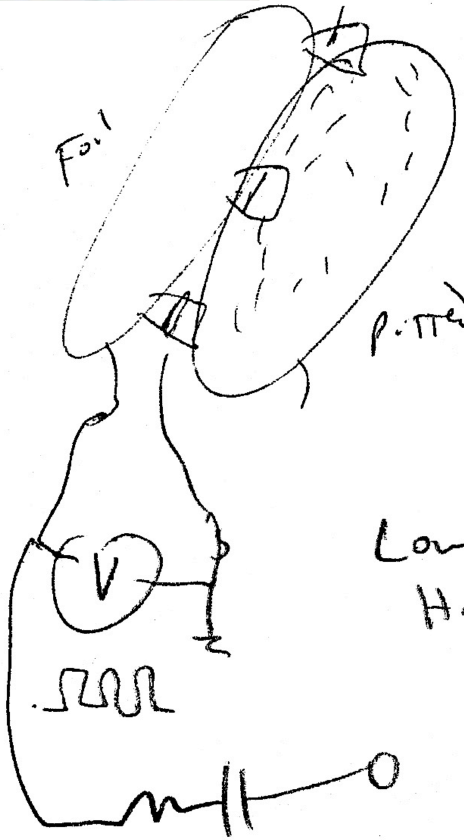
Beamwidth and aperture width are conjugate variables!

Ultrasonic Transceivers



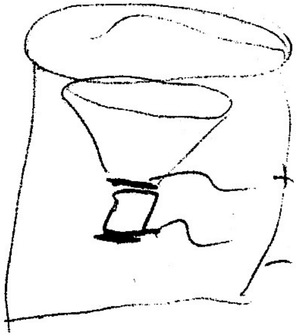
Electrostatic

Pz



Lower Q (Broadband)
Higher Output

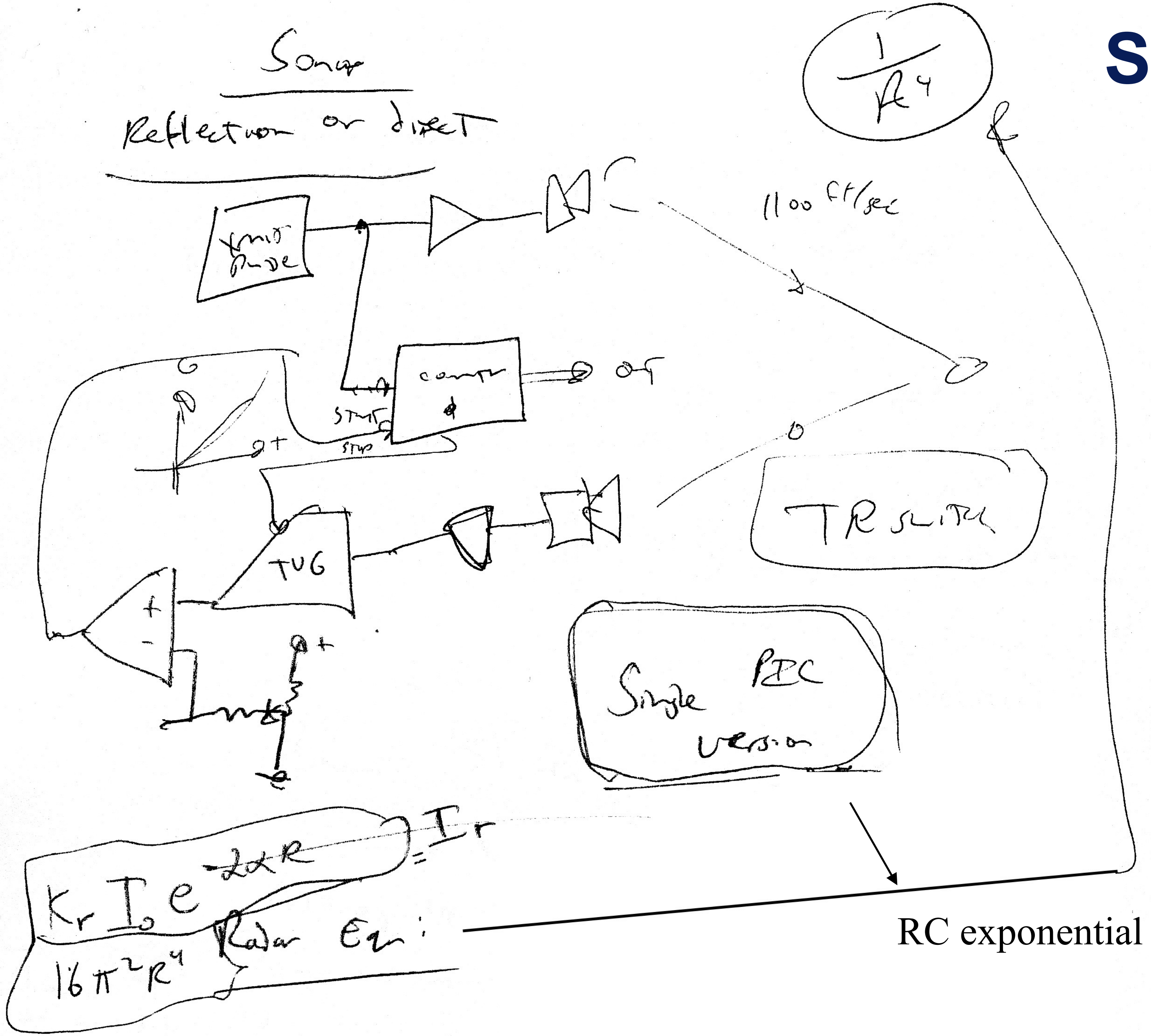
50 Khz
Polaroid
35 Ft.



Hi Q
Limited output
[Except...]

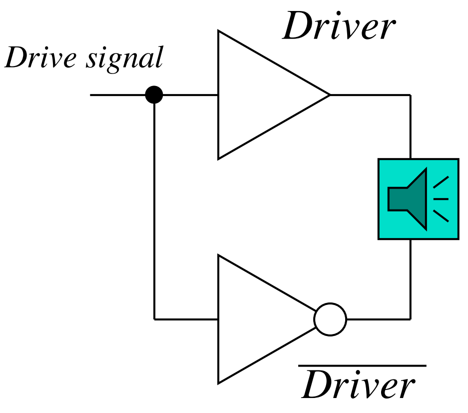
40 Khz
Panasonic, Murata...

Sonar



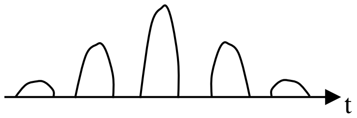
RC exponential threshold

Sonar with Totem-Pole Driver and Diode-Based T/R Switch

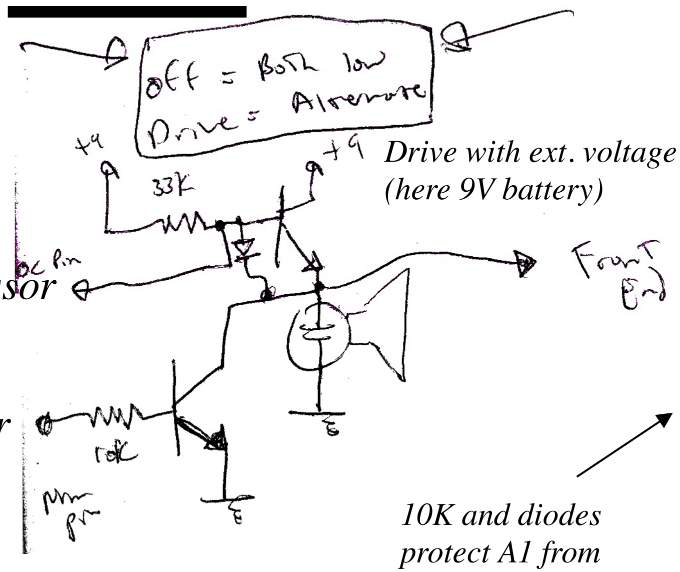


Complementary drive gives twice the drive voltage vs. driving single-ended to ground

As A1 is not biased up, its output is half-wave rectified (e.g., we only see positive cycles) - this can lead to full-cycle jumps in timing.



A1



Drive with ext. voltage (here 9V battery)

Open Collector Pin from Processor

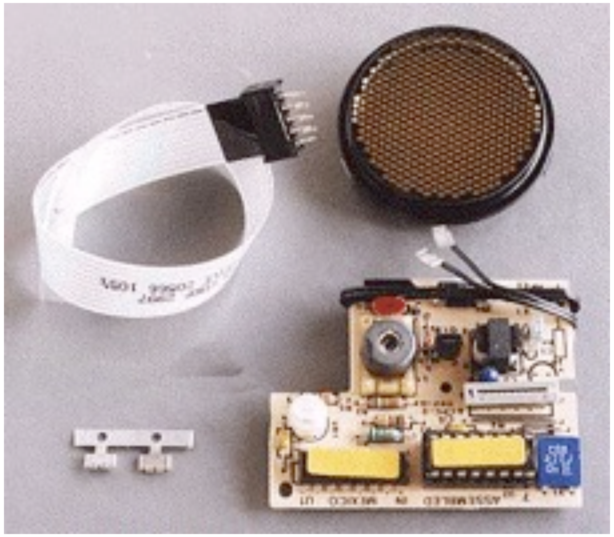
Normal Pin from Processor

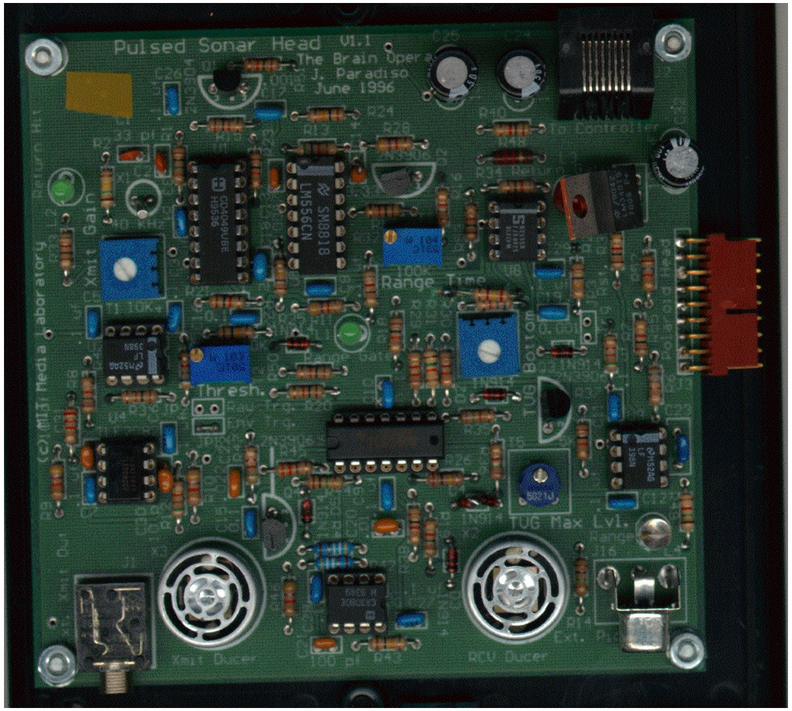
10K and diodes protect A1 from overvoltage

A2

- To drive sonar, the two pins from the processor are driven in opposite polarity (complementary)
- To listen to sonar, both pins are held low
- Both pins positive is a forbidden state (prohibited by the diode between the transistors)

Sonar Photos...





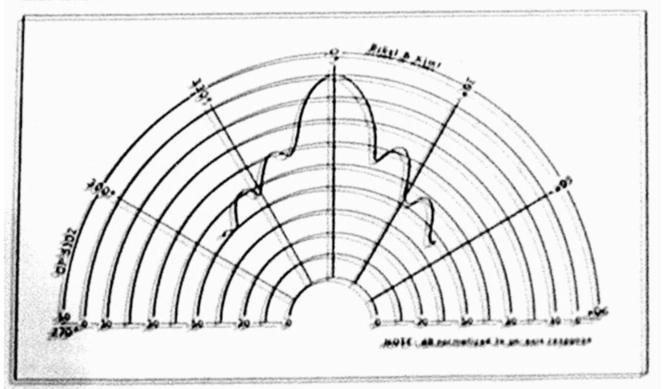
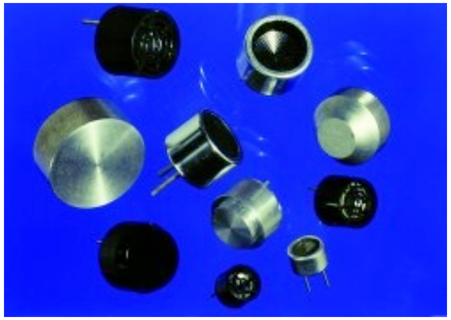


Figure 3: The transducer's beam pattern at 50 kHz



50 kHz, narrow beamwidth, clicks!

Polaroid electrostatic

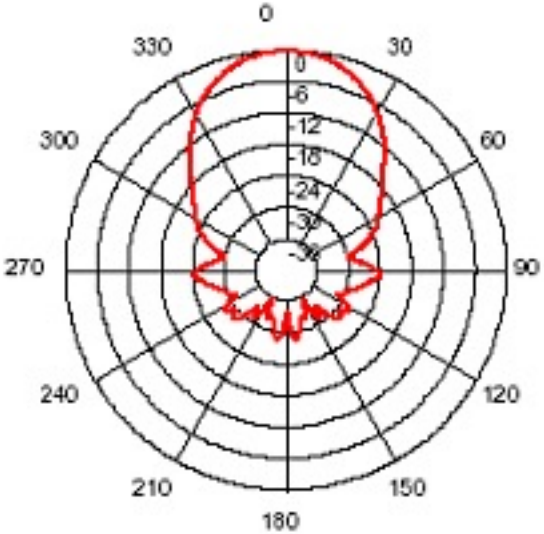
Generally 40 kHz, 40° - 80° beam, qui

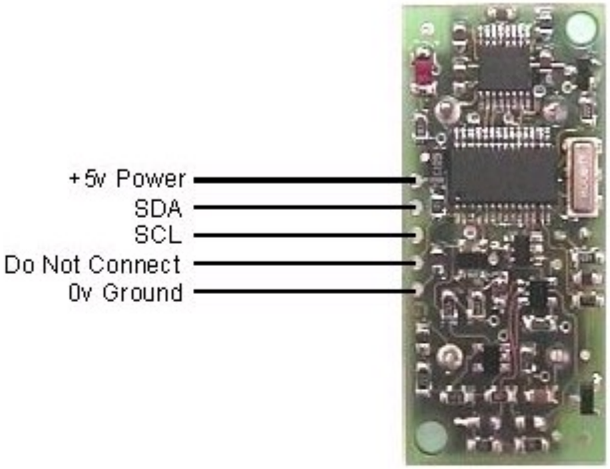
Piezoceramic (Murata, Panasonic, APC)

1997

More 1997

The SRF08





- Available off robotics sites
- Minimal components – uses dual PZT ‘ducers
- Uses TVG
- Claims Range of 6 meters
- Onboard processor – talks via I^2C

sonoSens® Monitor

Mobile Motion Analysis

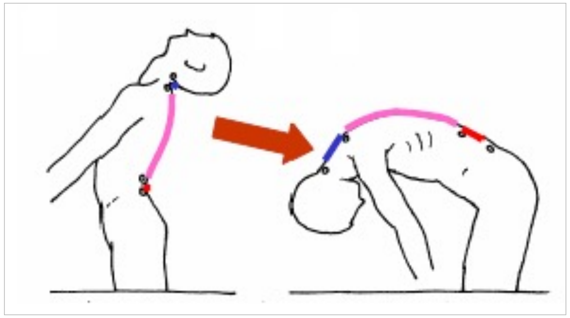
Application of sensors along the spine.

Body movements can be assessed using sonometry.

The sonoSens® Monitor captures body motion by measuring distance changes between sensors attached to the skin (spine, knee, shoulder, hip, etc.). Sensor movement is caused by the elasticity of the skin – the skin over joints stretches and relaxes according to joint motion. Data is stored in the main unit of the device and transferred to the PC after recording. Maximum measurement time is up to 60 hours.

Videos:
Seat
Breathing

Because of the small sensor size and the light weight of the device (150 g), free motion is possible. Additionally there are no location restrictions; outdoor measurements are therefore possible.



Sensor movement is caused by the elasticity of the skin.

Launch ultrasound into skin - measure distributed delay times