# THERMAL TRANSDUCERS

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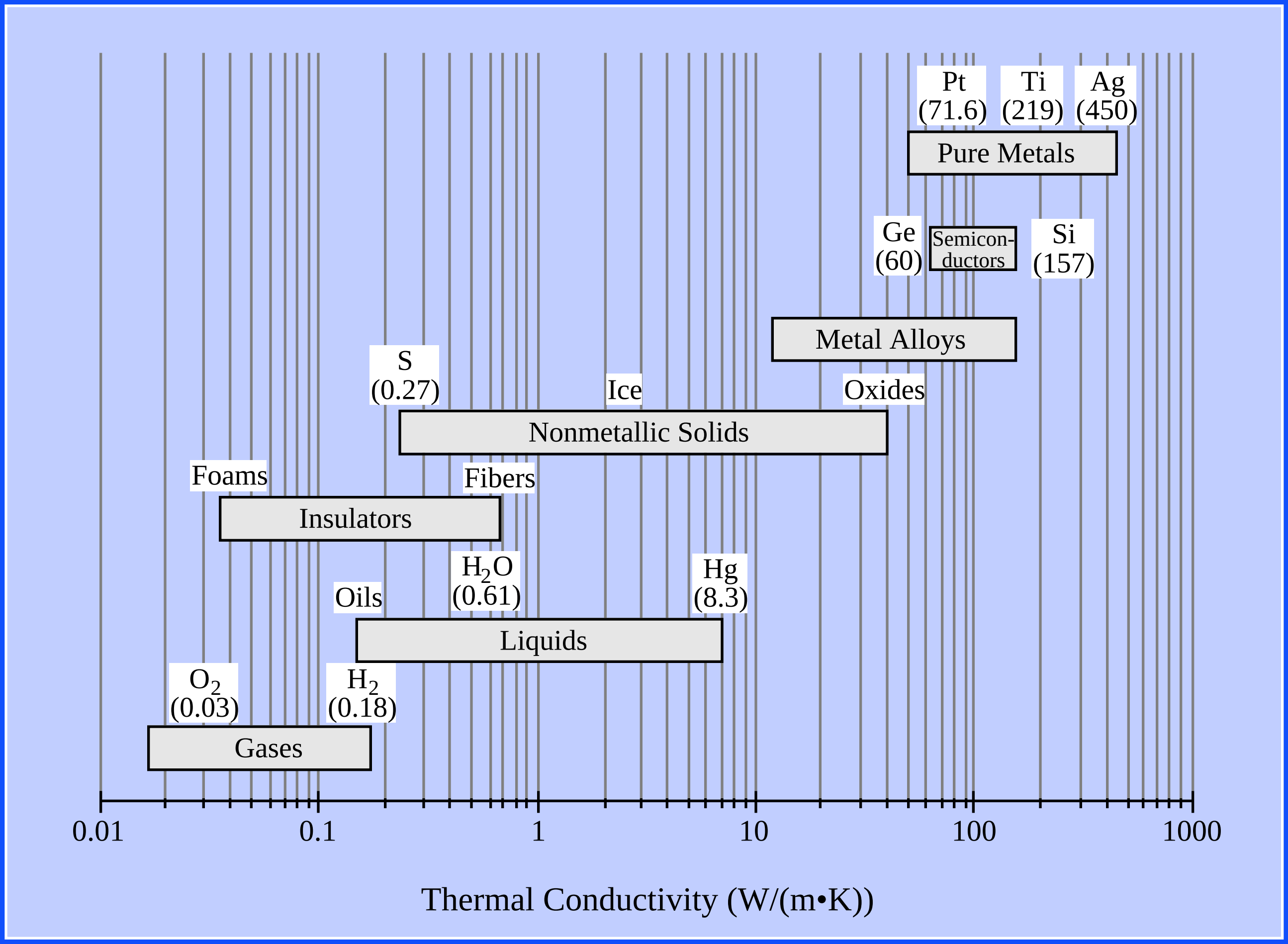
## Stanford University

# THERMAL TRANSDUCERS

- **Temperature sensors**
- **Micro heaters**
- **Flow sensors**
- **Vacuum sensors**
- **Thermal actuators**

| Temperature | K | °C | °F |
|---|---|---|---|
| Boiling point of copper | 2,868.0 | 2,594.9 | 4,702.7 |
| Boiling point of lead | 2,017.0 | 1,743.9 | 3,170.9 |
| Melting point of copper | 1,356.0 | 1,082.9 | 1,981.1 |
| Boiling point of mercury | 630.0 | 356.9 | 674.3 |
| Melting point of lead | 601.0 | 327.9 | 622.1 |
| Boiling point of water | 373.15 | 100.0 | 212.0 |
| Normal human body temperature | 310.2 | 37.0 | 98.6 |
| Comfortable room temperature | 293.2 | 20.0 | 68.0 |
| Freezing point of water | 273.15 | 0.0 | 32.0 |
| Zero of Farenheit scale | 255.4 | -17.8 | 0.0 |
| Melting point of mercury | 234.0 | -39.1 | -38.5 |
| Coincidence of °C and °F scales | 233.2 | -40.0 | -40.0 |
| Boiling point of oxygen | 90.2 | -183.0 | -297.3 |
| Boiling point of nitrogen | 77.4 | -195.8 | -320.4 |
| Melting point of nitrogen | 63.3 | -209.9 | -345.8 |
| Melting point of oxygen | 54.8 | -218.3 | -361.0 |
| Boiling point of hydrogen | 20.3 | -252.8 | -423.1 |
| Melting point of hydrogen | 14.0 | -259.2 | -434.5 |
| Absolute zero | 0.0 | -273.15 | -459.4 |

# THERMAL CONDUCTIVITIES




**Reference: Incroprera, F. P., and DeWitt, D. P., "Fundamentals of Heat and Mass Transfer," Third Edition, John Wiley and Sons, New York, NY, 1990.**

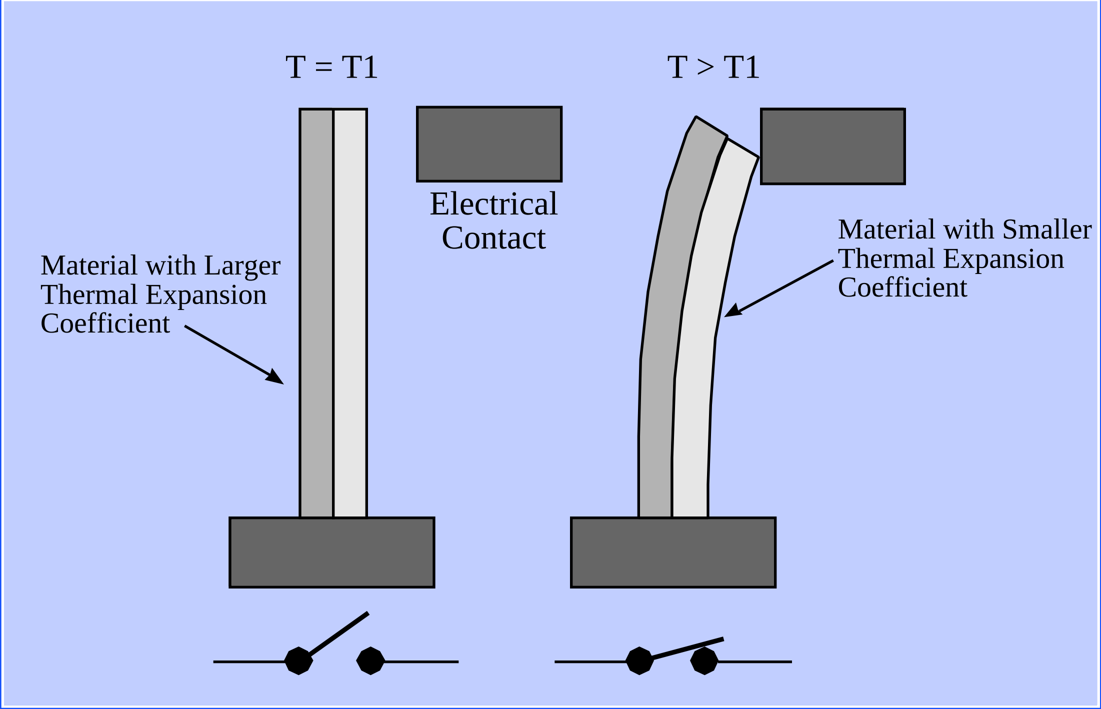
# THERMAL TRANSDUCER CONCEPTS

- Thermo-resistive devices make use of the (usually quite linear) temperature coefficient of resistance (TCR).
- Thermocouples rely on the Seebeck voltage generated between two different metals.
- Semiconductor circuits (diode and PTAT) use basic device properties ($I_s$(T) and $V_{be}$(T), respectively).
- Thermal expansion is used in several ways for sensing and actuation.
- Direct physical expansion of structures is readily used.
- Bimorph structures make use of bonded materials of different expansion coefficients that will deflect when heated.
- Phase change of materials is also useful.

# THERMO-MECHANICAL TRANSDUCTION

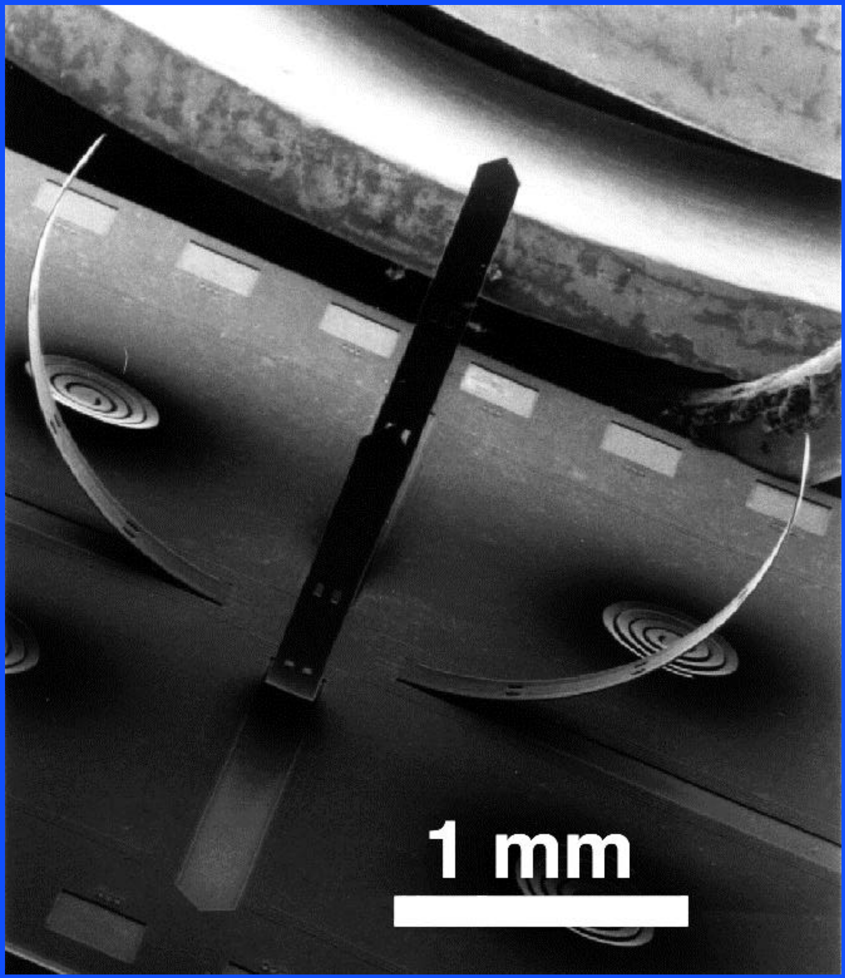
- **This is a very simple approach that typically makes use of a bilayer of materials with different thermal expansion coefficients, $\alpha$.**
- **For a bimetallic strip, the radius of curvature is given by,**

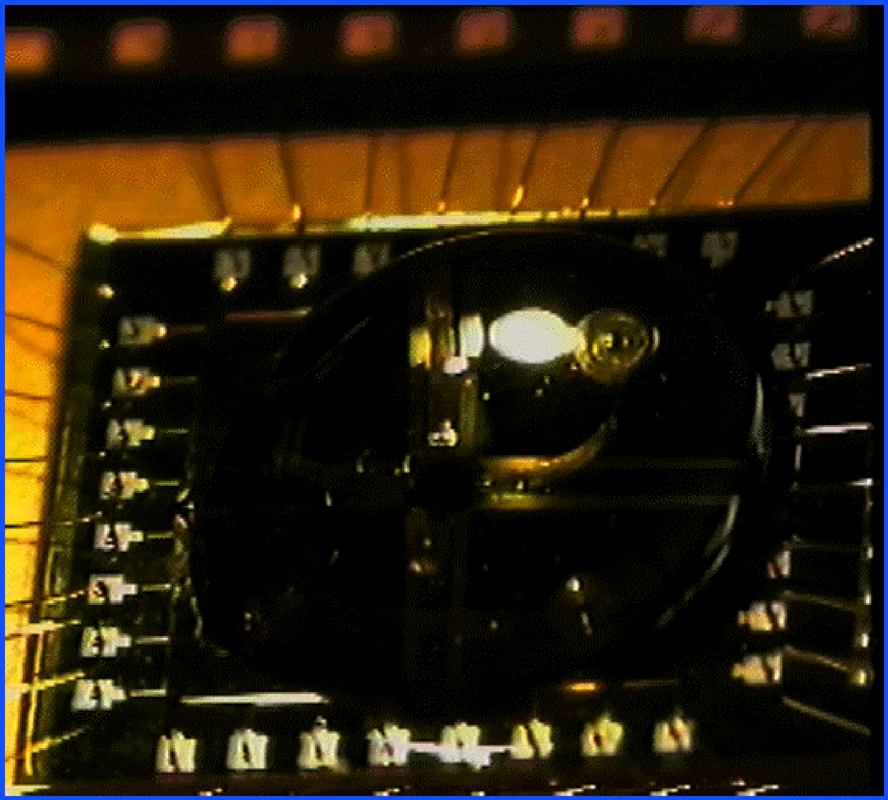
$$R = \frac{(t_1 + t_2)^2}{6\,(\alpha_{L1} - \alpha_{L2})(T_f - T_o)\,t_1 t_2}$$



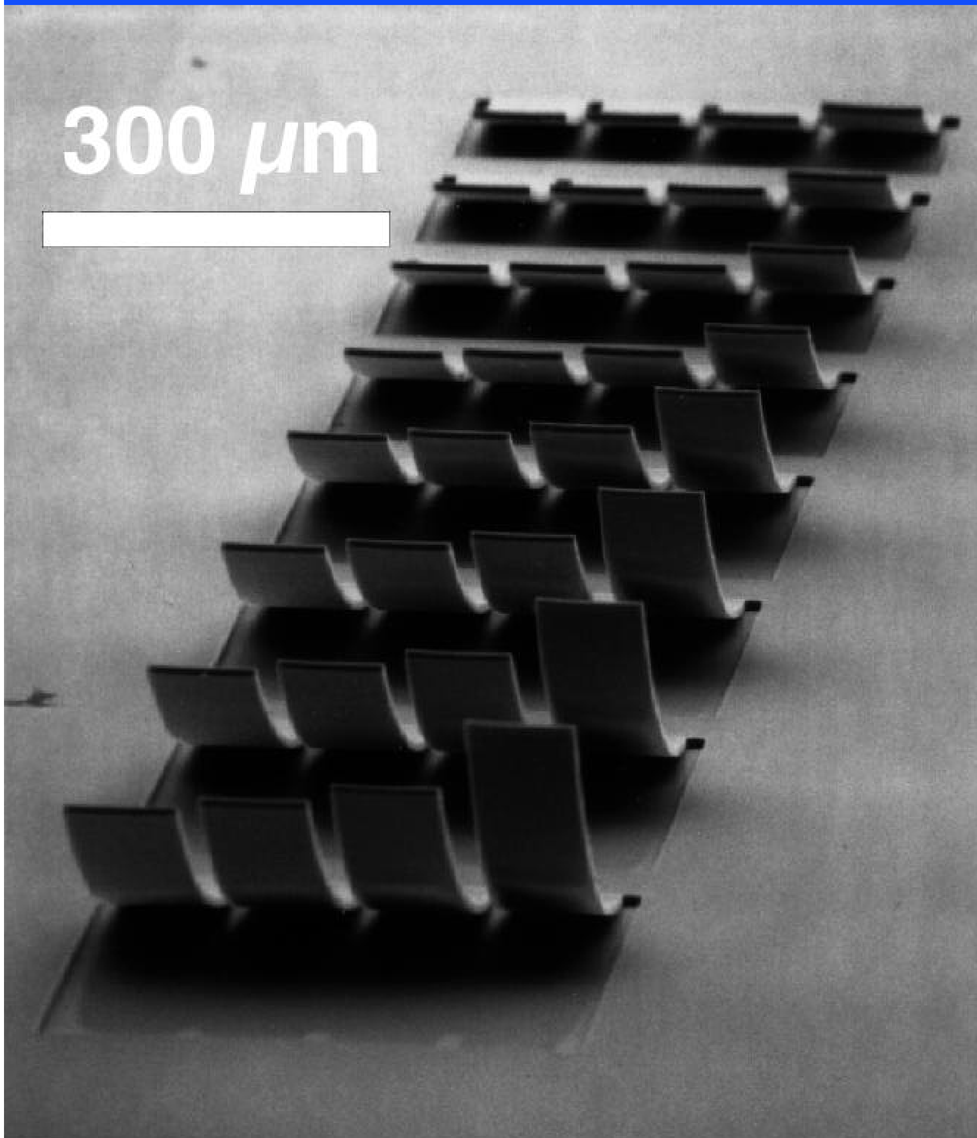
| Material | Thermal Conductivity W/cm•K (@300K) | Temperature Coefficient of Expansion, ppm/K |
|---|---|---|
| Aluminum | 2.37 | 25.0 |
| Aluminum Oxide (polycrystalline) | 0.36 | 8.7 |
| Aluminum Oxide (sapphire) | 0.46 | - |
| Carbon, Amorphous | 0.016 | - |
| Carbon, Diamond | 23 | - |
| Chromium | 0.94 | 6.00 |
| Copper | 4.01 | 16.5 |
| Gallium Arsenide | 0.56 | 5.4 |
| Germanium | 0.60 | 6.1 |
| Gold | 3.18 | 14.2 |
| Iridium | 1.47 | 6.40 |
| Iron | 0.80 | 11.8 |
| Molybdenum | 1.38 | 5.00 |
| Nickel | 0.91 | 13.0 |
| Platinum | 0.716 | 8.8 |
| Polyimide, Amoco Ultradel 1414 | - | 191 |
| Polyimide, Dupont PI2611D | - | 3.00 |
| Polyimide, Hitachi PIQ-3200 | - | 50.0 |
| Polysilicon | 0.34 | 2.33 |
| Silicon | 1.49 | 2.60 |
| Silicon Carbide | 4.90 | - |
| Silicon Dioxide (fused silica) | 0.0138 | 0.4 |
| Silicon Dioxide (thermal) | 0.0138 | 0.35 |
| Silicon Nitride | 0.16 | 1.6 |
| Silver | 4.29 | 18.9 |
| Teflon™ (PTFE) | 0.0225 | - |
| Tin | 0.67 | 22 |
| Titanium | 0.219 | 8.6 |
| Tungsten | 1.73 | 4.50 |

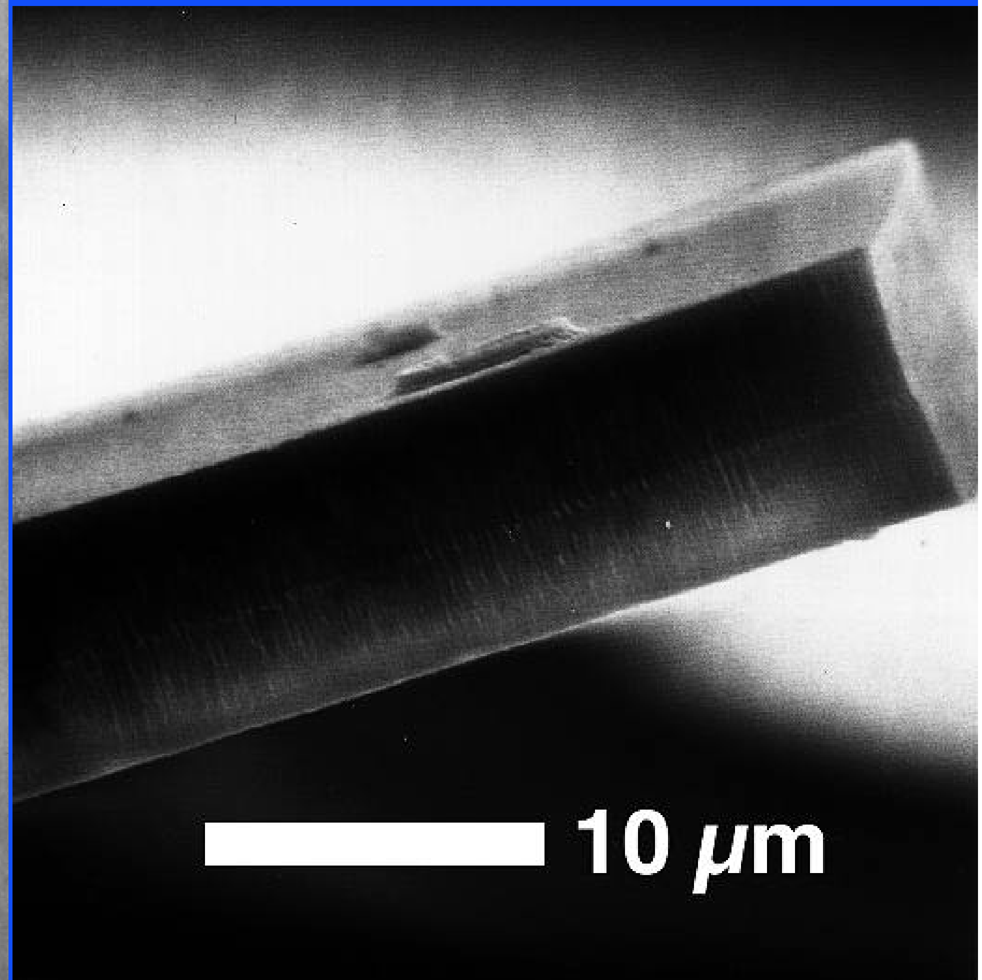
# THERMAL BIMORPH ACTUATORS



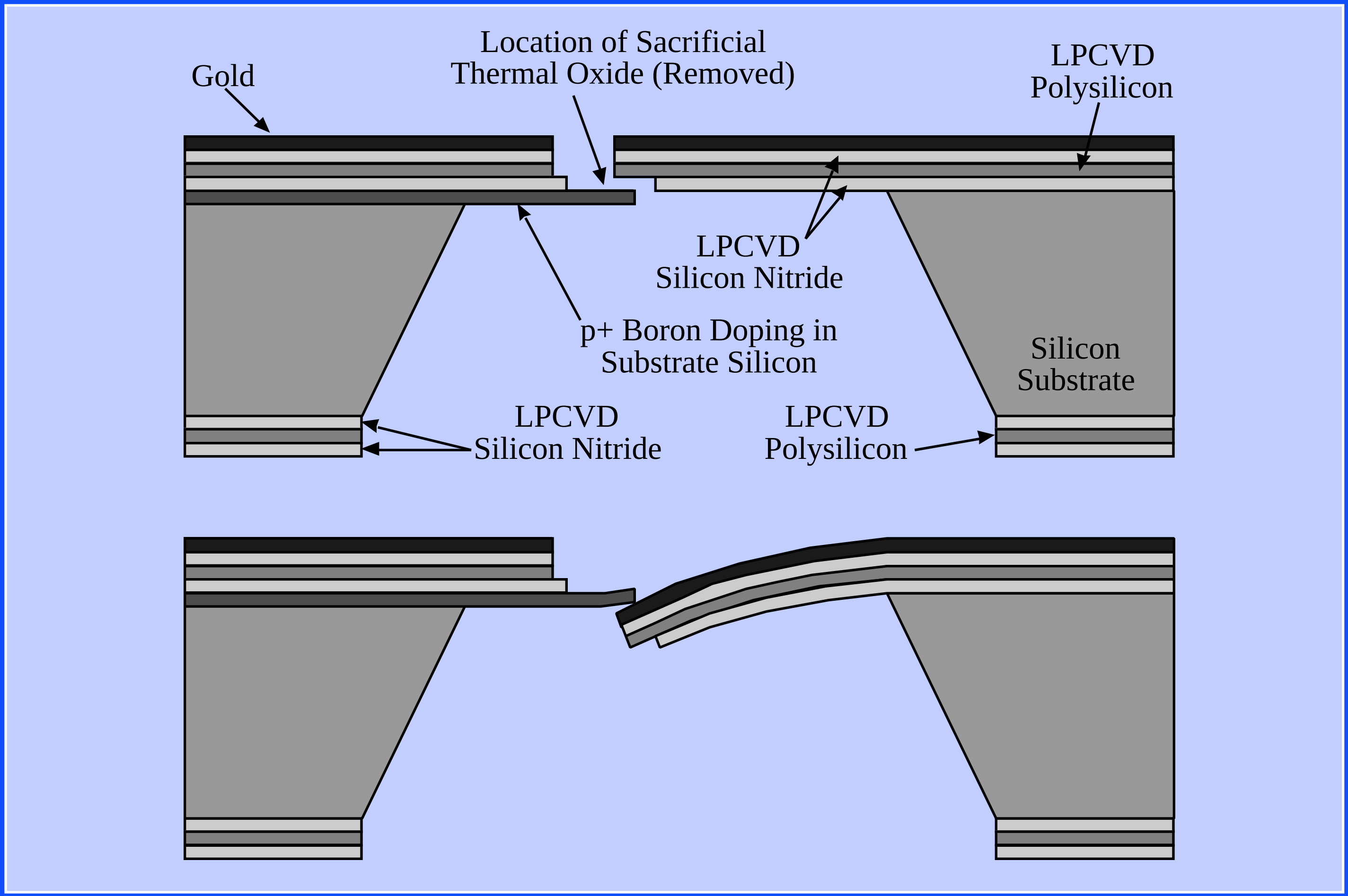



Reference: Suh, J. W., Storment, C. W. and Kovacs, G. T. A., "Characterization of Multi-Segment Organic Thermal Actuators," Digest of Technical Papers from Transducers '95/Eurosensors IX, Vol. 2, June 25 - 29, 1995, Stockholm, Sweden, pp. 333 - 336.


300 µm


10 µm

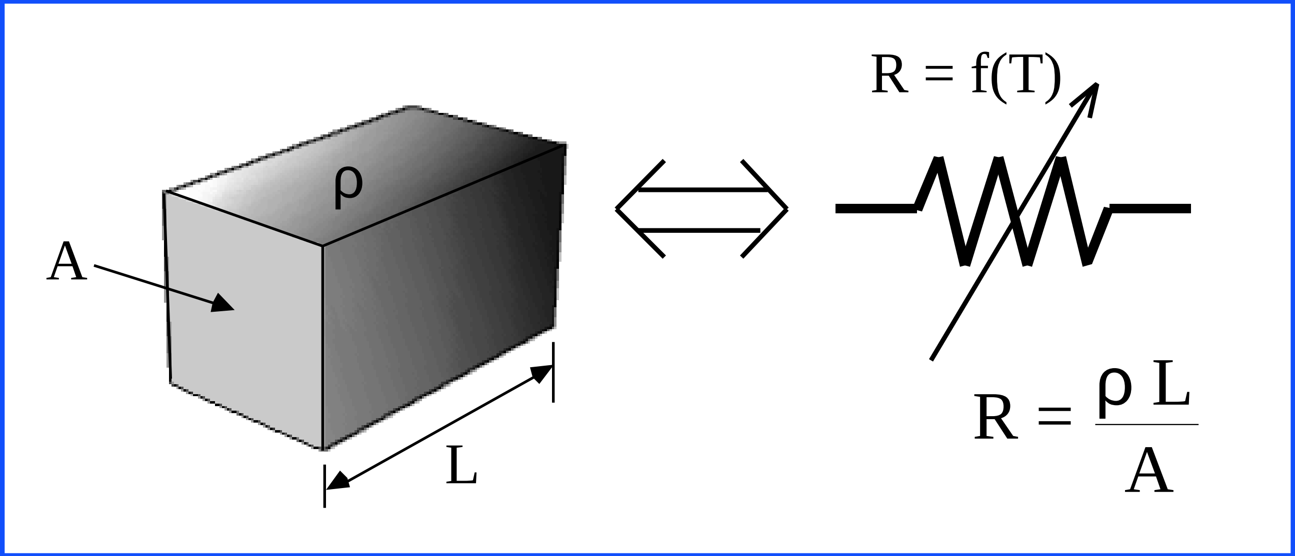
# LATCHING BIMORPH SWITCH




Reference: Goldman, K., and Mehregany, M., “A Novel Micromechanical Temperature Memory Sensor,” Proceedings of Transducers ’95, the 8th International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25 - 29, 1995, vol. 2, pp. 132 - 135.

# THERMORESISTIVE EFFECTS

- The resistivity of most materials changes with temperature.
- In general, the temperature coefficient of resistance (TCR) is positive.
- The TCR is generally quite small and sensors can be low SNR.
- Some, like Pt resistors are very accurate.



# EXAMPLE TCRs

| Material | Resistivity µΩ•cm | Temperature Coefficient of Resistance, ppm/°C |
|---|---|---|
| Carbon (graphite) | 1,390 | -500 |
| Manganin (alloy) | 48.2 | 2 |
| Nichrome | 101 | 1,700 |
| Chromium | 12.9 | 3,000 |
| Aluminum | 2.83 | 3,600 |
| Silver | 1.63 | 3,800 |
| Copper | 1.72 | 3,900 |
| Platinum | 10.6 | 3,927 |
| Tungsten | 4.20 | 4,500 |
| Iron | 9.71 | 6,510 |
| Nickel | 6.84 | 6,900 |
| Gold | 2.40 | 8,300 |

**Reference: Weast, R. C. [ed.], "CRC Handbook of Chemistry and Physics," CRC Press, Inc., Boca Raton, FL, 1988.**

# TCR LINEARITY

- **Approximation for 0 < T < 100 °C:**

$$R_T = R_o \left(1 + \alpha_R \left[T - T_o\right]\right)$$

- **More accurate (Callendar van Dusen Equation for Pt):**

$$R_T = R_o + R_o\alpha \left[T - \delta\,(0.01T - 1)(0.01T) - \beta\,(0.01T - 1)(0.01T)^3\right]$$

- **Can use the TCR in thermal feedback circuits to measure temperature of driven elements (sense and actuate with same element).**

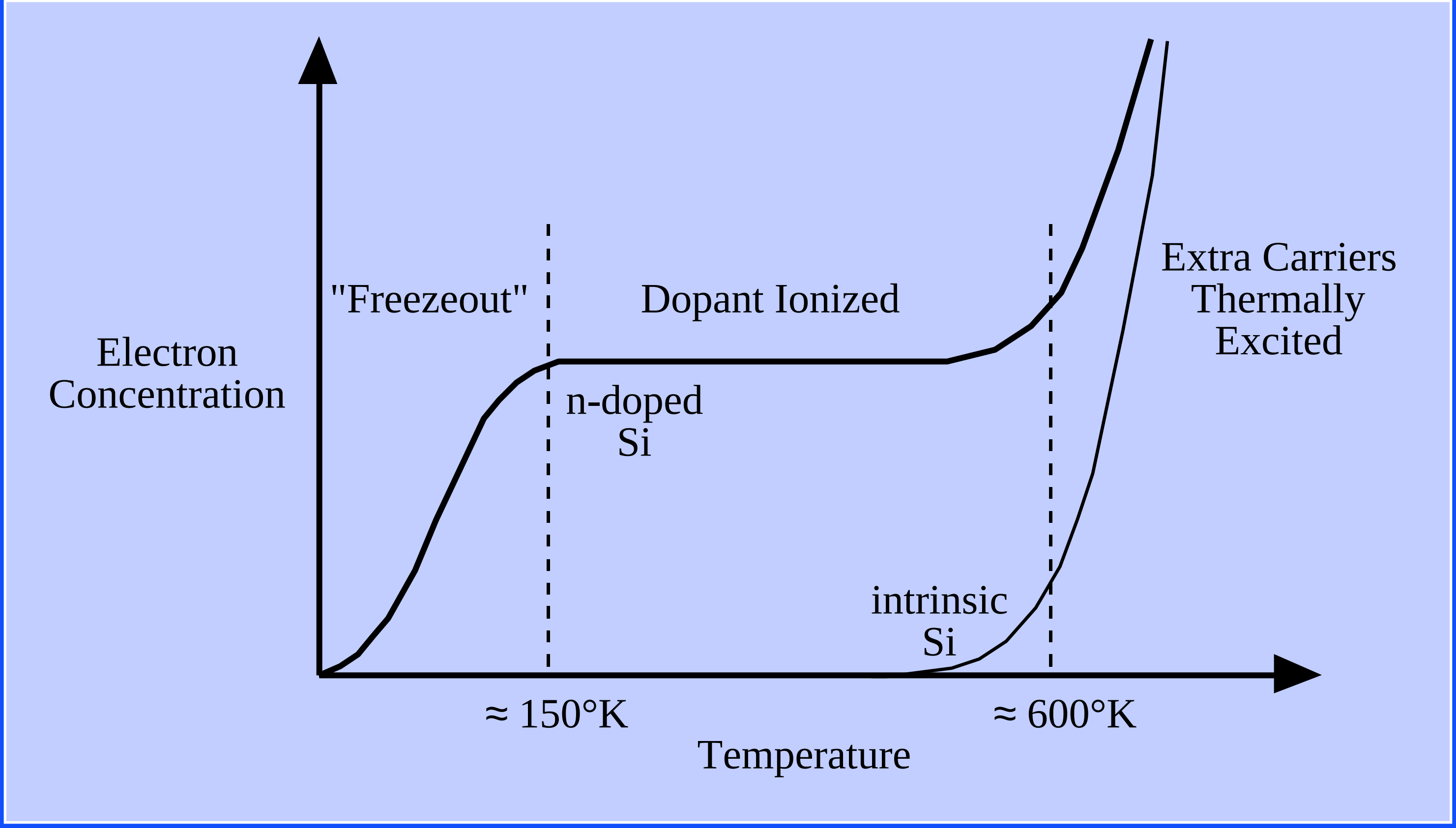
# THERMISTORS

- Sintered mixtures of oxides, selenides, sulfides, of Li, Cu, Co, Ti, Mn, Fe, Ni, U, etc., usually negative TCR (NTC).
- Can get large TCR values (4 - 6%/°C versus <1% for typical materials).
- Very interchangeable (+/- 0.1% devices are common).
- Can be integrated by plasma spray methods, etc., but little work has been done on this (other methods of sensing work well).
- Use Steinhart-Hart Equation for calibration:

$$T = \left\{a + b\ln(R) + c[\ln(R)]^3\right\}^{-1}$$

# SEMICONDUCTOR THERMORESISTORS

- **Not very practical for most temperature ranges, but can be used for cryogenics.**

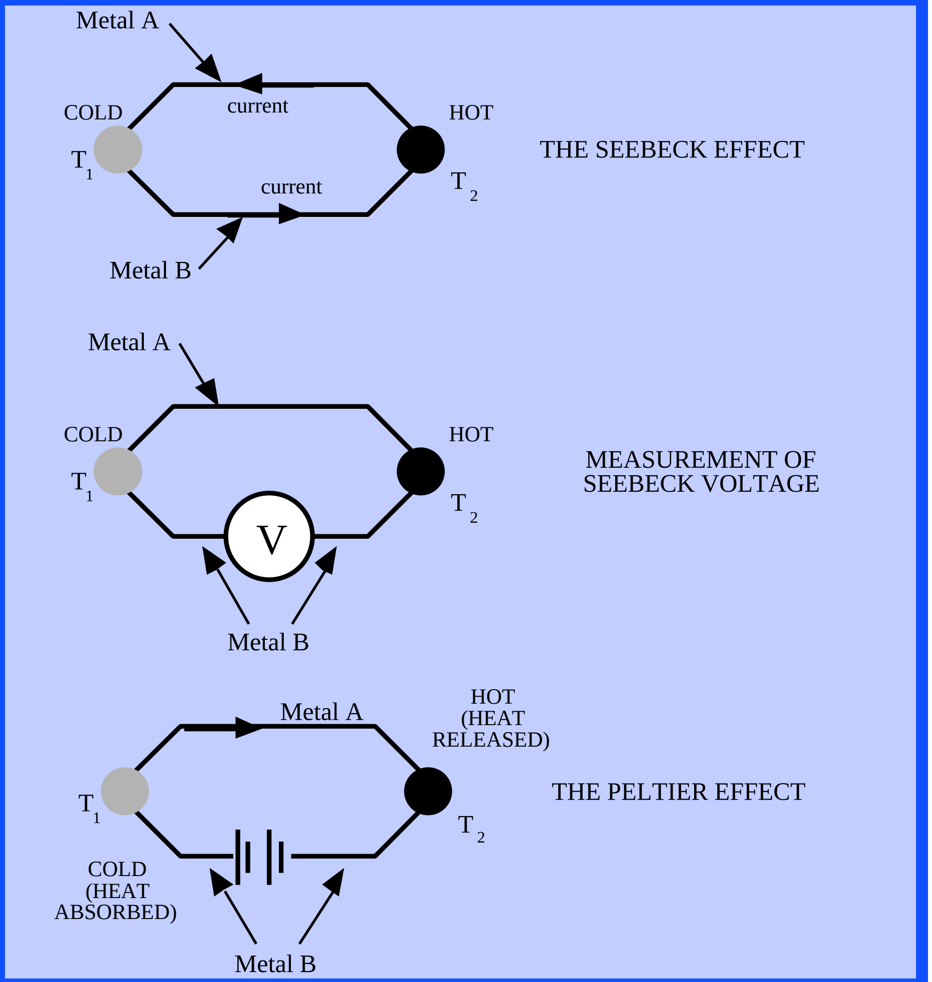



**Reference: Muller, R. S., and Kamins, T. I., "Device Electronics for Integrated Circuits," Second Edition, John Wiley and Sons, New York, NY, 1986.**

# THERMOCOUPLES

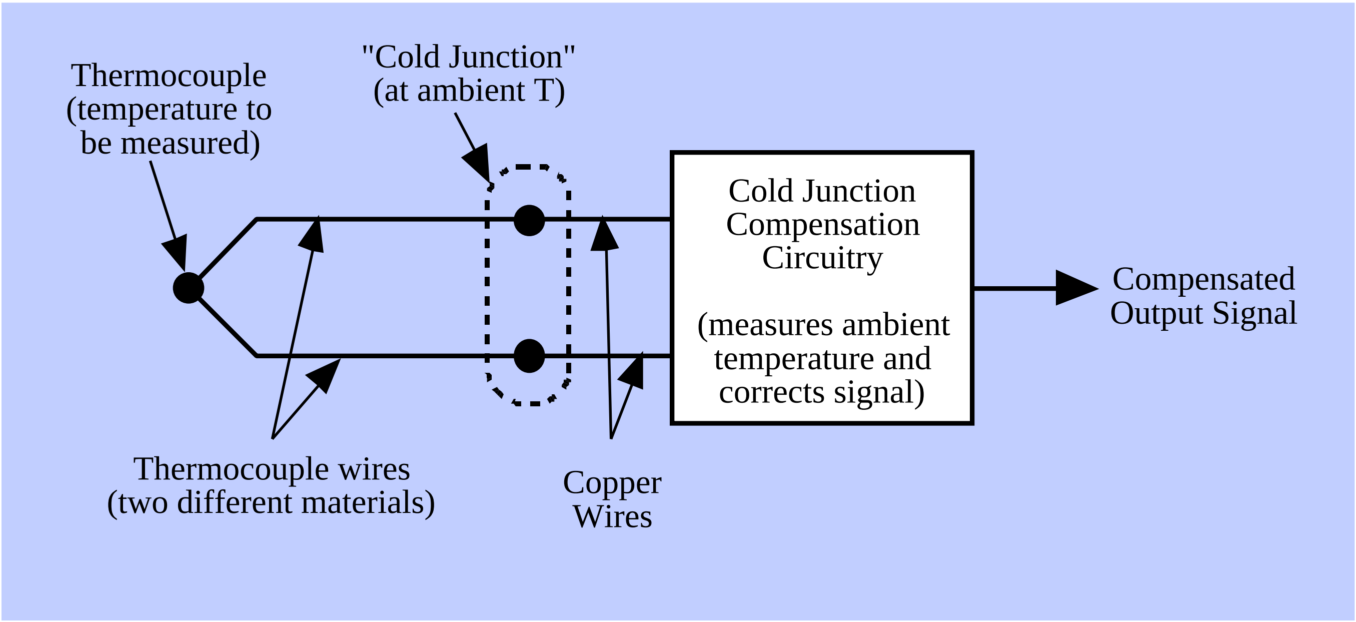
- Hot electrons on the hot side migrate to the cold side, setting up an electric field that opposes the diffusion of further hot electrons.
- Junction between two different conductors, output signals on the order of 50μV/°C and can cover temperatures as broad as -270°C to 2700°C.
- Accuracies are typically on the order of 0.5 - 2 °C.
- Easy to microfabricate!

$$V \approx \alpha\left(T_1 - T_2\right) + \gamma\left(T_1^2 - T_2^2\right)$$

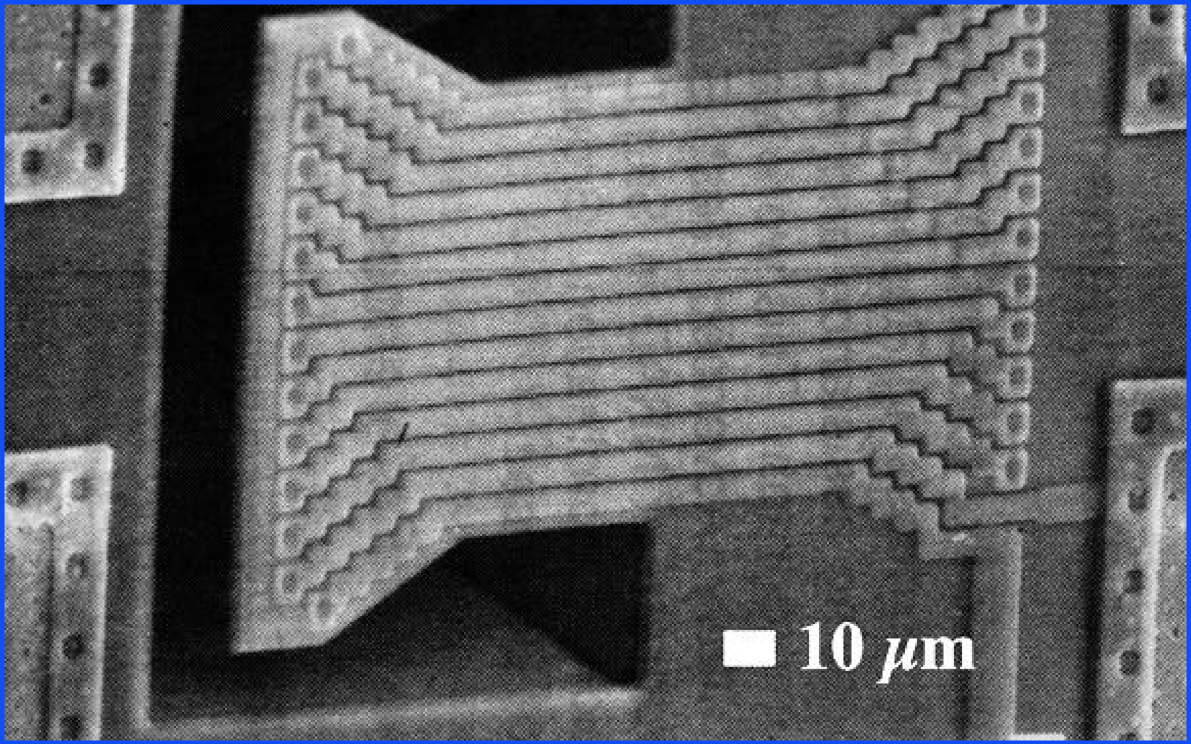


# THERMOCOUPLE OPERATION

- Normally refer a thermocouple to another thermocouple at a reference temperature ("cold junction") to get absolute temperature measurements.
- Solid-state techniques can be used to generate appropriate reference voltages.



# CMOS THERMOPILE




**EDP-undercut, Al/Poly-Si thermocouples shown have α ≈ 50 μV/°C.**

**Source: Gaitan, M., Kinard, J., and Huang, D. X., “Performance of Commercial CMOS Foundry-Compatible Multijunction Thermal Converters,” Proceedings of Transducers ’93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, pp. 736 - 741.**

# JUNCTION-BASED THERMAL SENSORS

- The current flowing in a forward biased diode with an applied voltage $V_D$ is,

$$I_D = I_S\left[e^{\left(\frac{qV_D}{nkT}\right)} - 1\right] \approx I_S e^{\left(\frac{qV_D}{nkT}\right)}$$

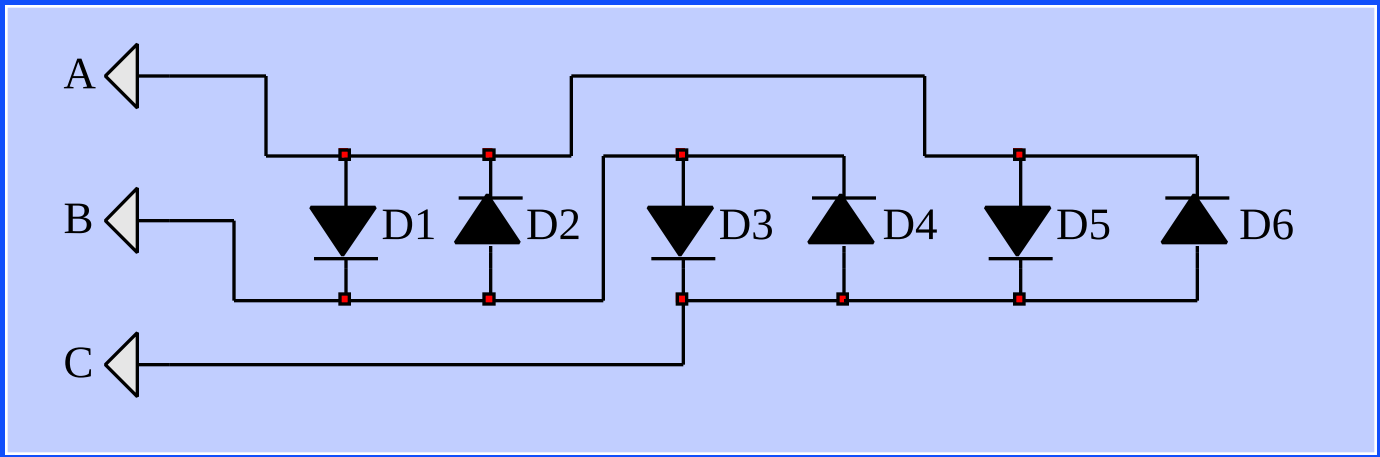
- For constant-current drive, this gives a temperature coefficient of -2 mV/°C, primarily due to $I_s$, which roughly doubles for every 5°C increase.

$$V_D = \frac{nkT}{q}\ln\left(\frac{I_D}{I_S}\right)$$

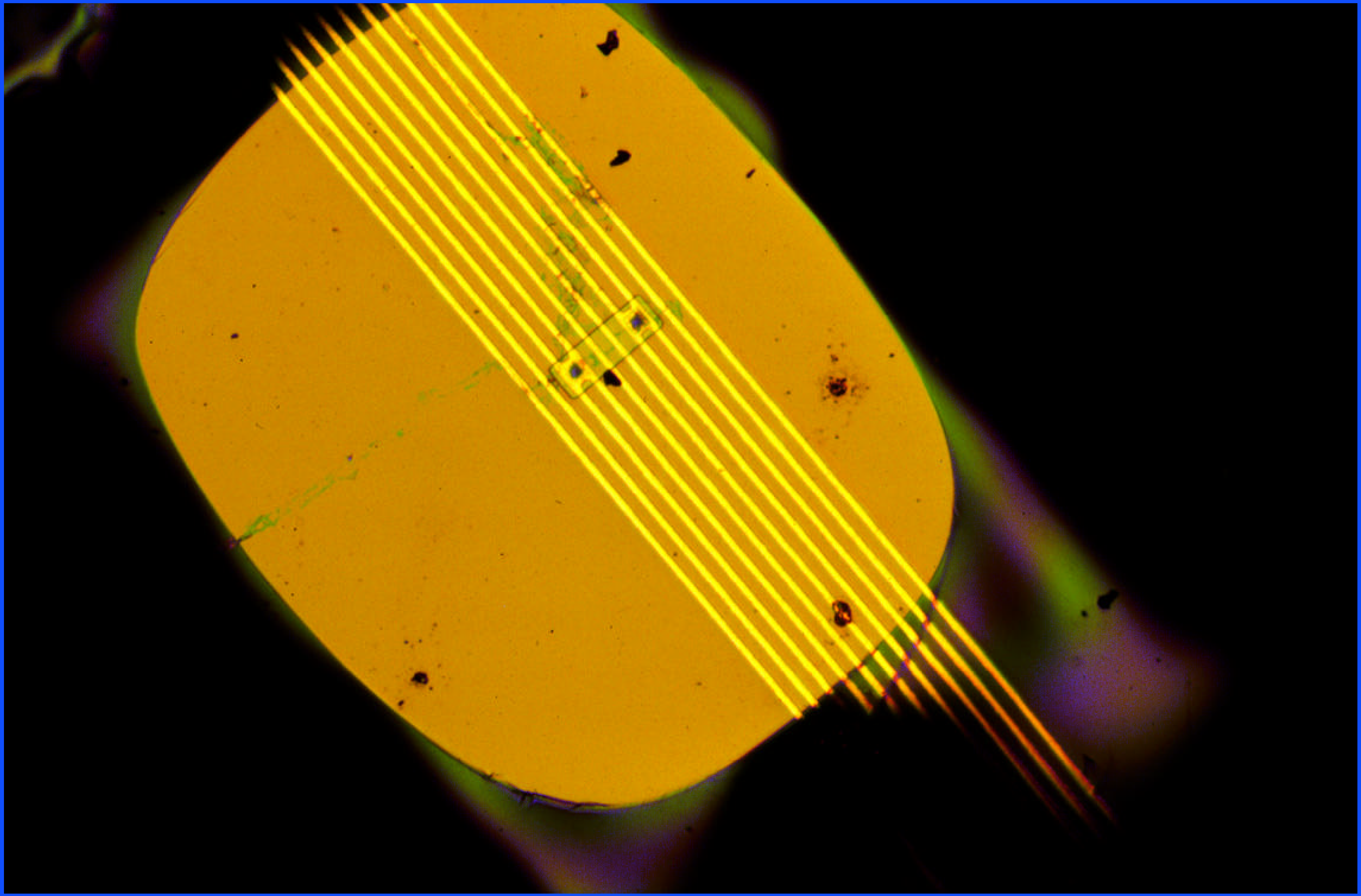
- The case for a bipolar transistor is similar,

$$V_{BE} = \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$$

# MICROMACHINED DIODE TEMPERATURE SENSOR ARRAY




Reference: Barth, P. W., and Angell, J. B., “Thin Linear Thermometer Arrays for Use in Localized Cancer Hyperthermia,” IEEE Transactions on Electron Devices, vol. ED-29, no. 1, Jan. 1982, pp. 144 - 150.



Reference: Barth, P. W., and Angell, J. B., “Thin Linear Thermometer Arrays for Use in Localized Cancer Hyperthermia,” IEEE Transactions on Electron Devices, vol. ED-29, no. 1, Jan. 1982, pp. 144 - 150.

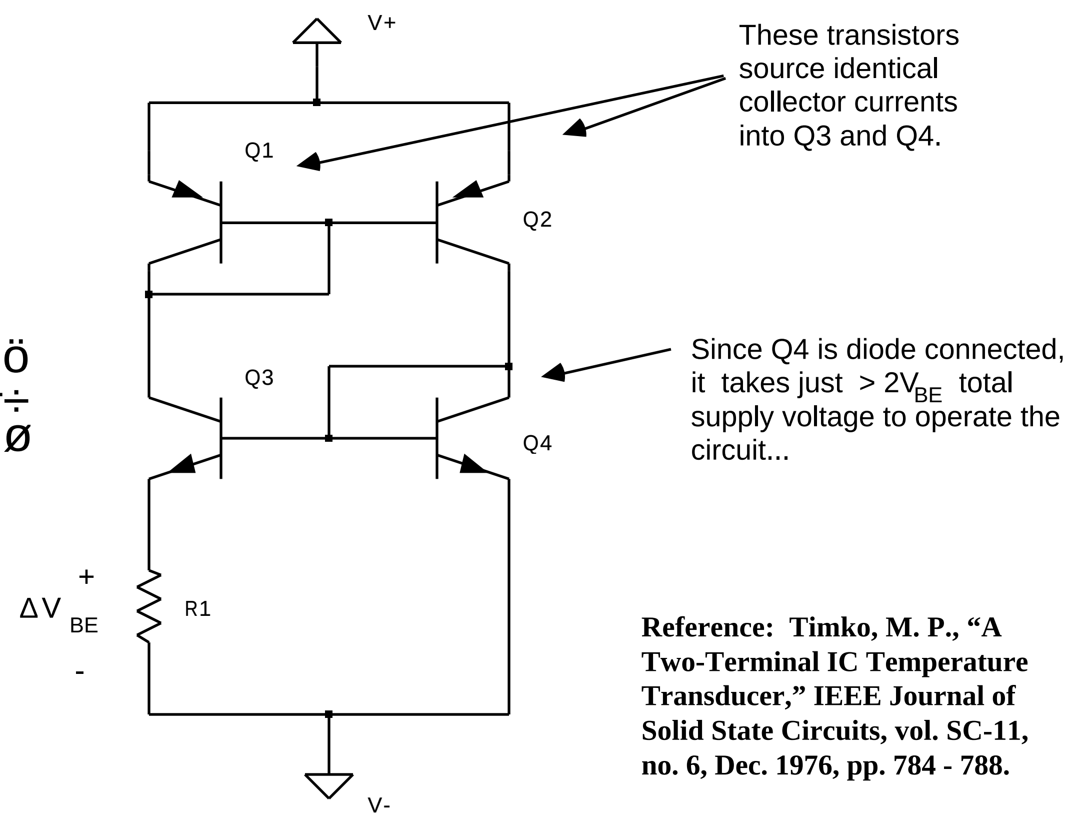
# PTAT CIRCUITS

- One can use a pair of BJTs with different emitter areas and the same $I_C$ and measure $\Delta V_{BE}$ to measure temperature, since $\Delta V_{BE}$ = k • T.

- It is possible to program the scaling factor through the emitter areas,

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln\left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}}\right)$$

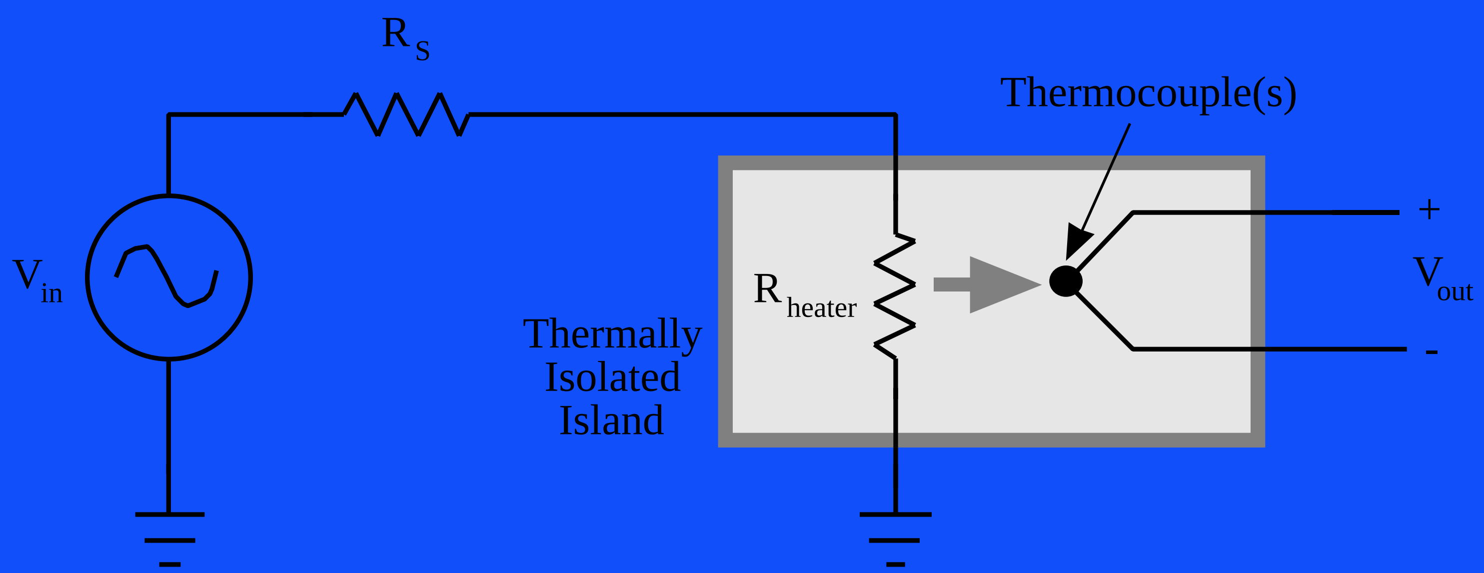
- The classic chip is the AD592, with 1 µA/°K output current over -55 to +125 °C.



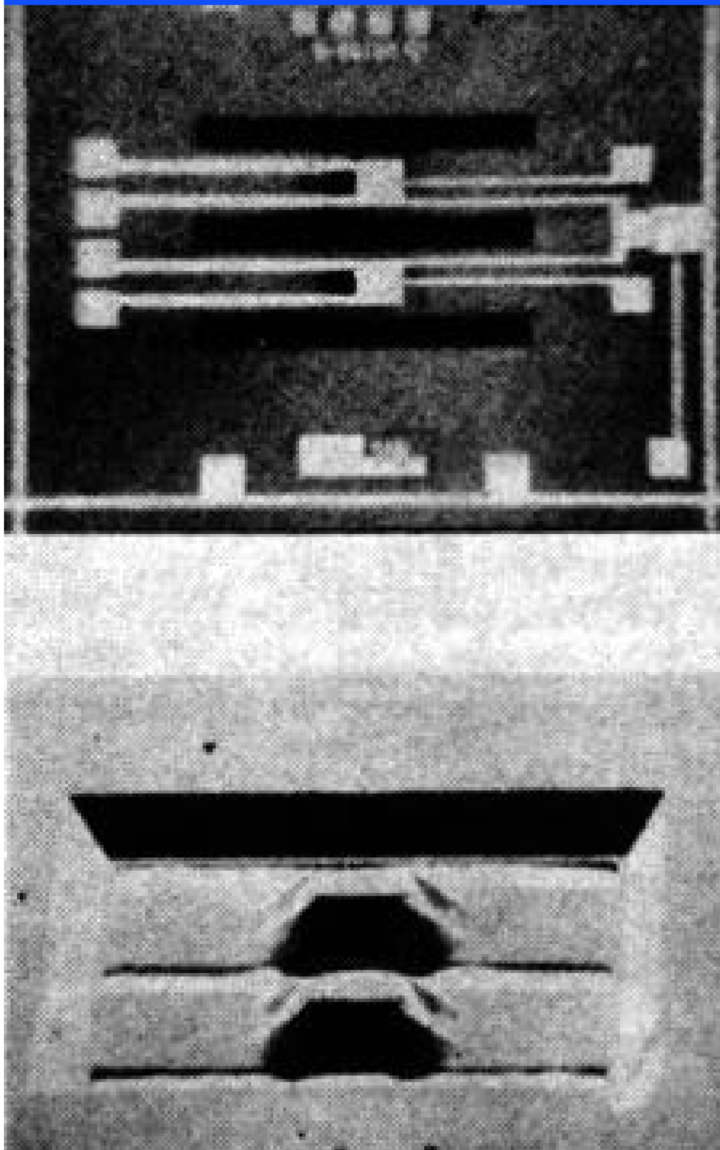

**Reference: Timko, M. P., "A Two-Terminal IC Temperature Transducer," IEEE Journal of Solid State Circuits, vol. SC-11, no. 6, Dec. 1976, pp. 784 - 788.**

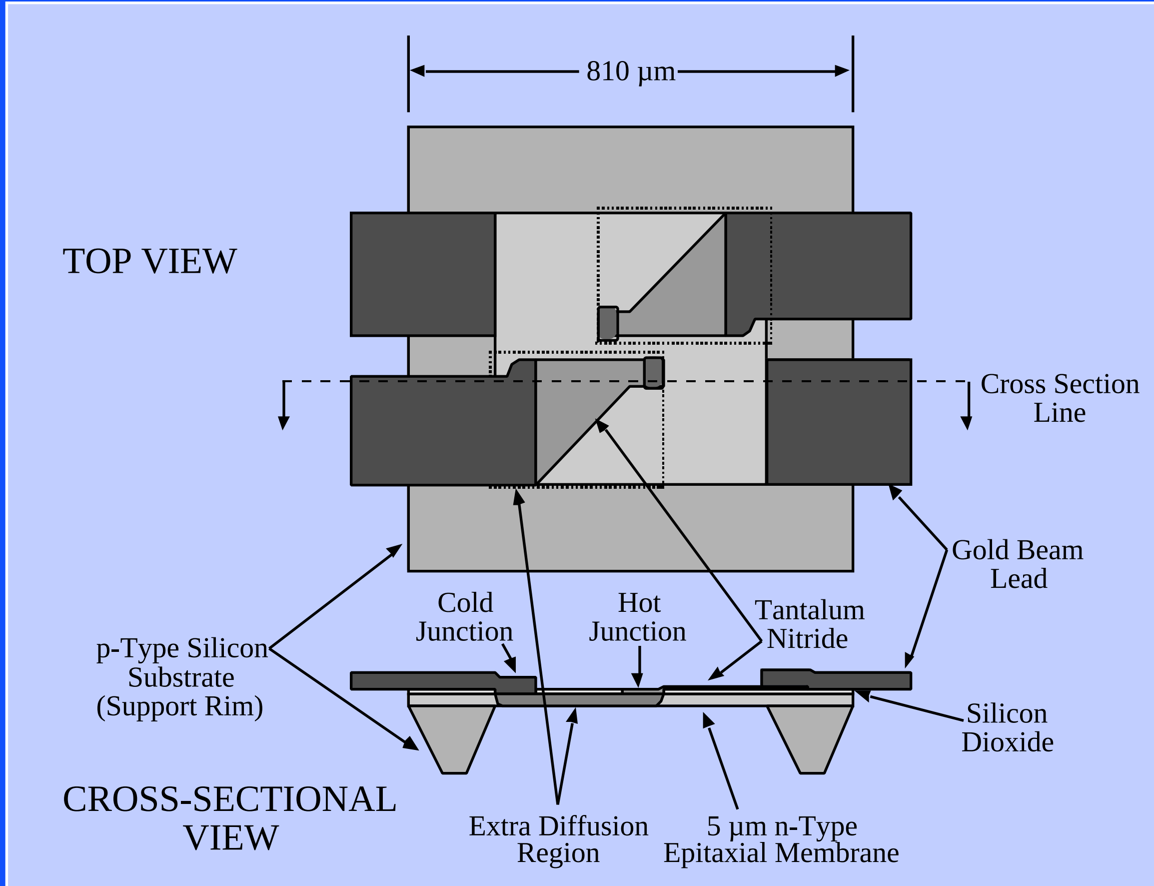
# THERMAL AC/RMS CONVERTERS

- Such devices can determine the RMS value of a signal up to very high frequencies (versus analog computation).
- Dissipate input signal power in heater resistor and measure the temperature of a thermally isolated (hopefully) region.
- Can measure with thermocouples, junctions, etc.

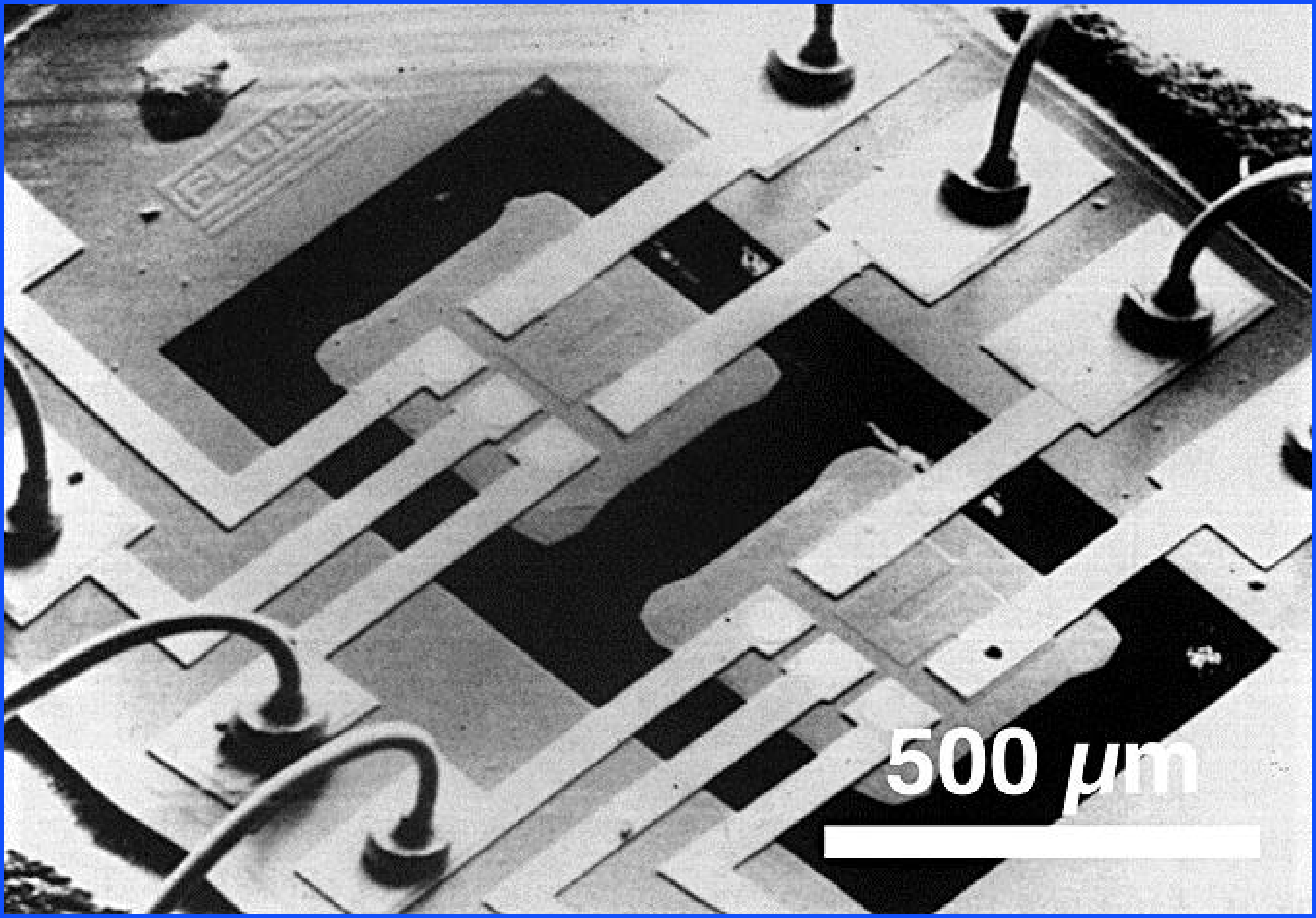


# HP THERMAL RMS CHIP

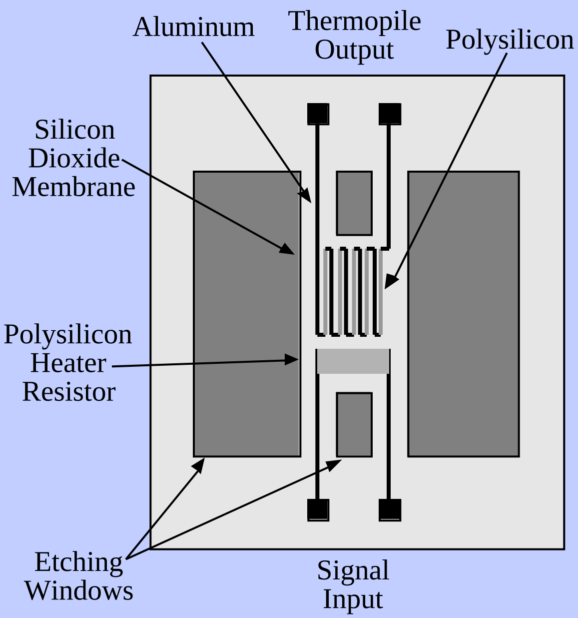




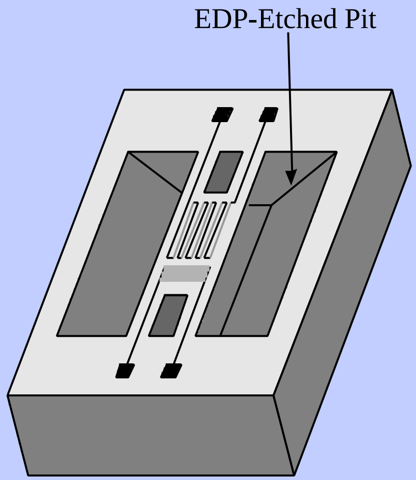

Source (Images): Jackson, W. H., "A Thin-Film/Semiconductor Thermocouple for Microwave Power Measurements," Hewlett Packard Journal, Sept. 1974, pp. 16 - 18.



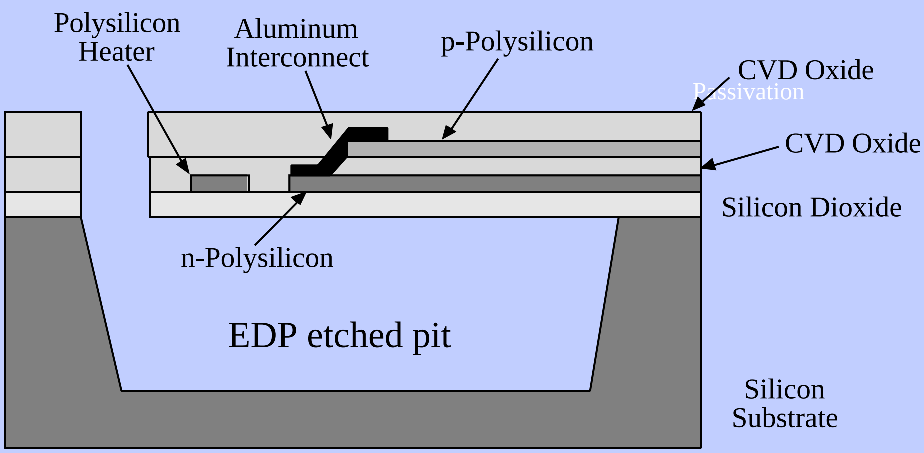

Source: van Herwaarden, A. W., and Meijer, G. C. M., "Thermal Sensors," Chapter 7 in, "Semiconductor Sensors," S. M. Sze [ed.], John Wiley and Sons, Inc., 1994.




Device as Received from CMOS Fabrication Service



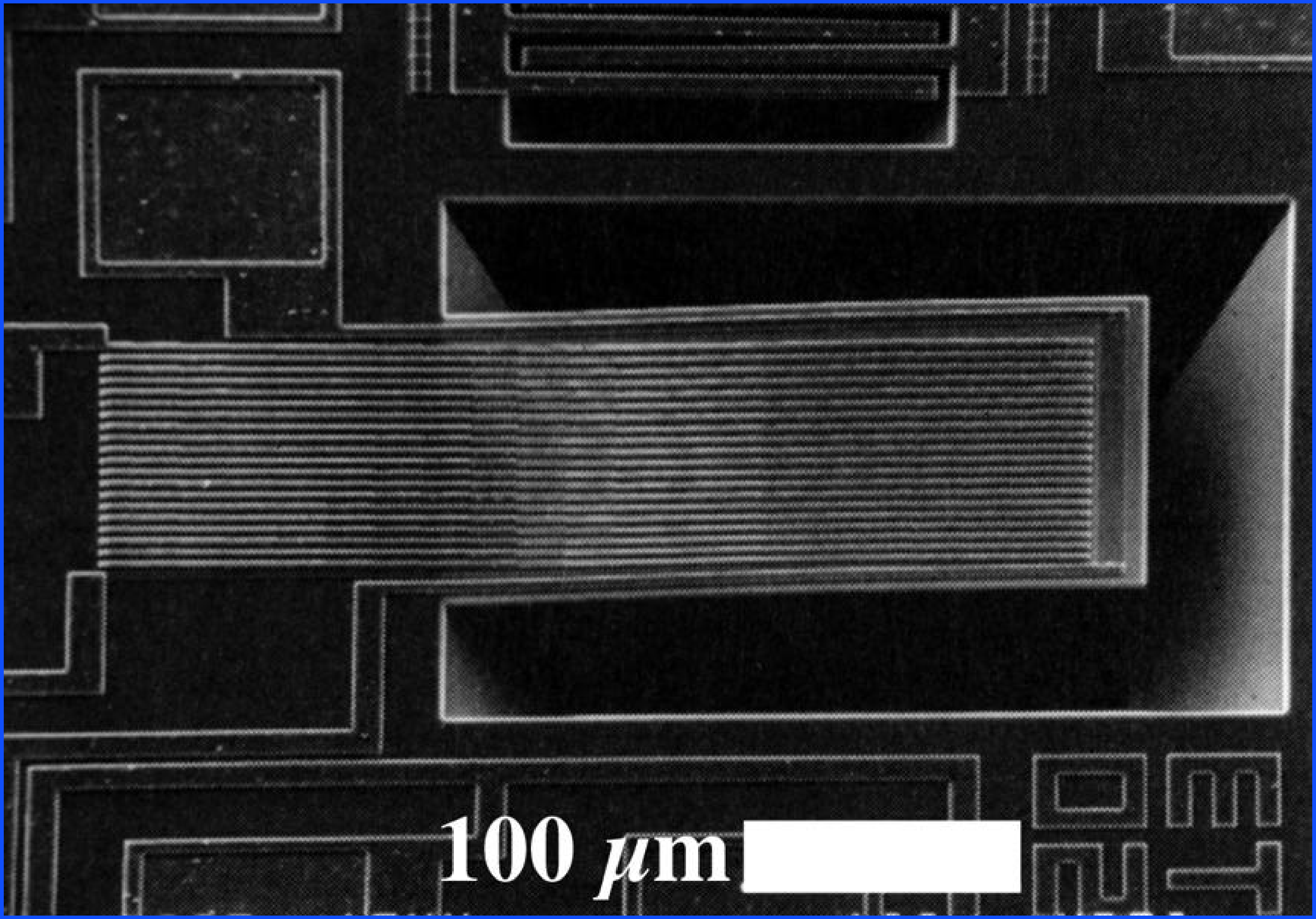

Device Following EDP Post-Processing Step



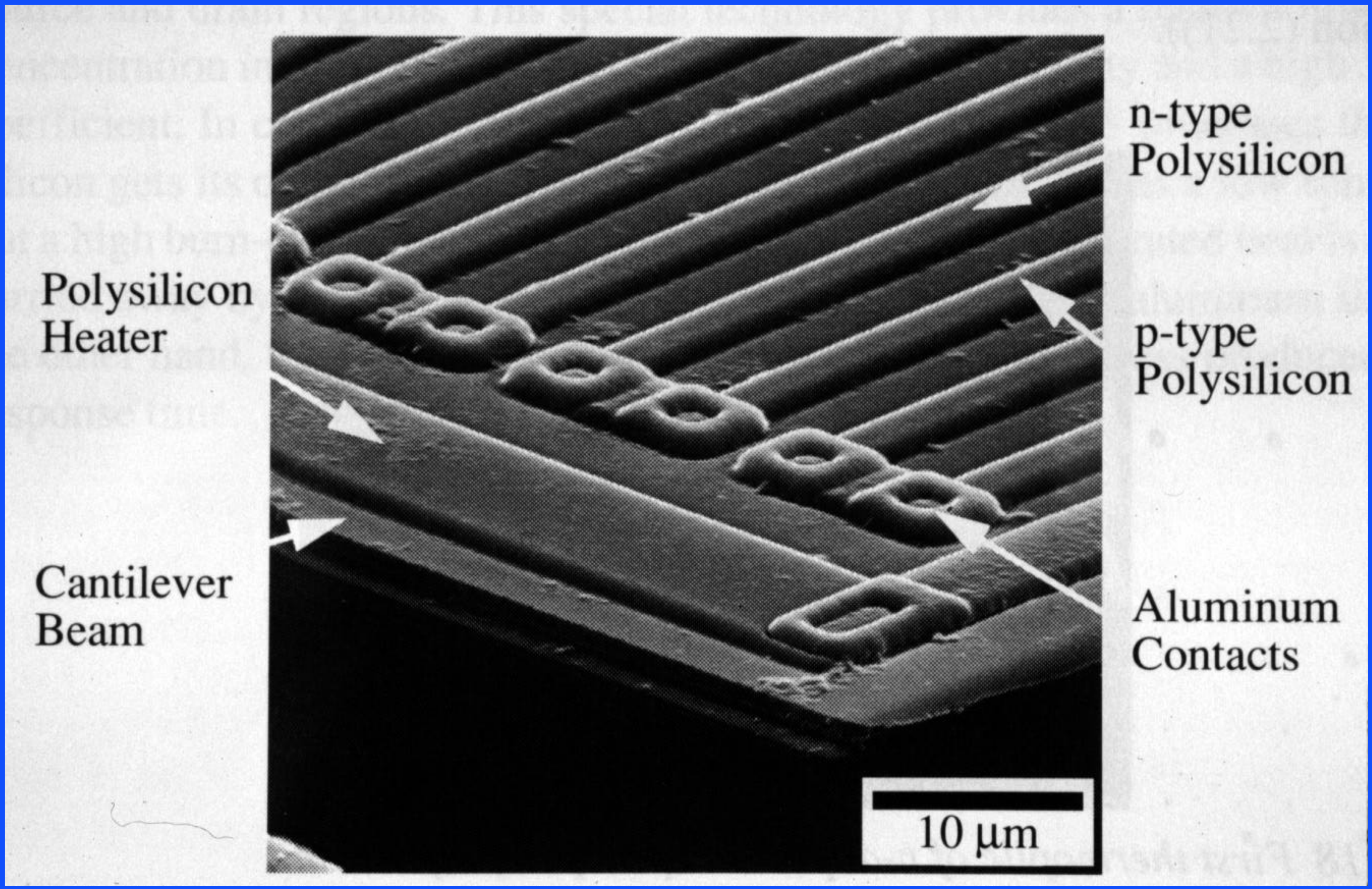

# CMOS THERMAL RMS CONVERTERS

**References: Jaeggi, D., Baltes, H., and Moser, D., "Thermoelectric AC Power Sensor by CMOS Technology," IEEE Electron Device Letters, vol. 13, no. 7, July 1992, pp. 366-368.**

**Baltes, H., and Moser, D., "CMOS Vacuum Sensors and Other Applications of CMOS Thermopiles," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, pp. 736 - 741.**



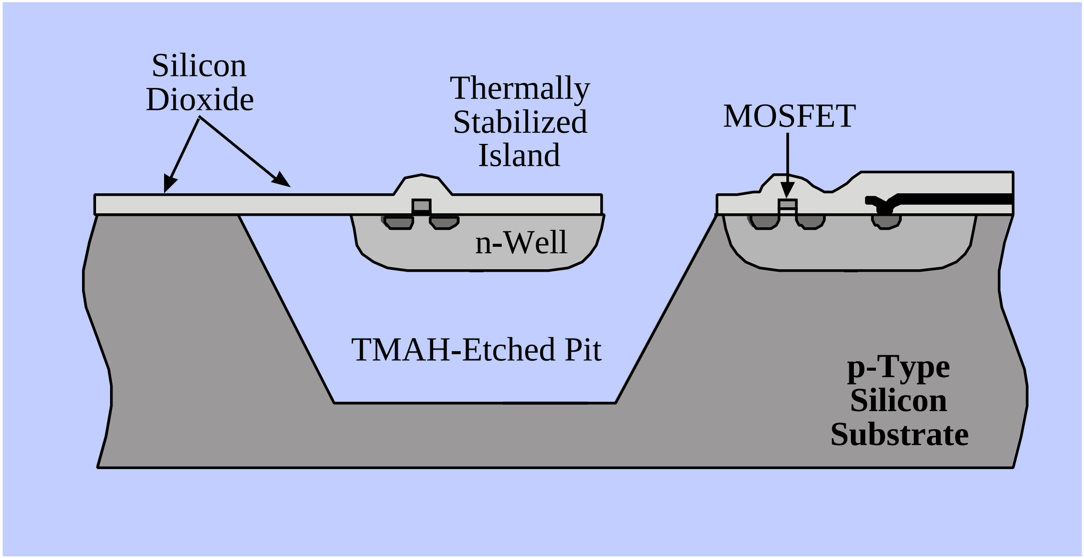

Courtesy Prof. H. Baltes, ETH Zurich.



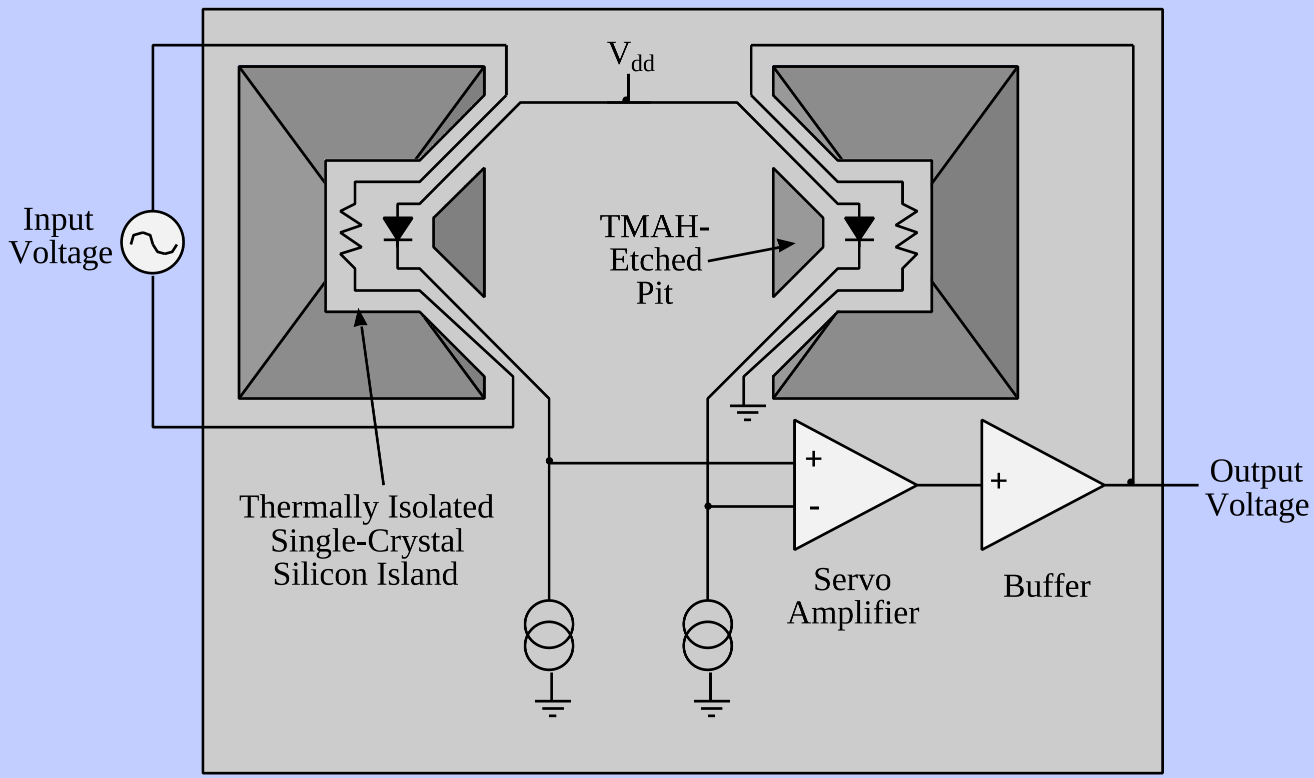

**Courtesy Prof. H. Baltes, ETH Zurich.**

# n-WELL ELECTROCHEMICAL ETCH-STOP

- Electrochemical etch-stop applied to CMOS n-wells.
- TMAH etchant does not attack exposed aluminum.
- Extremely high thermal isolation possible (> 60,000°/W)
- Will survive extreme shocks (mass very small!).
- Available devices: NPN BJTs, PNP lateral BJTs, PMOS transistors, diffused resistors, PN diodes, polysilicon heaters

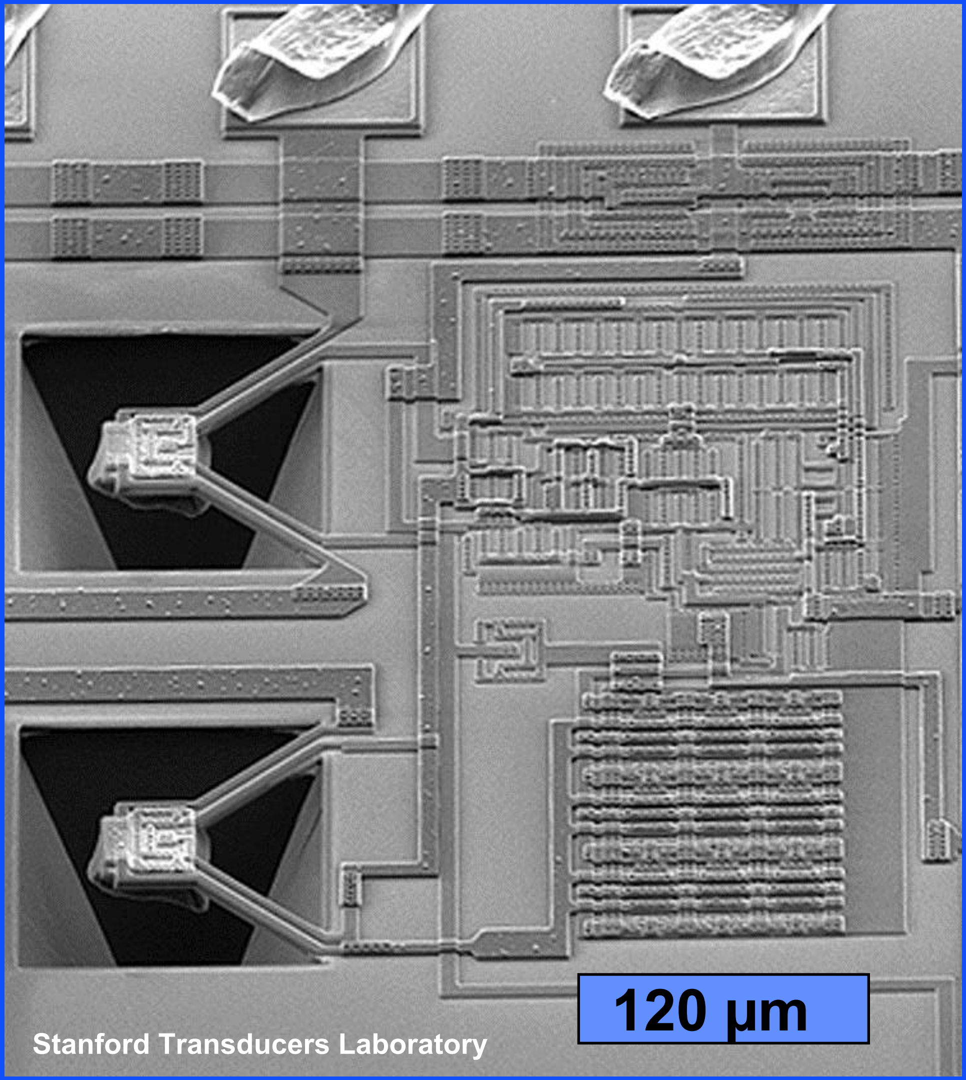


# SERVO RMS CONVERTER



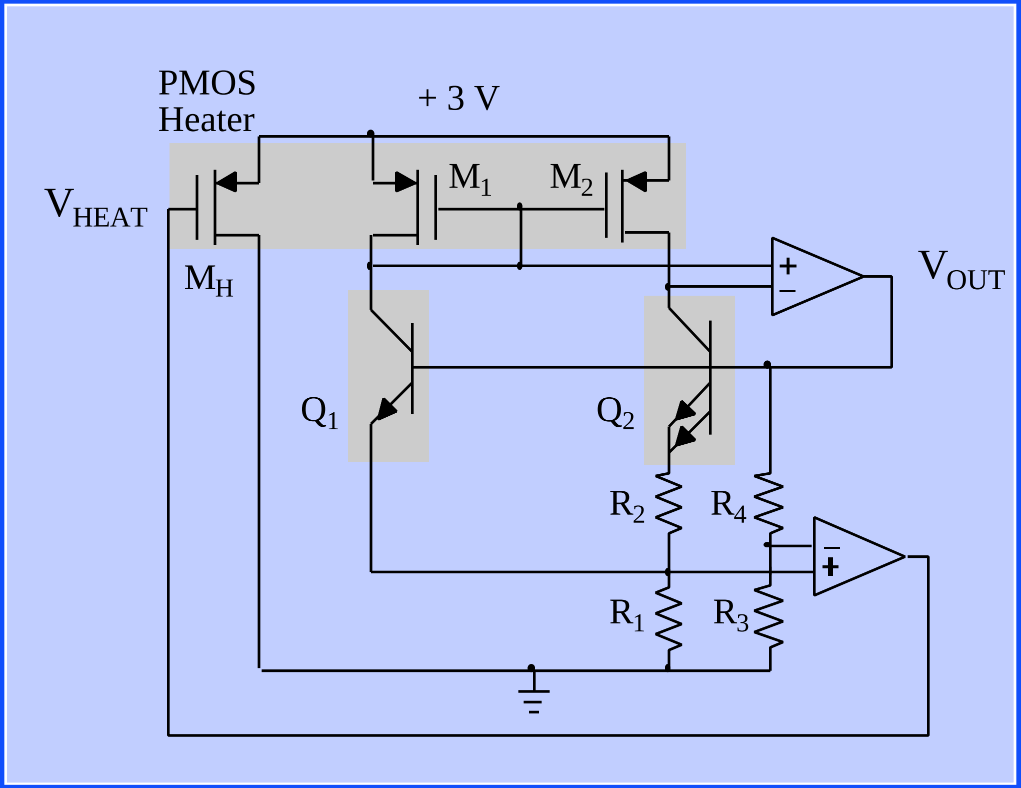
# THERMAL RMS CONVERTER

- On-chip servo matches DC power in one island to RF input power in other, inherently computing RMS input power.
- > 400 MHz response, 60 dB dynamic range, < 1% nonlinearity.
- 950 µW quiescent power, 400 X 400 µm including servo circuits.

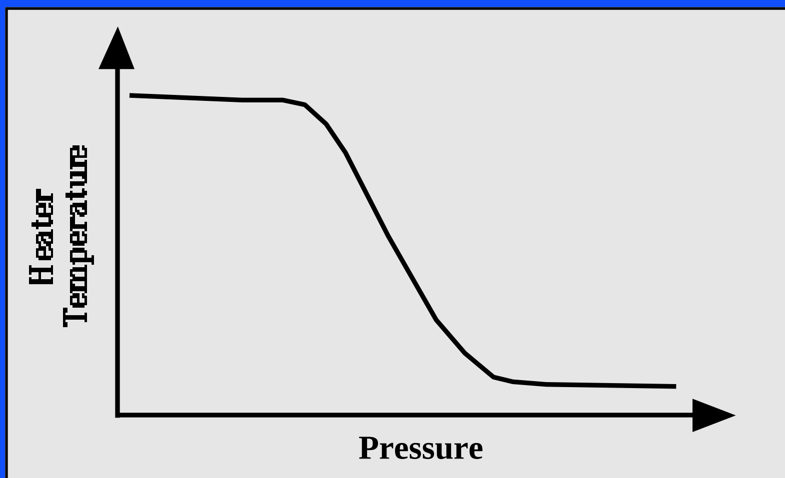


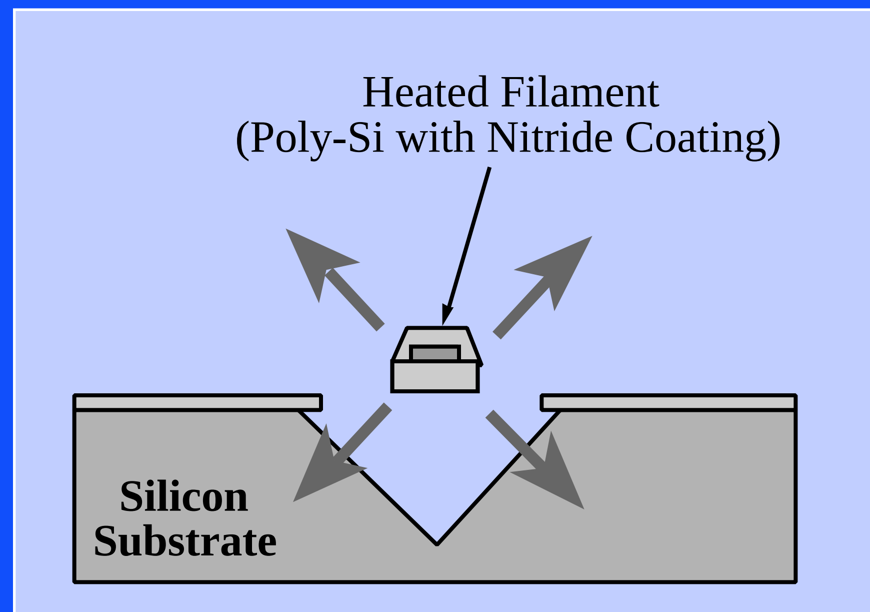

**Reference: Klaassen, E. H., Reay, R. J. and Kovacs, G. T. A., "Diode-Based Thermal RMS Converter with On-Chip Circuitry Fabricated Using Standard CMOS Technology," Digest of Technical Papers from Transducers '95/Eurosensors IX, Vol. 1, June 25 - 29, 1995, Stockholm, Sweden, pp. 154 - 157.**

# THERMALLY STABILIZED CIRCUITS



# PIRANI-TYPE PRESSURE SENSORS

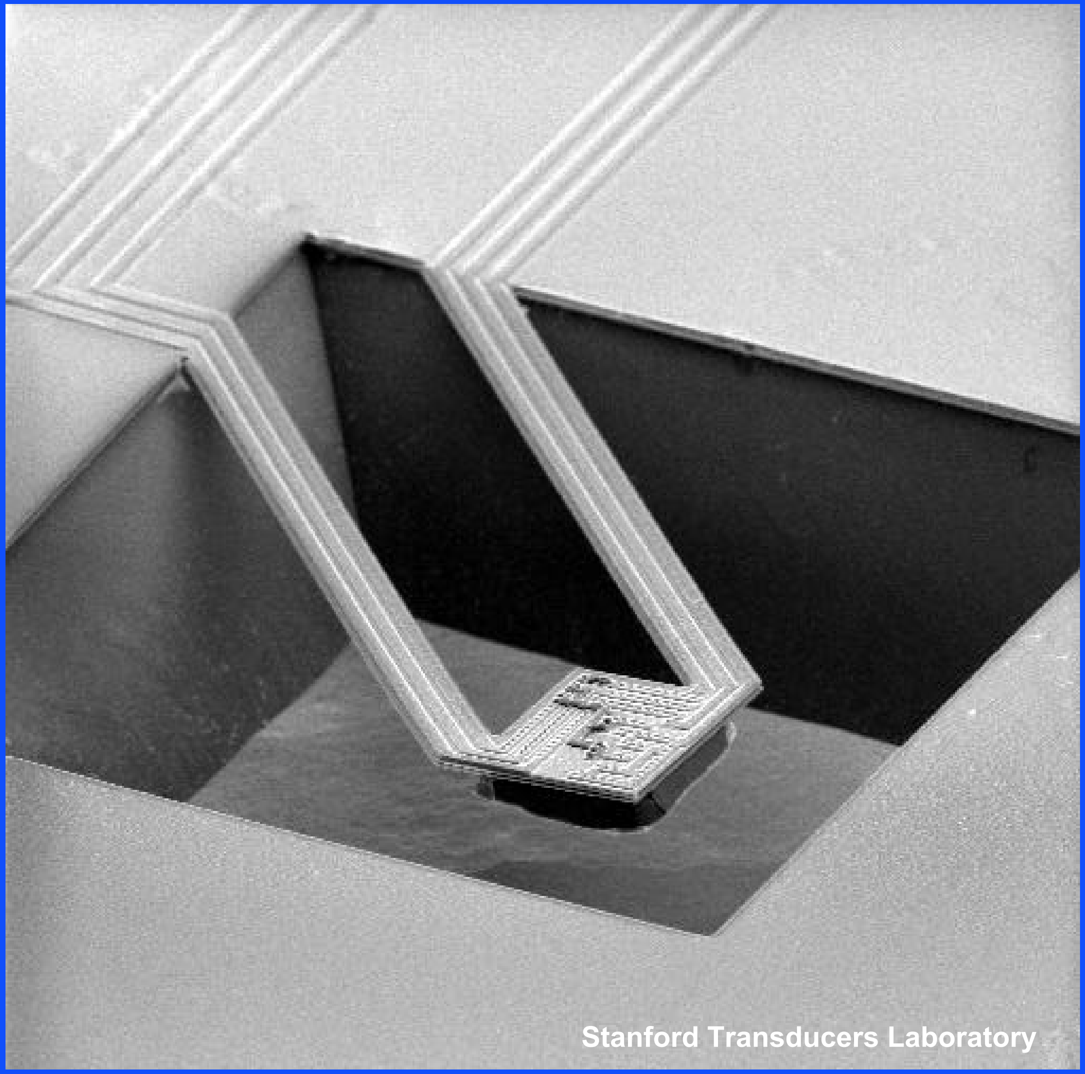



- **Heat a thermally isolated region with known input power and measure its temperature.**
- **Losses (and hence cooling) are related to conduction through gas (and perhaps convection in some cases).**

**Reference: Mastrangelo, C. H., and Muller, R. S., “Thermal Absolute-Pressure Sensor with On-Chip Digital Front-End Processor,” IEEE Journal of Solid-State Circuits, vol. 26, no. 12, Dec. 1991, pp. 1998 - 2007.**

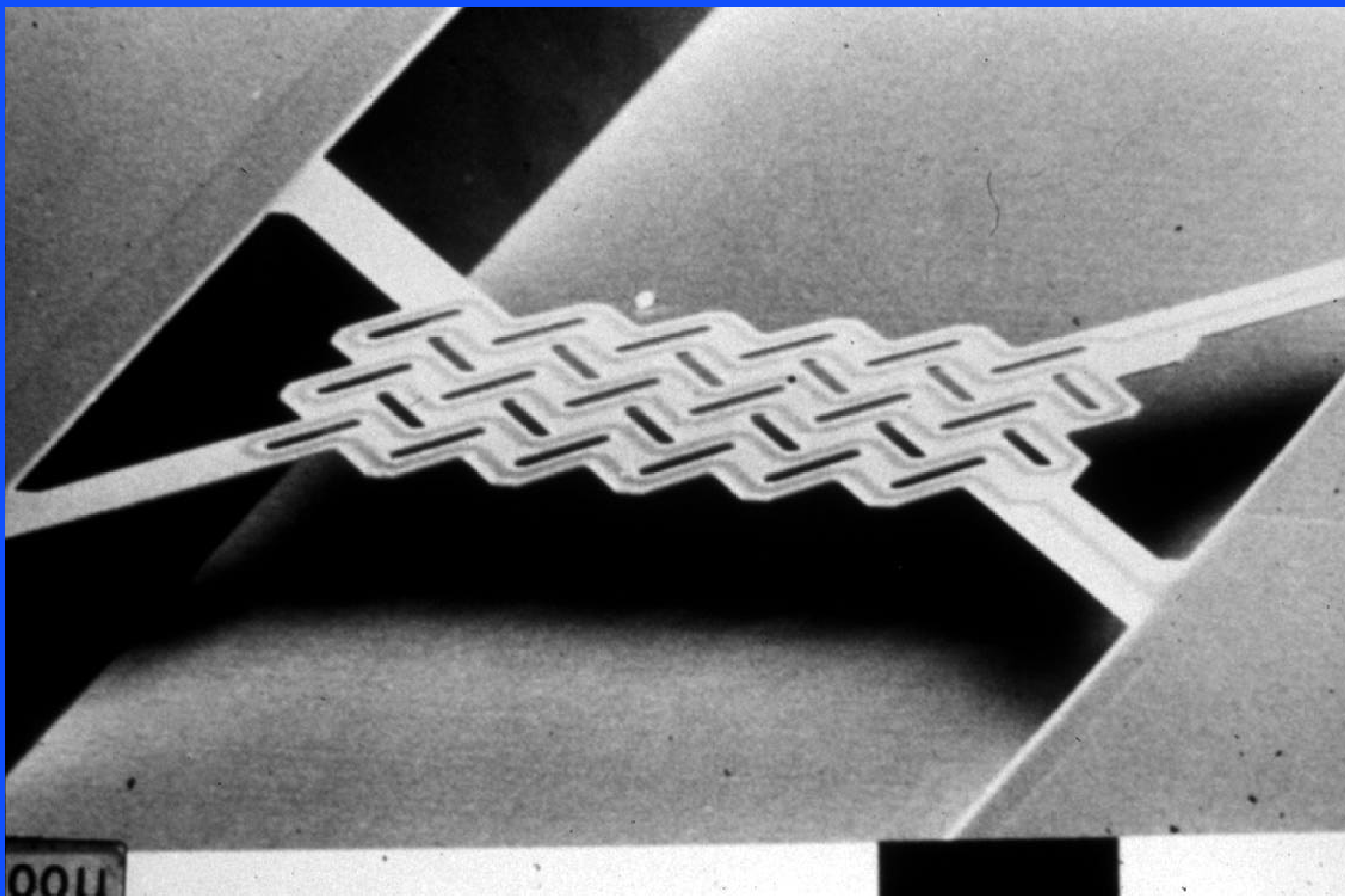
# THERMAL VACUUM SENSOR




- **Pirani type pressure sensor that makes use of measurement of heat loss to measure pressure.**
- **Heat loss decreases at low pressures.**
- **Good thermal isolation is essential or conducted loss dominates.**

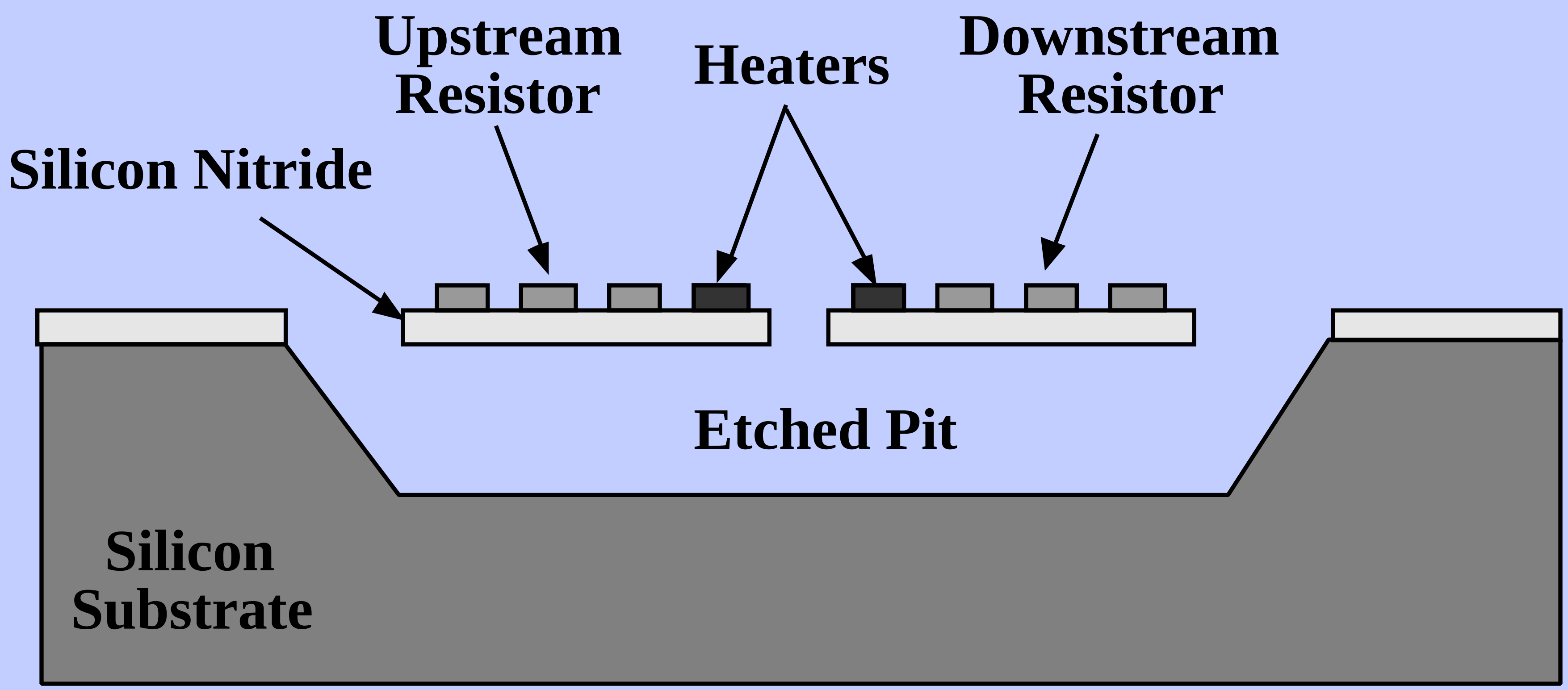
**Reference: Klaassen, E. H., and Kovacs, G. T. A., "Integrated Thermal Conductivity Vacuum Sensor," Sensors and Actuators, vol. A58, no. 1, Jan. 1997, pp. 37 - 42.**

# THERMAL MASS FLOW SENSOR

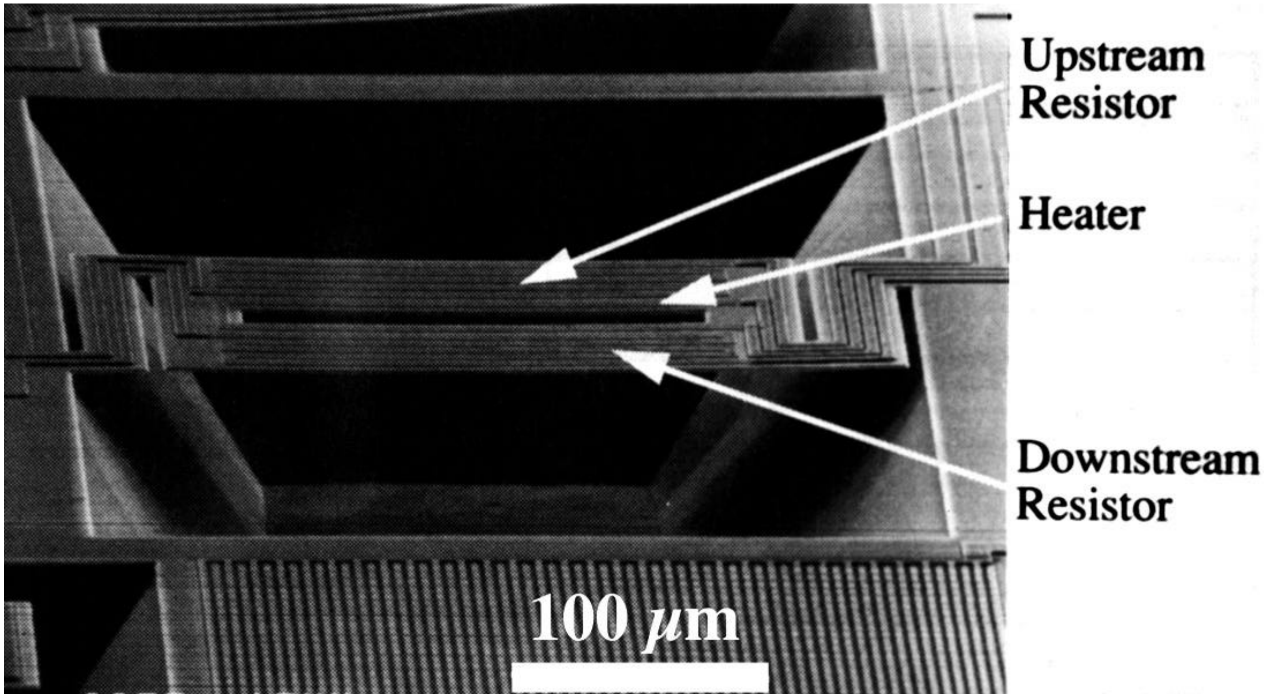


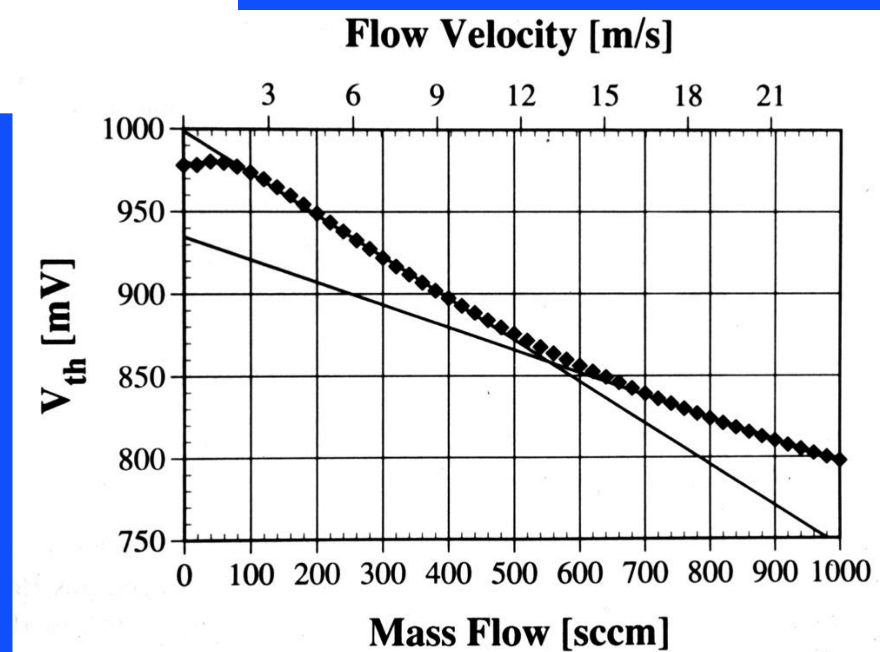
**Courtesy Prof. K. Petersen, Stanford University.**

# THERMAL MASS FLOW SENSOR

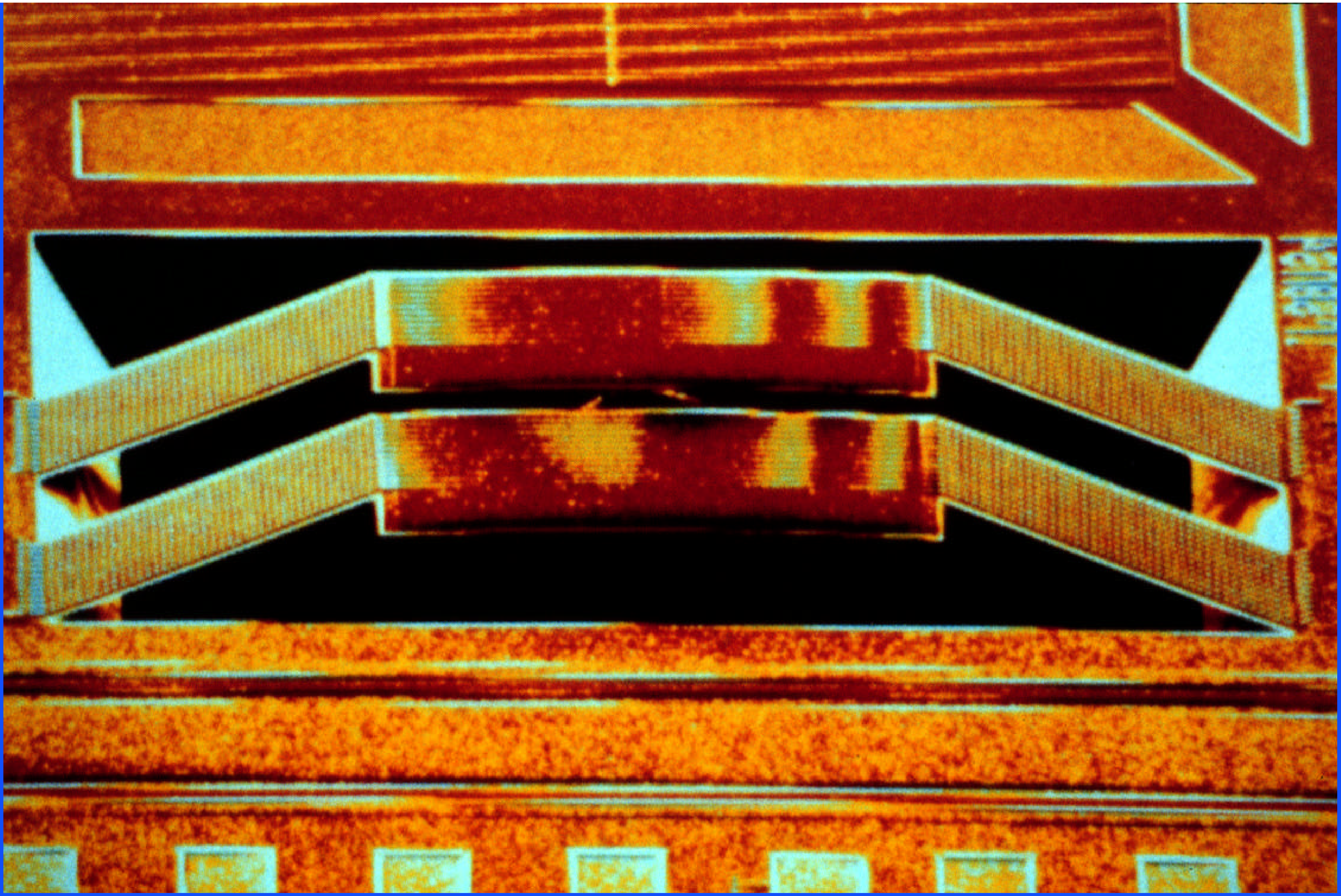



Reference: Johnson, R. G., and Higashi, R. E., “A Highly Sensitive Silicon Chip Microtransducer for Air Flow and Differential Pressure Sensing Applications,” Sensors and Actuators, vol. 11, no. 1, Jan. 1987, pp. 63 - 72.




Source: Moser, D., “CMOS Flow Sensors,” Doctoral Dissertation, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, No. 10059, 1993.

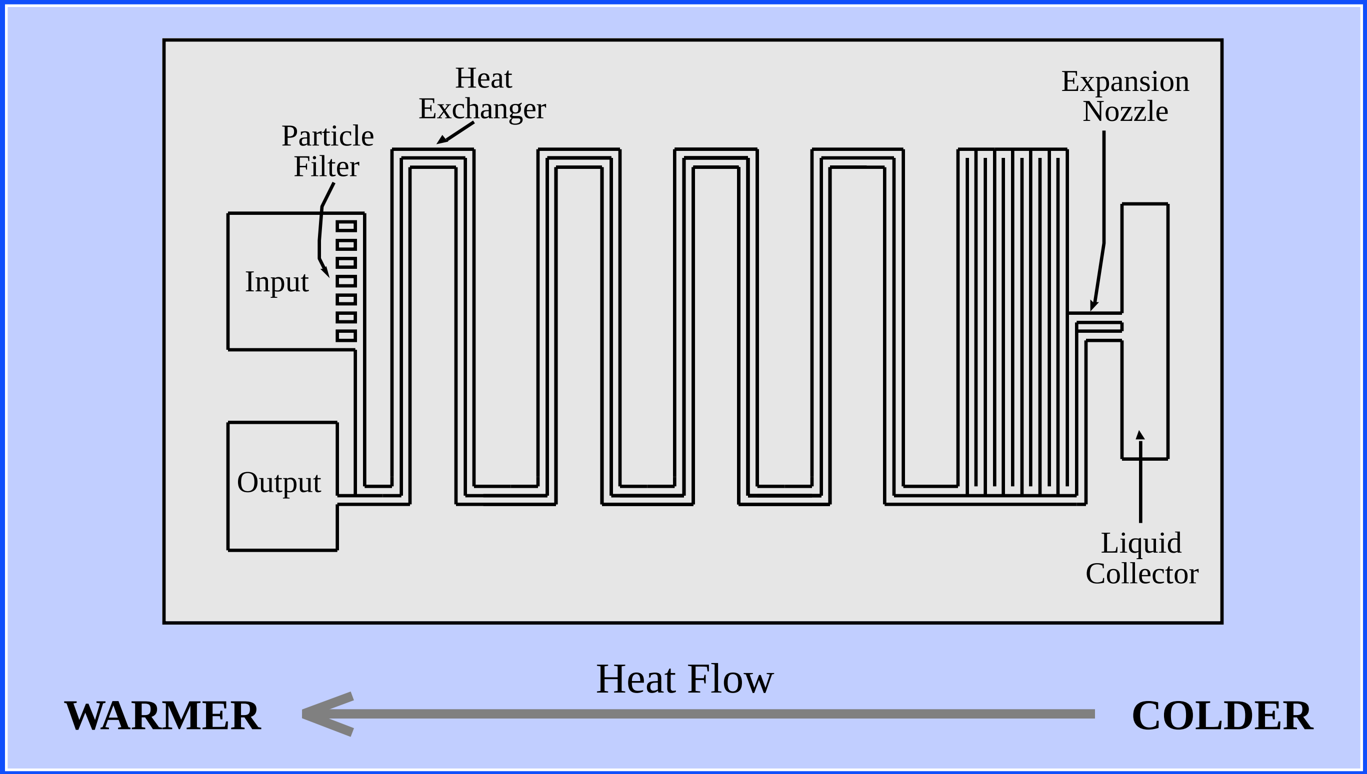


Source: Moser, D., “CMOS Flow Sensors,” Doctoral Dissertation, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, No. 10059, 1993.

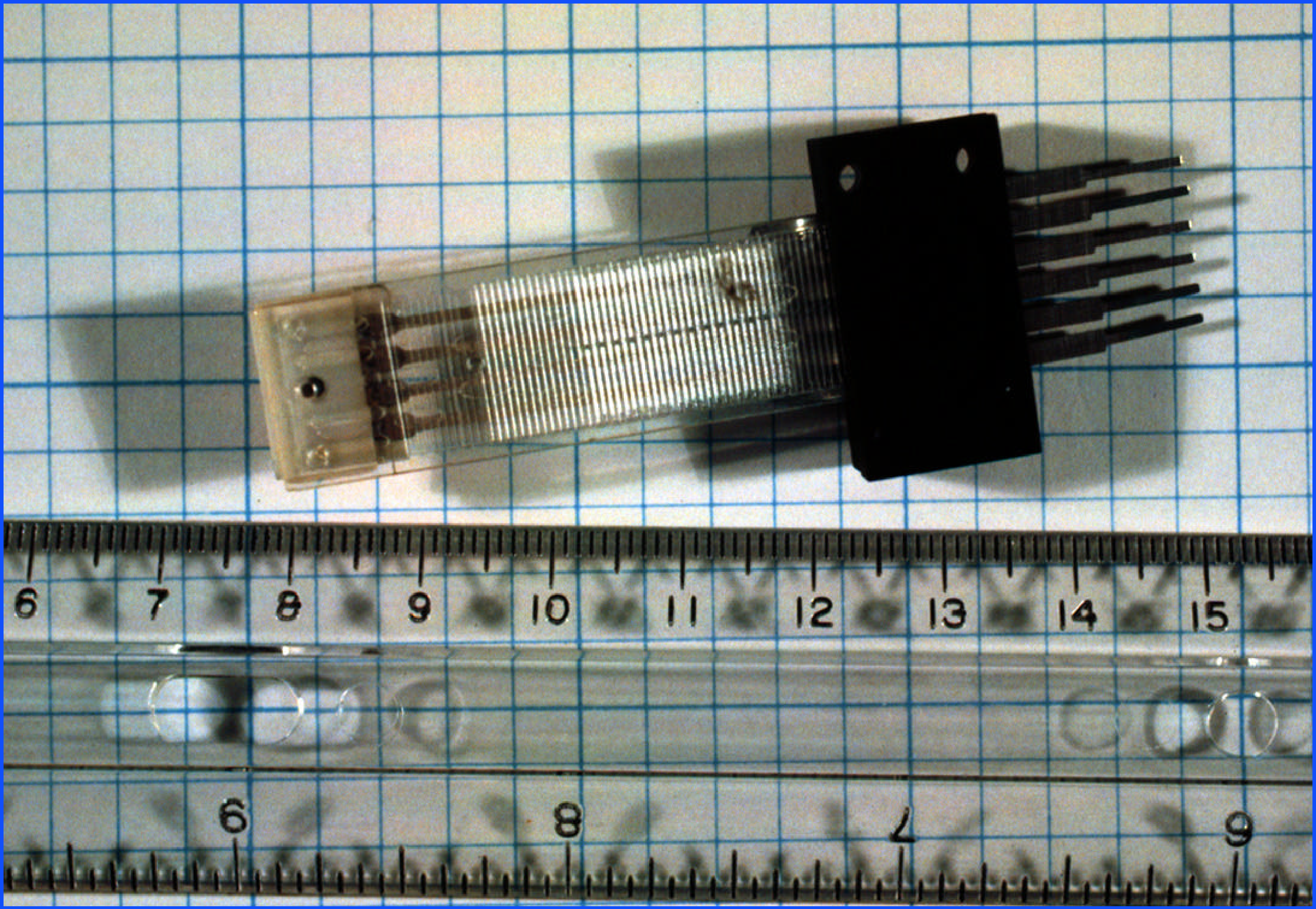
# OTHER THERMAL DEVICES

- Calorimeters (measure heat of energy of exothermic reactions).
- Dew-Point Sensors (use a refrigerator to cool a sensor until dew forms, for a humidity measurement).
- Thermal Actuators (covered elsewhere).
- Fluidic Cooling Channels (heat exchangers).
- Micromachined Refrigerators (use Joule-Thompson Effect - expanding gas cools).
- Peltier Effect Heat pumps.

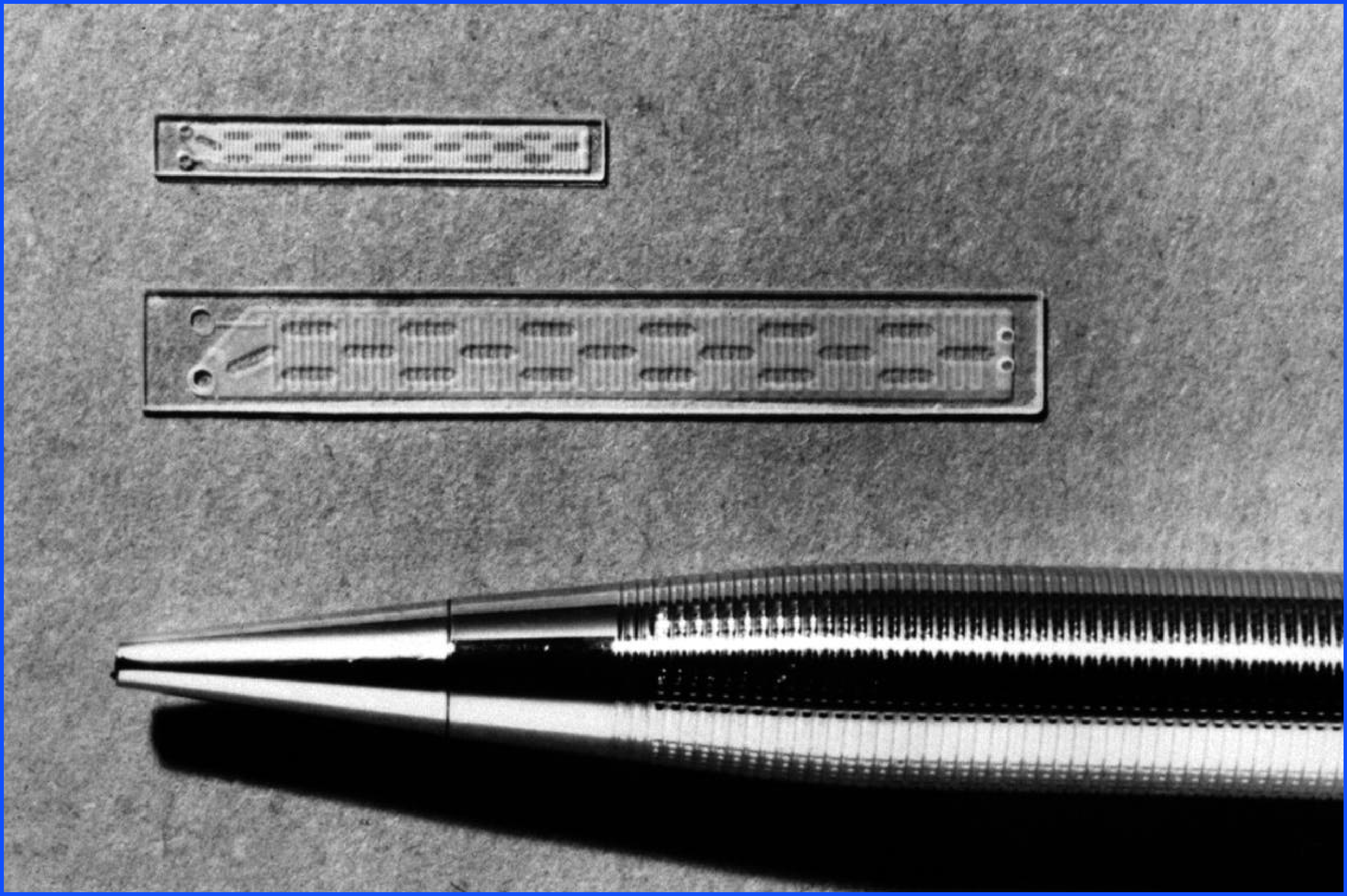
# MICROMACHINED JOULE-THOMPSON REFRIGERATORS




**Refrence: Little, W. A.,"Microminiature Refrigeration," Review of Scientific Instruments, vol. 55, no. 5, May 1984, pp. 661 - 680.**




**Device Courtesy Prof. W. Little, Stanford University.**



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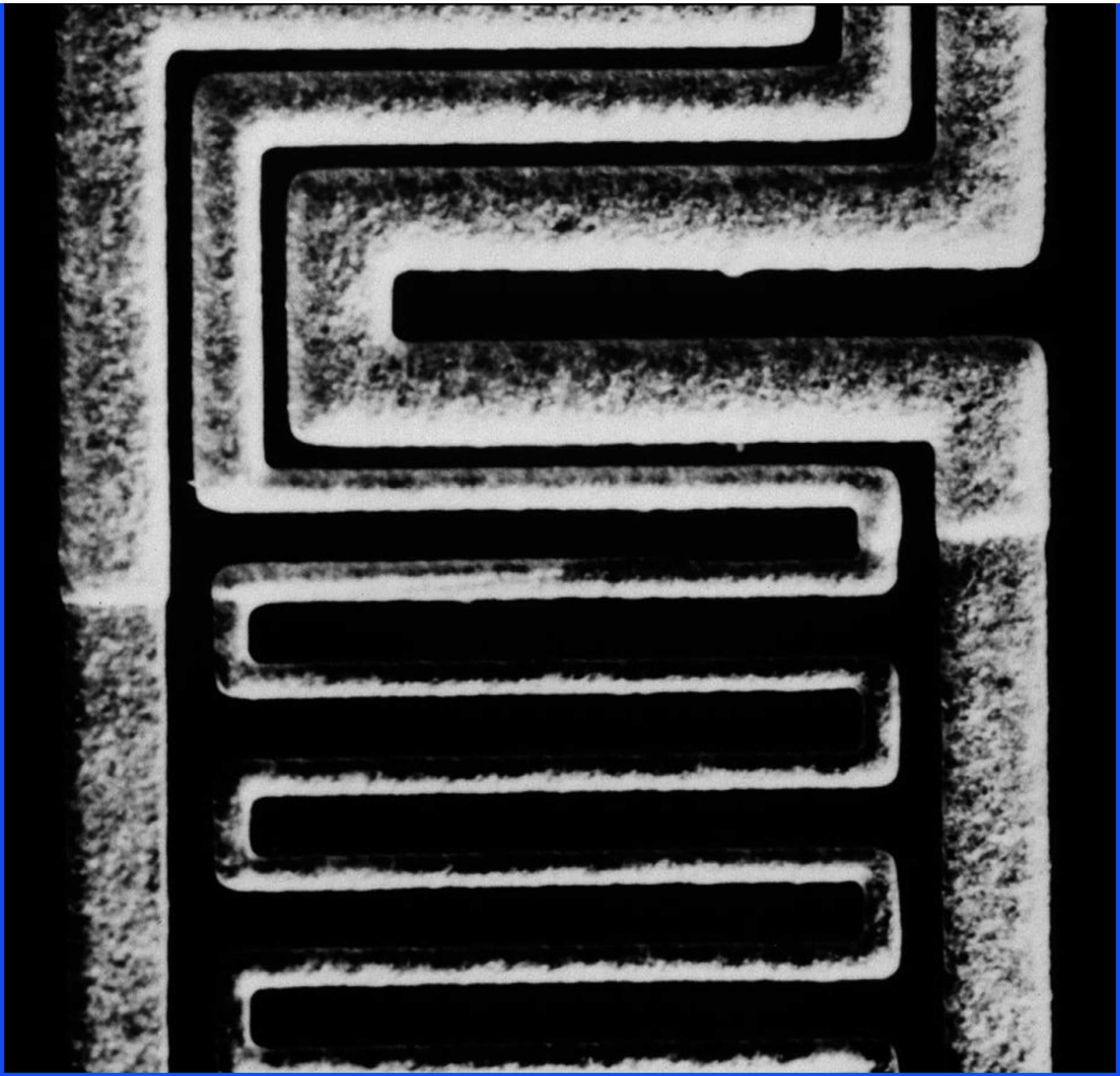

Courtesy Prof. W. Little, Stanford University.