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Physical Principles of Thermal Sensors

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We give an introduction to the physical principles on which silicon thermal sensors are based. We briefly describe the transductions and conversions involved in these sensors, and different thermal sensors and the physics on which they are based.

1. The Functional Principle of Thermal Sensors

In this paper, we describe thermal sensors based on silicon and related technologies, with an electrical output signal. The input signal can be any of the six signal types defined by Middelhoek and Audet,[1] i.e., mechanical, magnetic, chemical, radiant, thermal and electrical signals. In thermal sensors, the transduction of the input signal to the output signal is carried out in two steps. First the input signal is transduced into a thermal signal, and then the thermal signal is transduced into the electrical output signal.

1.1 *Thermal power sensors*

An important distinction among thermal sensors is that between power sensors and conductance sensors. In power sensors the input signal which is measured by the sensor is thermal power, which is used to generate the electrical power of the sensor output signal. Therefore, there is no output signal if the input signal is zero. These self-generating sensors have no offset, and need no biasing. They operate in three steps.

1) A nonthermal signal C is transduced into a thermal heat signal P, by the sensor-specific action Q.

$$P = QC \tag{1}$$

2) The heat P is converted into a thermal signal temperature difference ΔT, by a thermal resistance R.

$$\Delta T = RP \tag{2}$$

3) The temperature difference ΔT is transduced into an electrical voltage U, by a temperature difference sensor S.

$$U = S\Delta T \tag{3}$$

The total transfer ratio U/C of a thermal power sensor is given by

$$U / C = QRS \tag{4}$$

A psychrometer is an exception to this three-step operation. In this sensor, the nonthermal signal is transduced directly into a temperature difference.

1.2 *Thermal conductance sensors*

In the case of thermal conductance sensors, the input signal C changes the thermal conductance G between the sensitive area and the ambient. To measure the thermal conductance, the sensor is biased with a heating power P. The transfer in these modulating sensors is as follows.

1) The nonthermal signal C is transduced into a thermal conductance signal G, by a sensor-specific transduction action Q, G_o is the offset of the sensor.

$$G = QC + G_o \tag{5}$$

2) The conductance G is converted into a temperature difference ΔT, by the heating power P.

$$\Delta T = P / G \tag{6}$$

3) The temperature difference ΔT is transduced into an electrical voltage U, by a temperature difference sensor S.

$$U = S\Delta T \tag{7}$$

For thermal conductance sensors, the total transfer cannot be written in a multiplicative form. Instead we find

$$U = PS / (QC + G_o). \tag{8}$$

This equation indicates the offset character of modulating sensors. In some thermal conductance sensors, the electrical signal in step 3) has another form, such as a current or resistance, depending upon the type of temperature difference sensor used.

In this paper we concentrate on the first transduction step, the sensor-specific transduction action Q. We use various thermal sensors as examples. Considering the variety of thermal sensors described in the literature, a comprehensive summary is not given. The second and third transduction steps are described elsewhere.[2–4]

2. Heat Transfer Mechanisms

In most thermal power sensors, the heat is generated, and the transduction takes place in or on the sensor itself. In some, the transport of nonthermal power to the sensor involves heat transfer mechanisms. In thermal conductance sensors, on the other hand, the change in the conductance due to the nonthermal signal is in the ambient directly around the sensor, not in or on the sensor itself. In this case, heat transfer mechanisms are essential to the operation of the sensor. There are four heat transfer mechanisms, conduction, convection, radiation and phase transition.[5]

Conduction always occurs, and in thermal conductance sensors the first transduction step is based on the thermal conduction G_{cond} between the active area of the sensor and the ambient. The thermal conductance between two parallel surfaces with area A separated by a distance D is given by

$$G_{cond} = \kappa A / D, \tag{9}$$

where κ is the thermal conductivity of the medium present between the surfaces. The sensor action may be based on the dependence of the physical signal

— on κ (pressure dependence: vacuum sensor/Pirani gauge; fluid dependence: thermal conductivity and overflow sensor),
— on D (plate-spacing dependence: accelerometer), or
— on all three parameters κ, D and A (thermal properties sensor).

Convection, the second mechanism for thermal conductance sensors, is heat transfer to moving fluids, as in flow sensors. Usually convection is negligible in sensors other than flow sensors. Although convection conducts heat away from the active area, the physical principle is different from that of conduction, since the heat is not transferred by stationary molecules from neighbor to neighbor, but by a continuous supply of molecules flowing past. In the simplest formula for laminar flow over a flat plate, the heat transfer G_{conv} is given by

$$G_{conv} = 0.664 Pr^{0.33} Re^{0.5} \kappa / L, \tag{10}$$

where L is a characteristic length, for instance the length of the sensor, Pr is (the temperature dependent material constant) the Prandtl number, and Re is the Reynolds number, which is dependent on the flow velocity V, L and the kinematic viscosity ν (in m^2/s), that is $Re = VL/\nu$. The sensor action can be based on the flow velocity dependence of the Reynolds number (as in flow sensors), or on the pressure dependence of the viscosity and the conductivity, which are also constituents of the Reynolds number (as in some Pirani gauges for vacuum measurement near atmospheric pressure).

Radiation is heat transfer by electromagnetic waves, either as infrared radiation (thermal radiation), or other forms, such as microwaves or magnetic fields which generate heat in a dissipative layer (hysteresis in a magnetic layer, for instance). It is a self-generating effect, and is therefore utilized in thermal power sensors. Given below are two formulae for infrared radiation. One is for the heat transfer between parallel plates, which, when both plates are at around room temperature, is equal to

$$G_{ir} = \varepsilon \times 6\ \mathrm{W/m^2K}, \tag{11}$$

where ε is the emissivity or absorptivity of one plate. The other plate is assumed to be black with emissivity $\varepsilon = 1$. All materials emit infrared radiation, but usually it does not contribute significantly to the heat exchange of a thermal sensor with the ambient.

The other formula describes the heat transfer between an infrared sensor with black detecting area A_D (as viewed from the object) and temperature T_D and an object of area A_{obj} (as seen from the sensor), temperature T_{obj} and emissivity ε. The exchanged power is

$$P_{ir} = (\varepsilon\sigma/\pi)\,(A_{obj}/d^2)\,A_D\,(T_{obj}{}^4 - T_D{}^4). \tag{12}$$

Here, σ is the Stefan-Boltzmann constant (56.7×10^{-9} W/K^{4}m^2), and d is the distance between the sensor and the object. When a sensor with a sensitive area of 1 mm^2 at 300 K is exposed to an object at 301 K with an emissivity of 55% at a solid angle of 0.1 steradian (i.e., $A_{obj}/d^2 = 0.1$), the exchanged power is 100 nW.

Phase transition (for example, the heat generated by evaporation) is the last mechanism of heat transfer. Phase transitions are often induced by forced convection, which influences the thermal conductance. This is also a self-generating effect. Similar to radiation, phase transitions generate thermal power (be it negative or positive). A peculiarity of heat transfer by phase transition is that in some situations heat can be transferred from a cold to a hot object.

Table 1 gives an overview of the heat transfer mechanisms described above, together with typical magnitudes of the heat transfer for different mechanisms. It shows the large variations in magnitude among heat transfer mechanisms. In general, heat transferred by conduction and convection is much greater than that transferred by radiation for room-temperature structures. However, since the power emitted from objects in the form of infrared radiation is proportional to the fourth power of absolute temperature, the situation is different at high temperatures. Free convection is seldom significant for microstructures, since it is a size-dependent phenomenon, and is insignificant in comparison with conduction in small structures. However, at very high temperatures (> 300°C) there is significant free convection even in microstructures. Phase transitions such as evaporation should be avoided in self-generating sensors used to measure other heat signals, since evaporation can give rise to significant parasitic heating or cooling even in thermal equilibrium.

Table 1
Overview of heat transfer mechanisms and the magnitude of heat transfer for typical 500 μm microsensors.

Type	Characteristic of effect	W/Km^2	Remark
Radiation	between black surfaces	6	objects at around room temperature
		500	objects at around 1000°C
Conduction	between surfaces 500 μm apart		
	air at vacuum	1	1 Pa pressure
	air	50	atmospheric pressure
	water	1,200	
	silicon	300,000	
Convection	for sensors 500 μm long		
	free convection	-	often negligible in microstructures
	forced convection in air	150	1 m/s flow
	forced convection in water	15,000	1 m/s flow
Phase transition	evaporation of water	1000–10,000*	with forced convection

*Temperature difference not required for phase transition heat transfer to occur.

3. Overview of Thermal Sensors

Below we discuss the physical transduction principles of various thermal sensors in more detail. Table 2 gives an overview of the thermal sensors discussed below.

In Table 2 the first five sensors are self-generating thermal power sensors, and the others are modulating thermal conductance sensors, which use an electrical resistance to generate heat. With the exception of the EM-field sensor and the psychrometer, all of these sensors have been realized using both silicon and thin-film technology.

3.1 *Microcalorimeter*

A microcalorimeter measures the heat generated during chemical reactions. Bataillard describes various applications.[6] A chemical reaction occurs between two solutions in the reaction volume of the sensor (near the active area of the thermal sensor) after they are supplied via two tubes. Alternatively, a catalyst or enzyme is immobilized on the active area of the microcalorimeter, which initiates a chemical reaction when a single solution comes into contact with it. (See Fig. 1). This setup ensures that the transfer of reaction heat to the sensor is optimized. It is even possible to measure the heat generated by microorganisms such as bacteria immobilized near the active area of the microcalorimeter. The heat produced by the bacteria (of the order of 1 pW per bacterium) is a measure of the concentration of nutrients in the solution, such as glucose, or of the growth rate of bacteria

Table 2
Overview of thermal sensors, their measurands and operation principles.

Sensor	Measurand	Operation principle
Microcalorimeter	concentration	heat of chemical reaction - catalyst/enzyme area
Psychrometer	humidity	heat of evaporation - wet wick
Infrared sensor	infrared radiation	black-body radiation - black coating
RMS converter	electrical power	Joule heating - heater resistance
EM-field sensor	EM fields	dissipation - resistive termination
Flow sensor	fluid flow	convection
Vacuum sensor	vacuum pressure	conduction - pressure dependence
Conductivity sensor	fluid type	conduction - type dependence
Mechanical sensor	acceleration	conduction - seismic mass
Thermal properties sensor	material properties	conduction and capacitance

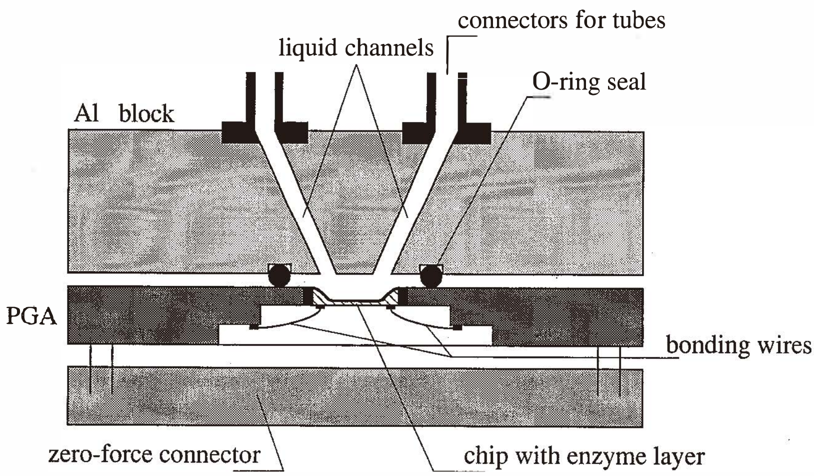

Fig. 1. Liquid microcalorimeter in a flow-injection analysis (FIA) setup.

when sufficient glucose is present.

In practice, in an enzyme-based liquid microcalorimeter for determining the concentration of glucose the transduction to the thermal domain takes place in the following two steps.[7,8]

First, the concentration C (in mol/m^3) of glucose in water is converted into a reaction rate M (in mol/s) by bringing the mixture into contact with the enzyme.

$$M = C(dK/dt) \tag{13}$$

The chemical conversion efficiency dK/dt (in m^3/s) depends on the chemically active layer (catalyst or enzyme) and the particular experimental setup. For instance, one glucose oxidase molecule can convert a maximum of 1000 glucose molecules per second, but converts less if the solution is not replenished. When the solution is replenished, the chemical conversion efficiency depends solely on the chemically active layer (a material property) and not on the experimental setup.

Next, the reaction rate M of the concentrate is transduced into heat of reaction P (in W) by the change in enthalpy.

$$P = M(-\Delta H) \tag{14}$$

The enthalpy change $-\Delta H$ is the energy released during the chemical reaction (in J/mol) and is determined experimentally. For enzymatic oxidation of glucose, a value of 80 kJ/mol is found. According to eq. (13) a monolayer of glucose oxidase could produce a maximum power of approximately 3 $W/m^2/mol/m^3$.

3.2 *Psychrometer*

In this sensor the relative humidity of air is determined by measuring the psychrometric temperature reduction ΔT_{psych} of a wetted thermometer due to evaporation. This sensor is therefore based on a physical phase transition. The first transduction step can be described by

$$\Delta T_{psych} = Q\,(p_{dry} - p_{wet})/P_{atm}. \tag{15}$$

Here p_{dry} and p_{wet} are the partial vapor pressures of water at the air temperature and at the wet-thermometer temperature, and P_{atm} is the atmospheric pressure. The sensor-specific transduction factor Q is of the order of 1700 K.[2] ΔT_{psych} in eq. (15) cannot simply be converted to the relative humidity, because it depends on temperature and humidity, and is much smaller than the dew-point temperature reduction. An estimate is obtained by multiplying Q by 30% $\times\, p_{dry}/P_{atm}$. At room temperature with P_{atm} = 100 kPa and $p_{dry} \approx 2$ kPa, the sensitivity is typically of the order of 0.1 K / %RH.

Note, that in this sensor the nonthermal signal is transduced directly into a temperature difference. There is no conversion in the thermal domain, as there is in all other thermal sensors. Accurate transfer only occurs if good thermal isolation is maintained, and therefore design of an appropriate thermal resistance is necessary anyway. Some other measures, such as forced convection across the wetted thermometer of an appropriate magnitude are also essential for accurate transduction. No silicon version of this sensor is known to the author.

3.3 *Infrared Sensor*

From the transduction point of view this is a fairly simple sensor. The transduction from radiation to heat is carried out by a black absorber, which can have an efficiency of up to 99%. The first transduction step from incident radiation density P''_{inc} (in W/m^2) to thermal power P is given by

$$P = QP''_{inc} \tag{16}$$

$$Q = \alpha A_D \tau_{filter}. \tag{17}$$

The absorptivity α is between 0 and 1, and denotes the fraction of infrared radiation power which is absorbed by the black coating. Various black coatings are used for silicon infrared sensors. A simple and efficient method is to use the silicon oxide and silicon nitride layers produced in all semiconductor production processes.(9,10) Lenggenhager(9) observed an absorption of the order of 50% for radiation with wavelengths of 7 – 14 μm. Using the absorption of PVDF and metal electrodes is another way to implement this method.(11) Porous metal coatings are used to fabricate very black layers.(12) Gold black will absorb more than 99% of radiation over the entire infrared spectrum. A different method is used at Xensor Integration. The sensor is spin-coated with a black polymer. Using techniques very similar to normal lithographic and RIE processes, a pattern in a 5-μm-thick coating is obtained on the wafer, which absorbs about 90% of the infrared radiation. This layer is patterned in a similar way to other thin films on silicon, and can withstand further processing of the wafer. This is not the case for coatings such as gold black, which are very vulnerable and cannot be handled once they have been applied.

A_D is the sensitive area of the sensor (usually the area that is coated with black), while τ_{filter} is the transmission of the filter that is usually incorporated when the sensitive area is encapsulated. This filter can be broadband, transmitting infrared radiation with wavelengths between 2 and 14 μm, high pass, transmitting wavelengths between 7 and 14 μm, for detection of objects at room temperature which emit radiation with a typical wavelength of 10 μm (intrusion alarm), or band-pass, transmitting, for instance, radiation at a wavelength which is in the absorption band of a gas. Using appropriate filters, a gas sensor can be constructed in which the radiation intensity is measured in a reference path and a path in which the gas mixture under investigation is present. The difference in intensity is due to the presence of the radiation-absorbing gas. This method is used for detection of CO_2 and CO.

3.4 *RMS converter*

In the RMS converter, the first transduction step, from electrical to thermal, is simply performed by dissipation in an electrical resistor. Complications arise due to parasitic thermoelectric Thomson and Peltier effects in DC signals, and skin effects and parasitic capacitances and inductances at high frequencies, which cause differences in the heat actually generated in the heater. These problems have been studied by calibration engineers,(13) and will not be discussed here.

3.5 *EM-field sensor*

The EM-field sensor has also been studied by calibration engineers. The EM-field sensor is in between the infrared sensor and the RMS converter. The infrared sensor detects optical signals with very high frequencies of around 10^{15} Hz. The RMS converter detecs electrical signals with frequencies of up to 10^9 Hz and the EM-field sensor measures intermediate frequencies. The EM-field sensor transduces from radiant to electrical signals, as does the infrared sensor.

No semiconductor EM-field sensors are known to the author, but current research is focused on the termination of waveguides by metal patterns on glass plates, which convert the EM-field energy into heat, that is subsequently detected using a bolometer. Here, the first transduction step, from radiant to thermal signals, is carried out using a specifically designed metal pattern which yields a lossless, reflectionless termination of the waveguide. The actual design depends on the wave frequency and waveguide geometry.(14)

3.6 *Flow sensor*

Flow sensors are based on the transfer of heat to moving fluids. This effectively increases the overall thermal conductance between the sensor and the ambient. For flow sensors, the physics of the second and third steps in the transduction process are as simple as those for all thermal sensors, but the similarity ends here. The physics of the first transduction step, from flow to thermal signals, and the encapsulation of the sensor, are much more complicated than those for most other sensors. Also, the encapsulation has a great influence on the first transduction step, because it influences the type of flow. In laminar flow, the fluid flows along straight lines, and in turbulent flow it flows in irregular patterns and the local flow direction is unrelated to the average flow direction. In microstructures laminar flow often occurs, although in thermal windmeters, microturbulent flow is also encountered.(2) The dependence of the heat transfer on flow velocity is different for laminar and turbulent flow. For laminar flow, the first transduction step can be approximated by

$$G \approx G_o + HV^{1/2}, \tag{18}$$

where G is the total thermal conductance from the sensor to the ambient, G_o is the offset (the conduction part), and H is the heat transfer normalized by the flow velocity V. The convective part of the thermal conductance is proportional to the square root of the flow velocity. The variable H includes such parameters as the sensor size, flow history, and fluid characteristics (viscosity, thermal conductivity, temperature).

The fluid flow upstream of the sensor can greatly influence the exact flow pattern over the sensor and its heat transfer characteristics. That is why the encapsulation of the sensor is important (see Fig. 2). The temperature profile of the flow sensor also influences the heat transfer to the flow.(2,5,15)

3.7 *Vacuum sensor*

This sensor is used to measure gas pressures below atmospheric pressure by measuring the pressure-dependent thermal conductivity of gases. At very low pressures, when the mean distance travelled by a molecule between collisions is much larger than the distance between two surfaces, heat transfer between the surfaces occurs via individual molecules. The rate of heat transfer is therefore proportional to the rate at which molecules hit the surface, which is the absolute pressure. At higher pressures (atmospheric for surfaces 500

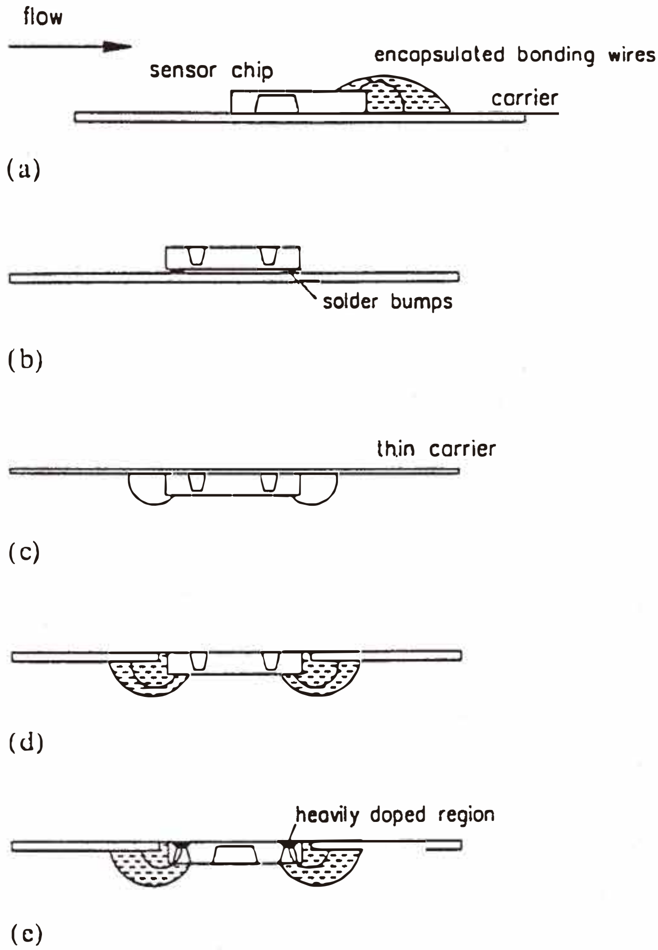

Fig. 2. Different methods of encapsulating silicon flow sensors.

μm apart), molecules transfer heat not from surface to surface, but by collisions with other molecules. Doubling the pressure doubles the number of molecules transferring heat, but the distance over which they transport the heat (the mean free path between collisions) is halved, and the thermal conductivity of the gas is then independent of pressure. For low pressures P (in Pa) the sensor-specific transduction action Q is given by

$$G = QP = (G''_0 / P_0)\, P. \tag{19}$$

Here, G''_0 is the low-pressure thermal conductance, typically of the order of 1 W/m^2K for gases such as nitrogen and helium, for a reference pressure P_0 of 1 Pa. For the entire pressure range, the relation between thermal conductance and pressure becomes

$$G = (G''_0 P\kappa / D)/(G''_0 P + P_0\kappa / D), \tag{20}$$

where κ / D is the thermal conductance between two plates separated by a distance D for a gas with thermal conductivity κ (see Fig. 3 and eq. (9)).[2,16]

3.8 *Conductivity sensor*

This sensor is similar to the vacuum sensor, since it measures the thermal conductance of a gas surrounding the sensor. However, in this case the conductance does not depend upon the pressure, but, at atmospheric pressure, upon the gas type (or liquid type) instead, since all gases have different thermal conductivities. For instance, for air the thermal conductivity is $\kappa = 26$ mW/Km at room temperature. Hydrogen has the highest conductivity at more than 180 mW/Km. For helium it is about 150 mW/Km while gases such as argon (18 mW/Km) and xenon (6 mW/Km) are even less conductive than air. The conductivity sensor can be used in various ways. By measuring the thermal conductance it can be used to determine the type of gas (see Fig. 3), or the composition of a binary gas mixture. For the latter case, a complex formula describes the thermal conductivity of a gas

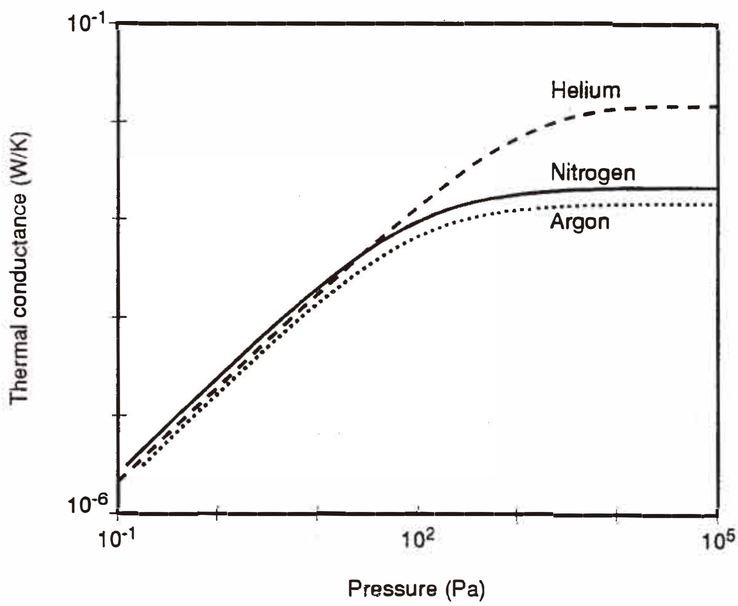

Fig. 3. Thermal conductance of different gases between two parallel plates saparated by a distance of 0.5 mm versus pressure.

mixture with volume fractions a of the first component and $(1 - a)$ of the second.[17]

$$\kappa_{mix} = a\kappa_1/(a + (1 - a)\phi_{12}) + (1 - a)\kappa_2/((1 - a) + a\phi_{21}) \qquad (21)$$

In this formula, the auxiliary variable ϕ_{12} depends upon the viscosity and molecular weight of the gas molecules, as

$$\phi_{12} = \{8(1 + M_1/M_2)\}^{-1/2} \times \{1 + (\mu_1/\mu_2)^{1/2}(M_2/M_1)^{1/4}\}^2, \qquad (22)$$

where M_1 is the molecular weight of the first gas component, and μ_1 is its dynamic viscosity. In the equation for ϕ_{21}, the indices are reversed.

Finally, the conductivity sensor can be utilized as a level sensor, since the thermal conductivity of a liquid is much higher than that of a gas. It can be used to detect overflow, or to measure level in a continuous manner, although the range is limited by the sensor dimensions.

3.9 *Mechanical Sensors*

In mechanical thermal sensors such as the accelerometer, the mechanical signal acceleration a is converted into a force F by a seismic mass m. Then the force is converted into a gap size change D by mechanical springs with a spring constant K using the damping characteristics of the surrounding gas to obtain an appropriate frequency behavior. Finally, the gap size is transduced into a temperature difference by the thermal conductance of the gas in the gap. (See Fig. 4). Therefore, for the accelerometer, the steady state transfer is given by

$$F = ma \qquad (23)$$

$$D = KF \qquad (24)$$

$$G = \kappa A/D + G_o. \qquad (25)$$

Here, A is the area of the gas conducting heat from the sensor to the seismic mass, and G_o is the offset thermal conductance from the sensor to the ambient via other paths, parallel to the conductance in the gap. The physical principle of the thermal accelerometer does not differ greatly from that of the capacitive accelerometer. The gap is measured thermally, rather than capacitively. This means that the first two conversion steps are very similar for these two devices. Therefore I refer the reader to literature on capacitive accelerometers and refs. (18) and (19).

3.10 *Thermal properties sensor*

Thermal sensor structures can also be used to measure the thermal properties of thin films and of the sensor materials themselves. In general, absolute measurements of the thermal resistance and the thermal time constants of a particular structure are made. For modern micromachined structures such as the floating membrane or cantilever beam, measurements are relatively simple. Figure 5 shows a structure in which a silicon island is

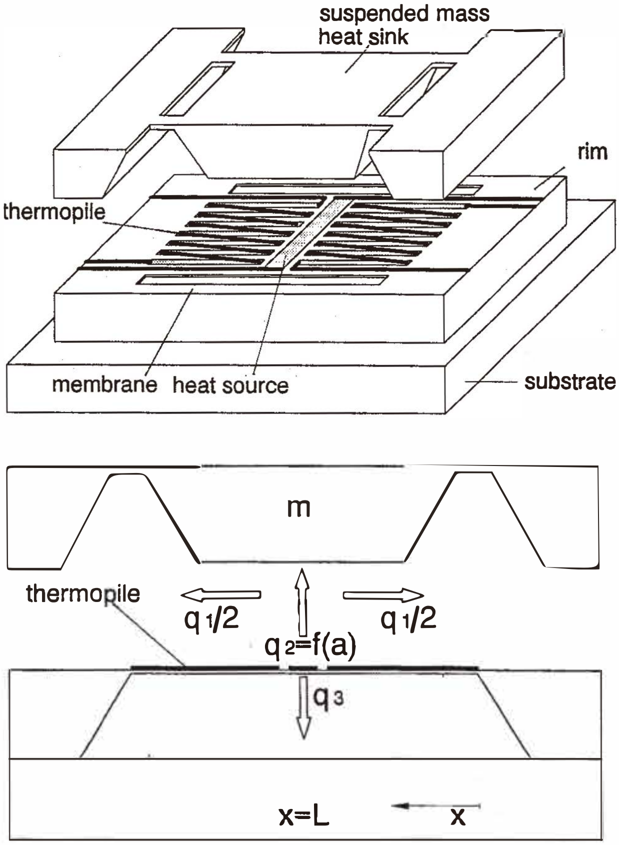

Fig. 4. Schematic drawing and cross section of a thermal accelerometer.

suspended in a closed silicon nitride membrane. This is a variation of the floating-membrane structure.[20] The measurements are performed in vacuum, so that only conduction in the solid material adds to the measured conductances (radiation effects are usually not significant). In this way, the thermal conductance κ and capacitance c_p of various materials have been determined, such as those for silicon (150 W/Km and 700 J/kgK), silicon dioxide (1–1.5 W/Km and 730 J/kgK), low-stress silicon nitride $SiN_{1.1}$ (3–3.5 W/Km and 700 J/kgK), polysilicon (18–30 W/Km and 770 J/kgK) and aluminum with 1% silicon (180–220 W/Km).[2,20–22]

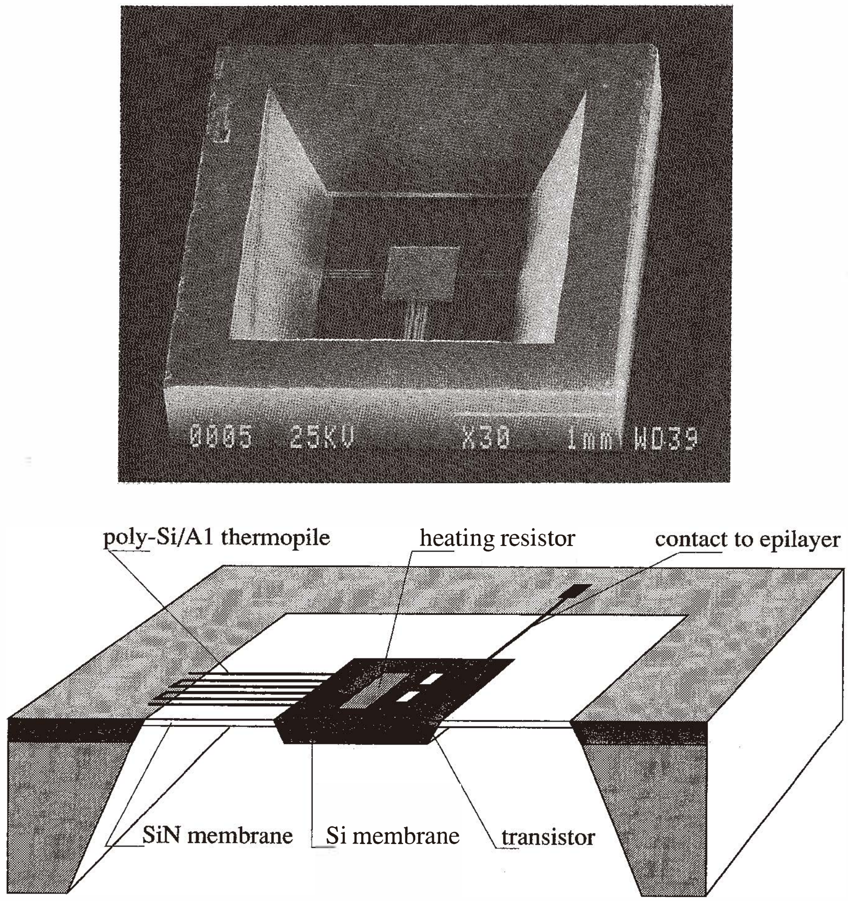

Fig. 5. Thermal properties sensor consisting of a silicon island suspended in a silicon nitride closed membrane.

4. Discussion

Many thermal sensors have been developed. Some of them are already used commercialy (such as infrared sensors for intrusion alarms), others are used for specific purposes (accelerometer), and some are not fabricated in silicon technology (psychrometer). There is a great difference in the applicability of various thermal sensors. Infrared sensors are very simple devices because they can be hermetically sealed during encapsulation. The same applies to RMS converters, the semiconductor version of which is becoming more and more popular. Research on semiconductor flow sensors is extensive, but the difficulties encountered in encapsulation and its influence on the sensor mean that the commercial success of these sensors is limited.

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