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# An overview of micromachined platforms for thermal sensing and gas detection

Ronald P. Manginell, James H. Smith, Antonio J. Ricco
Sandia National Laboratories
Albuquerque, NM 87185-1080

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## ABSTRACT

Micromachined hotplates, membranes, filaments, and cantilevers have all been used as platforms for thermal sensing and gas detection. Compared with conventional devices, micromachined sensors are characterized by low power consumption, high sensitivity, and fast response time. Much of these gains can be attributed to the size reductions achieved by micromachining. In addition, micromachining permits easy, yet precise tailoring of the heat transfer characteristics of these devices. By simple alterations in device geometry and materials used, the relative magnitudes of radiation, convection and conduction losses and Joule heat gains can be adjusted, and in this way device response can be optimized for specific applications. The free-standing design of micromachined platforms, for example, reduces heat conduction losses to the substrate, thereby making them attractive as low power, fast-response heaters suitable for a number of applications. However, while micromachining solves some of the heat transfer problems typical of conventionally produced devices, it introduces some of its own. These trade-offs will be discussed in the context of several micromachined thermal and gas sensors present in the literature. These include micromachined flow sensors, gas thermal conductivity sensors, pressure sensors, uncooled IR sensors, metal-oxide and catalytic/calorimetric gas sensors. Recent results obtained for a microbridge-based catalytic/calorimetric gas sensor will also be presented as a means of further illustrating the concepts of thermal design in micromachined sensors.

**Keywords:** microhotplate, microbridge, gas sensor, thermal sensor, heat transfer

## 1. INTRODUCTION

Micromachining is a broad term that encompasses several techniques for the production of structures with micron-sized dimensions. All of the structures discussed herein were produced by bulk micromachining and surface micromachining. The most import consideration for this discussion is that both of these techniques can be performed using the same techniques used by the microelectronics industry to make integrated circuits (ICs). IC fabrication technology offers (see for example references 1 and 2):

- Design flexibility
- The ability to make small (~1 μm) structures
- Tight dimensional tolerances (down to the diffraction limit of the UV lithography source used)[3]
- Batch fabrication at low cost
- Reliability, reproducibility and high yield
- Easy fabrication of sensor arrays
- Possibility to produce control electronics on the same chip
- Use of a well-established manufacturing infrastructure

These attributes make micromachining the ideal solution to most of the problems associated with conventionally produced sensors. Tight control on dimensions provides for easy fabrication of closely-matched devices, and batch fabrication has the potential to lower manufacturing costs. Sze has pointed out that the cost of technology facilities and labor is largely independent of the number of products produced. Thus, per-unit cost of manufactured goods decreases as production volume increases. Batch fabrication as used in the microelectronics industry illustrates this point.[4] The size reductions achievable by micromachining reduce power consumption significantly while simultaneously improving response times by reducing sensor heat capacity.[5,6] Arrays of sensors can be easily produced side-by-side by the thousands in

a single batch fabrication procedure.[7] Finally, control electronics and sensor elements can be monolithically integrated on the same substrate, reducing parasitic capacitance and improving sensor response.[1,8]

Most efforts to miniaturize, flow sensors, gas thermal conductivity sensors, pressure sensors, uncooled IR sensors, metal-oxide and catalytic/calorimetric gas sensors have focused on the use of micromachined dielectric platforms like microhotplates, and cantilevers as well as micromachined filaments or bridges. The manufacturability, low-power consumption, fast thermal response and high thermal sensitivity of these platforms have made them attractive for these sensing applications. Furthermore, the flexibility of the micromachining approach allows for precise tailoring of the heat transfer characteristics of these thermally-based sensors. This paper provides a brief review of micromachined thermal and gas sensors with attention to the use of this flexible approach to tailor designs to particular applications.

## 2. GAS SENSING WITH MICROHOTPLATES AND MICROBRIDGES

### 2.1 Calorimetric, combustible gas detection

Reliable detection and monitoring of the concentrations of combustible gases and vapors is crucial to safety in any situation where such gases are encountered. The most common situations are, of course, mining, underground construction, fuel transport lines, fuel tankers and industrial settings where the handling, storage and processing of combustibles takes place.[9] Frequently, leakages of flammable gases occur in less obvious, but equally dangerous situations such as residential gas mains. Not surprisingly there is significant interest in an inexpensive, reliable gas detection system for this application as well.[10] Combustible gas detection is also becoming important in the processing and handling of process gases for the semiconductor industry.[11] Here, the aim is not so much safety, as it is the detection of impurities in the process gases. Finally, combustible gas sensors are becoming important in the automotive industry.[12] With heightened emission standards, auto makers are trying to find ways to continuously monitor unburned hydrocarbon and nitrous oxide concentrations in auto exhaust.[13]

The lower explosive limit (LEL) is the concentration of gas in air below which it cannot be ignited. LEL has served as a practical concentration limit below which gas-air mixtures are considered free from explosions.[14] For this reason most combustible gas detectors are used to detect concentrations up to the LEL and provide a direct measure of the flammability of a gas-air mixture.[15] Combustible gas detection below the LEL is most often accomplished by catalytic, calorimetric means.[16] The heat of oxidation of the combustible species on the surface of a hot catalyst is measured by means of a resistance thermometer in proximity with the catalyst. This method is, therefore, calorimetric. The heated catalyst permits oxidation of the gas at reduced temperatures and at concentrations below the LEL. Three elements are necessary for this method: A catalyst, a method to heat it and a means to measure the heat of catalytic oxidation. In its simplest form, a Pt coil plays all three roles.[16,17] By passing an electric current through the coil it is heated to a temperature sufficient for the Pt surface to catalytically oxidize the combustible; the heat of oxidation is measured as a resistance variation in the Pt wire. The CERCHAR Pt wire coil, developed in 1960, and the Pt ribbons produced by such companies as Goodfellow are commercial examples of this device.[18,19]

### 2.2 Conductometric gas sensing

The electrical conductivity of semiconducting metal oxides varies with the gas composition of their ambient.[20] This principle has been used for detecting combustible gases such as $CH_4$ and $H_2$, as well as toxic gases like CO, $H_2S$, and $NO_x$.[21] Tin oxide, $SnO_2$, has been the most widely used semiconducting metal oxide due its good chemical stability and high sensitivity at low (400 °C) temperature.[22] Other materials such as $TiO_2$, $Ga_2O_3$ and $SrTiO_3$ are in development because of their ability to function at higher (800°C) temperatures.[10,13] This attribute makes them suitable for automobile exhaust monitoring, an area of increasing importance due to tightening emissions standards in first-world countries.[13] The general application of this type of sensor to quantitative gas sensing is limited by their poor long-term stability and, like pellistors, the effects of poisoning.[22] The impact of these limitations can be lessened, however, through the use of arrays.[23]

### 2.3 Microhotplates for calorimetric gas sensing

Most efforts to miniaturize calorimetric gas sensors have focused on the use of micromachined dielectric membranes as platforms upon which a sensor pair is fabricated. By placing heating resistors on a thin, free-standing, dielectric membrane, high temperatures can be rapidly achieved with low electrical input power. Microhotplates, as these devices have come to be known, are capable of reaching operating temperatures of 400-500°C in 1-20 msec with the application of 50-100mW.[2,6,7,24,25,26,27,28] Characteristic membrane dimensions are 100 - 250 μm on a side[2,7] but can be as large as 1.2 mm on a side;[6] membrane thicknesses are on the order of a micron. As an example of the fabrication and design considerations of microhotplates, consider the microcalorimetric sensor illustrated in Figure 1.

The first step in the fabrication of this device is the deposition of the supporting membrane on a {100} silicon substrate. Low-Pressure Chemically Vapor Deposited (LPCVD) silicon nitride is a preferred membrane material due to its low thermal conductivity. With a nominal conductivity of $3 \times 10^{-2}$ $Wcm^{-1}K^{-1}$, silicon nitride is roughly a factor of ten less thermally conductive than heavily-doped polycrystalline silicon,[29] and as much as 50 times less conductive than single crystal silicon.[3] This important attribute minimizes heat loss by conduction from the hot central portion of the membrane (heated by the deposited resistors) to its extremities. The fact that thin, free-standing films, 0.6 μm in the design of Figure 1, can be manufactured, yields a low heat capacity membrane; values as low as $10^{-8}$ J/K have been reported.[26] Low heat capacity contributes the observed rapid heating at low power.

The large thermal resistance of silicon nitride, however, yields rather non-uniform temperature profiles across the area of a microhotplate, a possible limitation for chemical sensors when reaction kinetics need be examined. Temperature gradients as large as 1°C/μm across a hotplate surface have been demonstrated. By simple deposition of a thin aluminum layer in the active region of the hotplate, though, temperature gradients can be reduced by almost two orders of magnitude. It should be noted that while this approach increases the thermal conductivity of the device, it also increases its thermal capacitance, which has important implications for device response time.[30,31]

Another drawback to stoichiometric silicon nitride films is their high intrinsic stress ($\sim 2 \times 10^{9}$ dynes/$cm^2$), which limits membrane integrity. A popular remedy to this problem is the construction of a composite membrane from alternating layers of compressive plasma-enhanced CVD (PECVD) silicon dioxide, and tensile PECVD silicon nitride.[6,11,32] For example, after annealing at 600 °C, a composite of 0.5 μm PECVD silicon dioxide, 0.1 μm PECVD silicon nitride deposited on a 0.1 μm LPCVD silicon nitride film had a small residual tensile stress of $6 \times 10^{8}$ dynes/$cm^2$, the two contrary stresses have nearly compensated one another.[6]

Returning to the microhotplate design of Figure 1, the next step in the fabrication sequence is the deposition and patterning of the heating resistor. Platinum and molybdenum[32] are excellent choices for resistor and thermistor applications due to their high temperature coefficient of resistance (TCR), typically in the range of 2500-3000 ppm/°C. Chemical resistant materials such as platinum are also attractive where microhotplates are to be used in chemically harsh environments. Microhotplate catalytic gas sensors reported to date have relied on thin-film deposition techniques, such as sputtering and evaporation, to deposit the metal heater/thermometer material. Photolithography, combined with wet chemical etching are typically used to pattern the deposited films.[5,28]

To protect the resistor from possible harsh chemical environments and to prevent evaporation of the platinum during high temperature operation, it can be protected by a 0.2 - 0.3 μm PECVD silicon nitride passivation layer. To fabricate the active element a catalytic layer is deposited directly above one of the two heaters. Both thin film and thick film techniques, including deposition from a slurry containing the catalytic metal[6] have been used for this fabrication step.

The final step in the fabrication sequence is the formation of the membrane. Using a double-sided aligner, an etch mask is formed on the back-side of the wafer, opposite from the sensor pair. The silicon substrate is then etched in a solution of aqueous KOH; the anisotropic etch is halted by the upper-side silicon nitride membrane material. Inasmuch as the silicon substrate is etched to release the membrane material, this process is considered bulk micromachining. Close examination of Figure 1 reveals a possible limitation to bulk micromachining. When {100} silicon is etched in KOH, the

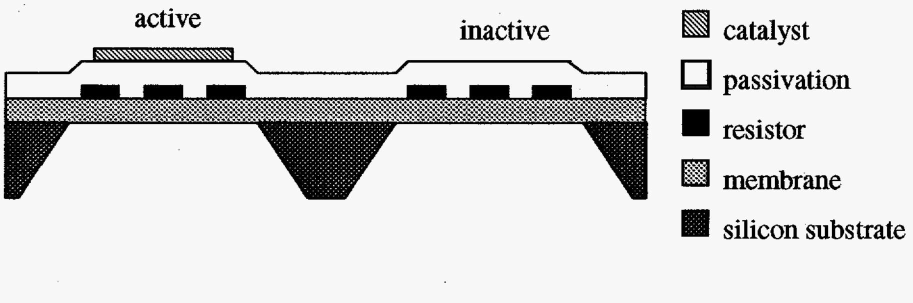

*Figure 1: A cross-section of side-by-side microhotplates composed of a dielectric membrane on an etched silicon wafer, and platinum resistors/heaters. The device on the left has a deposited catalyst making it the active element. ( See reference 6.)*

{111} facets are revealed[3] and a 'v'-shaped groove is necessarily formed; this characteristic groove can be seen in the figure. The walls of the groove are inclined at 54.7° to the surface of the wafer which means, therefore, that if deep grooves need be formed, large amounts of substrate material will be consumed in the process. This is a particular problem if etching is initiated from the front side of the wafer, since much of the precious wafer surface surrounding the membrane will be etched. Finally, long times required to etch deep trenches can be prohibitive.

Most existing hotplate designs for calorimetric, catalytic gas sensors are very similar in design and fabrication to that just given. Designs in which a separate catalytic film is heated by a resistor[6,24,25,33] are very similar to conventional pellistors. Others utilize noble metal lines as resistor, heater, thermometer and catalyst,[34] and though they sometimes call themselves planar pellistors,[24,28] they are in actuality more similar to a simple hot-wire gas sensor. It should be noted that occasionally both the active and inactive elements are built on the same membrane without a silicon heat sink separating them.[34] This design is acceptable for low heating applications, but is not favored due to the likelihood of thermal cross-talk between the two elements,[35] which ultimately limits device thermal sensitivity. Finally, one of the earliest designs of a microhotplate calorimetric gas sensor was actually the most complicated.[36] Here, bipolar transistors were used as the heater and temperature sensor. Increased processing steps without significant improvements in device performance make this design less attractive than the simpler one presented above.

### 2.4 Microhotplates for conductometric gas sensing

Conventional conductometric gas sensors are operated at fixed temperatures in the range of 150-700°C, depending on the gas to be detected and the metal oxide used.[2,37,38,39,40,41] Microhotplates serve as low power, fast-response heaters for metal oxides.[7,11,42] Furthermore, arrays of such devices are easily fabricated, as aforementioned. Finally, the self-heating capability of microhotplates can be utilized to place the sensing film selectively on the hotplate by thermal decomposition of a suitable precursor.[7] Without this feature, an additional photolithography step is required in the traditional microfabrication sequence to pattern a sputtered or evaporated metal-oxide film.

The design of some microhotplates for conductometric gas sensors (Figure 2) is slightly different that that shown in Figure 1 and merits discussion. In this design, heat loss by conduction to the substrate is reduced by the use of four bridges made of silicon nitride or a composite material. The aluminum "plate" creates a more uniform temperature distribution across the membrane. And, the four aluminum contact pads allow for 4-point measurement of the metal oxide resistance during exposure to gas mixtures.

This design is capable of reaching 400 °C at 47 mW with a rise time of about 1 msec. With $SnO_2$ as the sensing material it detected 0.1% if $H_2$ in air. Because of the fast thermal response, it can be used in a pulsed mode to further reduce power requirements. If 10 msec pulses are applied every 1 sec, for example, the power consumption is only 470 μW, and the device could be powered with a 9V battery for nearly a year.[2]

## 3. GAS SENSING WITH MICROBRIDGES

Another popular approach to miniaturization of calorimetric gas sensors is the use of free-standing micromachined filaments, or microbridges.[19,43,] It is common to deposit and pattern a thin film of platinum on a glass substrate and then etch the glass to produce a free-standing filament; only the very ends of the filament remain attached to the unetched portions of the substrate. This free-standing design minimizes heat loss to the substrate and permits rapid heating at low power. Thermal time constants of the order of 10 msec have been achieved[43] with the application of about 200 mW. These devices have much in common with conventional hot-wire gas sensors wherein a platinum resistor is used as heater, thermometer and catalyst. The similarites also include, unfortunately, steady base-line drift due to evaporation of platinum at operating temperature. Drift can be reduced by operation in a discontinuous mode,[18] but never eliminated. Low internal Pt resistance, furthermore, yields small sensor signals and low signal-to-noise ratios.[43]

### 3.1 Polysilicon microbridge gas sensor

A calorimetric gas sensor based on a polysilicon microbridge platform was recently reported.[44] Similar microbridges have been explored as potential incandescent light sources and hot-wire anemometers,[45,46] but have yet to be fully exploited for chemical sensing. Here, a free-standing polycrystalline silicon filament is used as the catalyst heater and as the resistance thermometer (Figure 3). A typical filament is 10 μm wide, 2 μm thick and is elevated above the substrate by a 2 μm air gap; lengths range from 100 μm to 1 mm. A thin, 0.25 μm PECVD silicon nitride film envelopes the polysilicon and passivates it against oxidation at operating temperatures. A high surface area catalyst is deposited on the encapsulated filament by a special, highly selective, "micro-CVD" process.

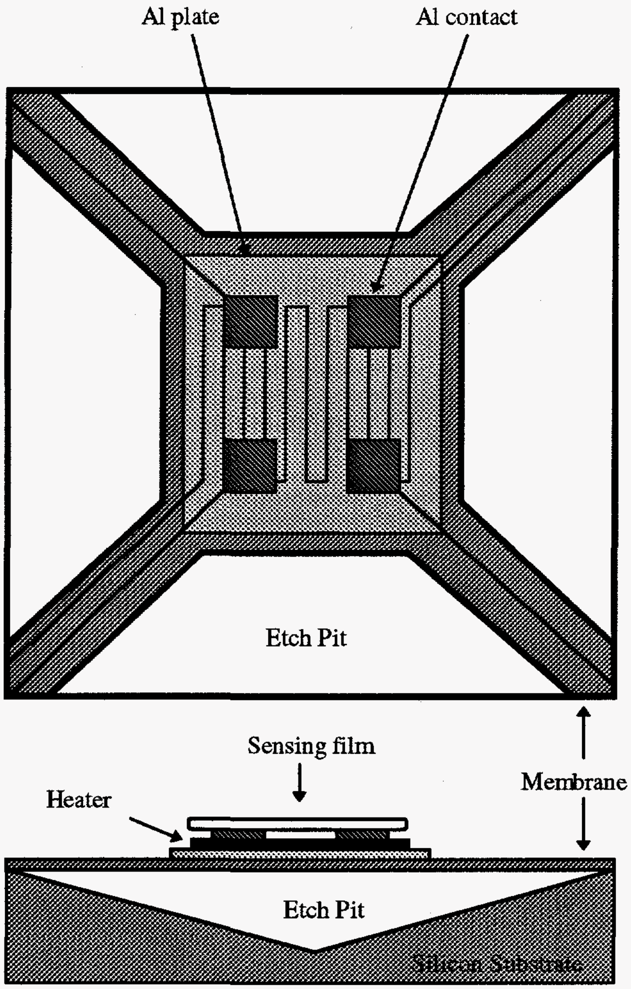

*Figure 2: Top and cross-section views of a microhotplate. This design minimizes heat conduction to the substrate. The meandered heater warms the Al plate to a nearly uniform temperature. 4-point Al contacts are used to measure resistance variations in the metal oxide sensing film. (Based on ref. 2)*

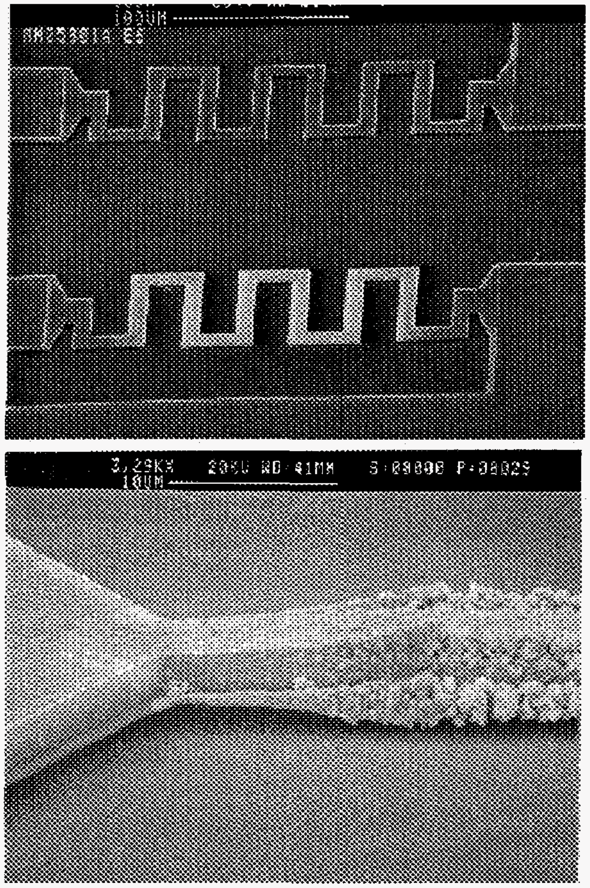

*Figure 3: Top: A Scanning Electron Micrograph (SEM) plan view of two meandered polysilicon microbridges. The lower meandered bridge was selectively coated with a thin (~0.1 µm) layer of platinum using Sandia National Laboratories' micro-Chemical Vapor Deposition (micro-CVD) process. In a differential gas sensing mode, the upper, uncoated, filament acts to compensate changes in the ambient, while the lower, is used to calorimetrically detect combustible gases. Bottom: A near profile SEM of a Pt coated filament clearly shows the air gap beneath the bridge and the high surface area of the Pt catalyst.*

This design has many advantages over the microhotplates presented above. The principal advantage is speed. The microbridge, has extremely rapid heating because of its small heat capacity and the large thermal conductivity. Bulk-micromachined, microbridges reported in the literature reach 700 °C with thermal time constants less than 1 msec[47] Polysilicon microbridges[44] have thermal time constants on the order of 200-500 µsec to reach temperatures greater than 600°C. Also as a result of their small size, microbridges consume only 35 mW to achieve the same temperatures as microhotplates when using 50-100mW of power. They, moreover, consume far less area on the silicon wafer than bulk-micromachined bridges. Finally, microbridge gas sensors have the potential to be more chemically sensitive than those reported elsewhere. For example, hydrogen concentrations as low as 100ppm of $H_2$ in 10% $O_2$ have been detected,[44] whereas the published microhotplate detectors have a sensitivity limit of 1000ppm for the same mixture.[6] Most of these gains can be attributed to the improved thermal response of the microbridge device over that of the microhotplate.

A seeming disadvantage to the microbridge gas sensor when compared with calorimetric microhotplate sensors is the non-uniform temperature distribution along the filament. Microbridges have steady-state temperature distribution with a hyperbolic cosine form[29] with a maximum at the center point. Temperature profiles have been measured by this author using an infrared microscope. When the center-point of a 100 μm long filament is at 200 °C, for example, the endpoints remain near room temperature. While this gradient would prevent easy extraction of chemical reaction kinetics, it does not prevent its use as a gas sensor. Other microbridge gas sensors and conventional hot-wire devices alike have similar temperature variations, yet are nonetheless useful gas sensors. Furthermore, if chemical kinetics are truly important, this information can be effectively extracted through the use of microbridge arrays.

A comparison of a conventional pellistor and a microbridge gas sensor are given in table 2 and demonstrate the effectiveness micromachining in improving sensor characteristics.

| | **Commercial Pellistor**[†] | **Microbridge Gas Sensor**[‡] |
|---|---|---|
| **Estimated cost [$]** | 50 | <1 |
| **Sensor size** | ~ 1 mm$^3$ | 100 x 10 x 2 μm$^3$ |
| **Power consumption [mW]** | 250-450 | 35 |
| **Thermal sensitivity**[ϒ] **[°C/mW]** | 1-2 | 16 |
| **Thermal response time**[*] | ~15 sec | <500 μsec |

*Table 1: Comparison of a commercially available pellistor and a micromachined version. [†]City Technology Limited 4P series; [‡]Microbridge gas sensor produced at Sandia National Laboratories[44] [ϒ]Ratio of 550°C operating temperature to electrical power required to achieve 550 °C; [*]Time to reach 90% of steady-state operating temperature.*

## 4. UNCOOLED INFRARED DETECTORS

Infrared detectors can be separated into two types: Photon detectors and thermal detectors.[48] Photon detectors require cooling to liquid-nitrogen temperatures to achieve good signal-to-noise ratios. This markedly increases their cost as the cooling apparatus is the most expensive part of this type of detector. In contrast, almost all thermal detectors are operated at ambient temperature; because no cooling is required, they are referred to as 'uncooled' IR detectors.

Thermal IR detectors convert IR radiation into heat and then into an electrical signal. Due to the high thermal sensitivity of microhotplates, IR radiation incident upon them is efficiently converted to heat, and small IR signals yield detectable changes in microhotplate temperature. This temperature rise is converted to an electrical signal and measured in one of two ways: with bolometers[48,49,50,51] or with thermopiles.[52,53,54,55,56]

Bolometers measure temperature through a resistance variation in a conductor. The resistor embedded in the microhotplate shown in Figure 4, for example, measures the temperature rise of the microhotplate due to incident radiation. To improve the device performance the resistor material should have a high TCR. For this reason platinum and vanadium dioxide[51] are good choices. Tanaka et. al have pointed out that the bolometer material should also be characterized by a small thermal conductivity to prevent heat losses due to conduction along the bolometer itself.[48] Titanium is therefore a fine choice, for it has a TCR of about 4000ppm/°C at room temperature[57] and a thermal conductivity of 0.22 Wcm$^{-1}$K$^{-1}$. Platinum,[57] in contrast, has a TCR of roughly 3000 ppm/°C and a thermal conductivity of 0.7 Wcm$^{-1}$K$^{-1}$. Finally, titanium is good economic choice since is a standard material available in integrated circuit facilities.[48]

Thermopiles have also be used to measure the temperature increase of a microhotplate. A cantilever-based microhotplate design with an integrated thermopile is illustrated in Figure 5. The cold reference junction is located on the substrate, while a heater on the membrane is incorporated for calibration purposes. The output voltage of the thermopile, V, is given by $V = \sum_{i=1}^{n} \alpha \Delta T_i$ where n is the number of thermocouple junctions comprising the thermopile, $\alpha$ represents the Seebeck coefficient of an individual junction, and $\Delta T_i$ is the temperature difference across the $i^{th}$ thermocouple.[51]

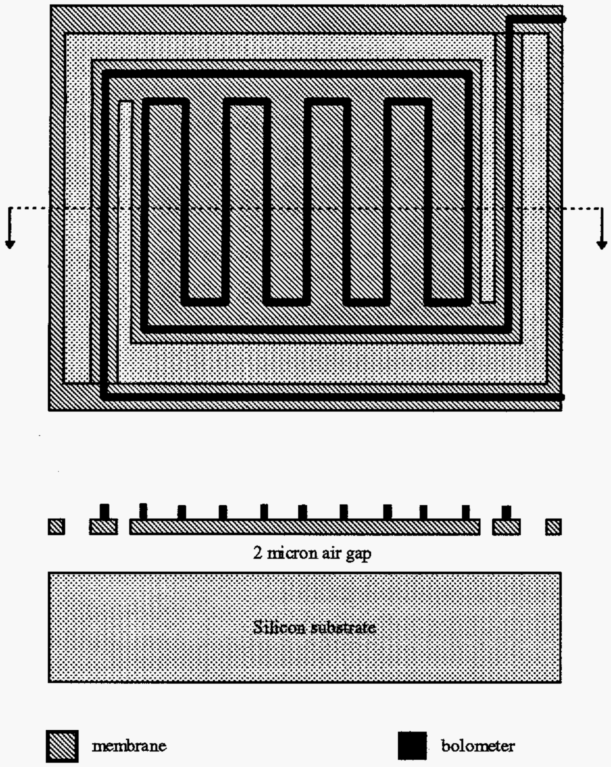

*Figure 4: Surface micromachined IR detector with an embedded bolometer temperature sensor.*

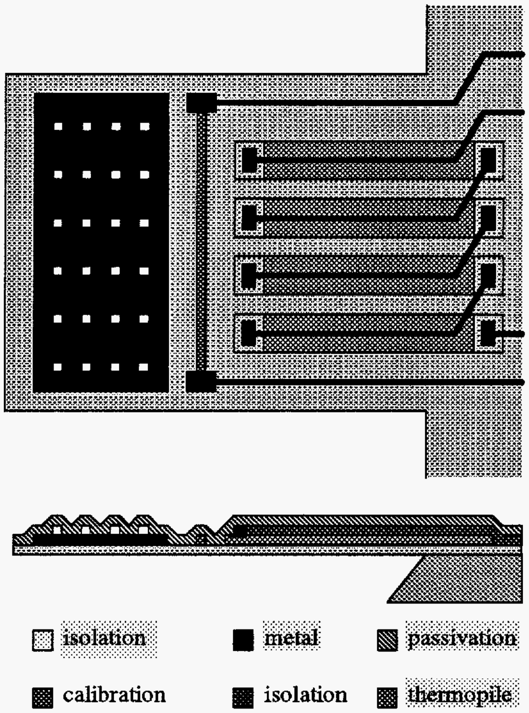

*Figure 5: A cantilevered IR sensor. The metal and patterned isolation material act as an IR absorber. (After reference 54.)*

As with the starting material for bolometers, thermocouple materials that are compatible with CMOS fabrication requirements have a distinct manufacturing and cost advantage. Polysilicon and aluminum are the most widely used CMOS-compatible thermocouple junction materials, but because of their high thermal conductivity [29,57] ($\kappa_{poly}$=0.3Wcm$^{-1}$K$^{-1}$ and $\kappa_{Al}$~2 Wcm$^{-1}$K$^{-1}$), device performance is degraded. $Si_{70\%}Ge_{30\%}$ is also CMOS compatible but offers a much lower thermal conductivity[58] because $\kappa_{Ge}$ = 0.048 Wcm$^{-1}$K$^{-1}$.

The performance of thermocouple materials can be fairly compared using the parameter[59]

$$z = \frac{\alpha^2}{\rho\kappa}. \qquad (1)$$

As mentioned, the thermal conductivity should be low to prevent heat losses to the substrate. The electrical resistivity, $\rho$, should be low so the device has low noise output as Johnson noise is proportional to the resistance R, through $\sqrt{4kTRf}$ . And, of course, the Seebeck coefficient should be large to give a large output signal. For aluminum/polysilicon and silicon/germanium, receptively, the z parameters are 50x10$^{-6}$ K$^{-1}$ and 27x10$^{-6}$ K$^{-1}$.

An array of IR sensors placed in the focal plane of an IR lens is known as a focal plane array (FPA) and each microhotplate constitutes one pixel of the array. Because surface micromachined microhotplates (see Figure 4) consume less wafer area, high density arrays of surface micromachined microhotplates can be achieved; pixel counts as high as 16,384 have been achieved.[52] Surface micromachined hotplates have another important attribute: Since the bulk silicon substrate remains intact below the hotplate membrane, it can be utilized as a location to construct CMOS control and readout circuitry for the hotplate above directly above it.[48,51] This technique saves valuable real estate on the wafer surface and permits even higher pixel counts.

The disadvantage to surface micromachined microhotplates is the small hotplate-to-substrate separations characteristic of this technology. Separations are usually no greater than 2 μm, so significant heat transfer by conduction through air, from the microhotplate to the substrate, limits the thermal sensitivity of surface micromachined hotplates. For this reason, they are generally vacuum packaged.[48,53] In applications where wide spectral bandwidth is necessary ($\lambda > 10\mu m$), it is difficult to find appropriate package windows.[53] However, in many applications such as night vision[60] and non-invasive tympanic-membrane temperature monitoring[61] silicon is an appropriate vacuum packaging material.

Current efforts to improve microhotplate IR detectors rely on (a) improving the absorptivity of the microhotplate, and (b) tuning the separation between hotplate and substrate so that IR reflections from substrate can be absorbed in the hotplate.[51] In the latter case, the separation is taken to be close to $\lambda/4$ where $\lambda$ is the center wavelength of the optical band of interest. However, even when optical resonance is not achieved, reflections from the substrate set up a double-pass condition through the hotplate and thereby increase its IR energy input.

The absorption characteristics of the microhotplate membrane are obviously very important to the performance of an IR detector. Most absorbers have been fabricated with unstructured layers of standard CMOS films.[62] Silicon dioxide,[48] stress-relieved composites of silicon dioxide and silicon nitride[53] and composites of silicon dioxide and aluminum[63] have all been used. Absorptivity can be enhanced by patterning the constitutive layers. By effectively corrugating the surface of the absorber (see Figure 5), diffraction effects can be exploited and absorptivity is improved.[62,64]

## 5. FLOW SENSORS

There are many applications for compact gas flow sensors. Their small size, fast response and low power consumption have made them well suited to mass flow controlling, and medical applications like blood flow and respiration monitoring.[65,66,67,68,69,70] Their small size is particularly important in medical applications because it minimizes flow disturbance by the sensor itself. Unlike conventional wind vanes, micro-flow sensors, and the hot-wire anemometers on which they are based, have no moving parts, so the problem of mechanical wear is eliminated.[71] Thermal flow sensors measure the heat transfer between temperature sensitive elements caused by fluid flow. The mechanism of heat transfer is, therefore, forced convection. A typical design consists of three equally spaced parallel wires that are oriented perpendicular to a flow channel. The central wire is heated by passing an electrical current through it, while the symmetrically-placed surrounding wires are used as temperature sensors. Fluid flowing through the flow channel, and passed the wires will cool the upstream resistor, while heating the downstream resistor. At first it would seem that this measurement only gives the direction of flow. However, further examination of the principles of forced convection show that the temperature difference between the upstream and downstream resistors (measured by their resistance variation in response to flow) is proportional to the square root of the flow speed.[72] Thus, both the direction and speed of flow can be determined by this method.

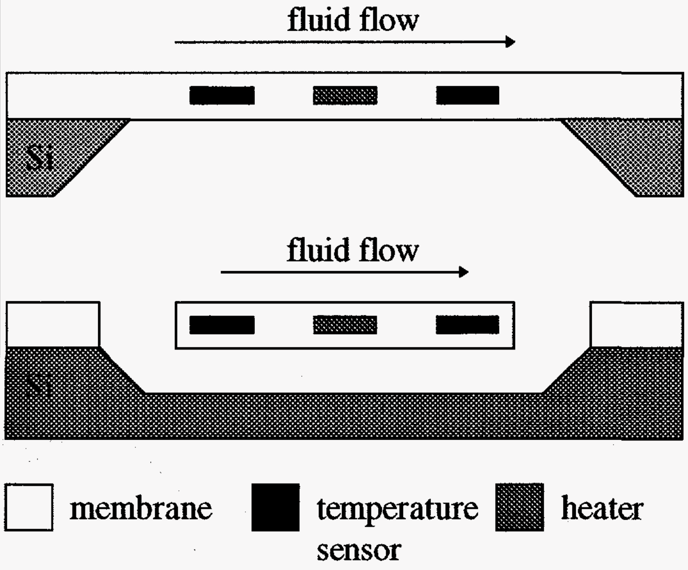

*Figure 6: Hotplate (upper) and bridge (lower) designs for micromachined flow sensors.*

Already by the early 1970s the benefits of integrating a transducer and its signal processing electronics on a single silicon monolithic chip were appreciated and applied to the fabrication of flowmeters. Van Putten et. al.[73,74] and Van Reit et. al.,[72] constructed the first integrated flowmeters on silicon. In the former approach, bipolar transistors were used as the heating and sensing elements, while in the latter diffused resistors were implemented. The pyroelectric effect in zinc oxide[75] and in lithium tantalate[76] has also been utilized to fabricate temperature sensors for monolithically integrated flow meters.

By the mid-1980s the benefits of micromachining were applied to hot-wire anemometry. Through the placement of the heating and sensing elements on micromachined dielectric bridges and hotplates, improvements in thermal sensitivity and time response were achieved.[77,78,79,80,81,82,83] Examples of micro-flow structures are shown in Figure 6 (after references 65,68). As with IR sensors, thermistors[84,85] and thermopiles[71,86,87,88] are the most popular temperature sensing elements, but diodes[89] have also been used. It should be noted that the flow sensor show in Figure 6 measures one-dimensional flows. Flow sensors for the measurement of two-dimensional flows have also been fabricated.[90] By orienting two hot-wire detectors orthogonally to one another, two temperature differences $\Delta T_x$ and $\Delta T_y$ are generated, and thus $v_x$ and $v_y$ are known. Hence, the vector flow at the location of the sensor is known.

## 6. PRESSURE SENSORS

A number of thermal-conductivity-based micromachined vacuum sensors have been reported recently.[91,92,93,94,95,96,97,98] These sensors indirectly measure pressure by detecting variations in ambient gas thermal conductivity. The Pirani gauge is the conventional predecessor to these micromachined pressure sensors. The extent to which heat is conducted away from the electrically heated wire of a Pirani gauge depends on the ambient gas pressure, which thus determines its equilibrium temperature. Pressure can then be correlated with the temperature-variable resistance of the wire. Miniaturized, micromachined versions of this sensor operate on the same physical principle.[29,95] In this case, however a microbridge or resistor supported on a microhotplate plays the role of the simple wire in the conventional case.

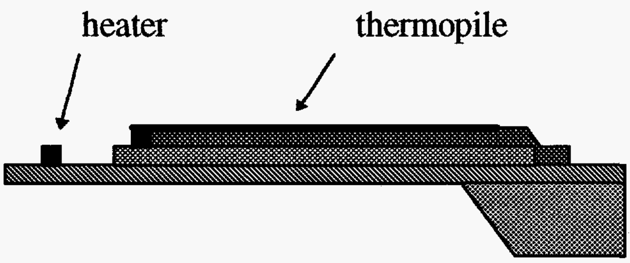

*Figure 7: Cantilever-based pressure sensor.*

The other popular design utilizes thermopiles to detect temperature variations of a heated microhotplate.[96] Figure 7 shows a representative design. Here a cantilever is heated by the resistor at the tip of the beam, and the thermopile measures the temperature difference between the resistor and the heat sunk substrate. The temperature difference is pressure dependent via the pressure-dependent cooling of the cantilever by the ambient.

## 7. CONCLUSIONS

Surface and bulk micromachined thermal and gas sensors offer increased performance, lower cost, improved manufacturability, and excellent design flexibility as compared with their conventional counterparts. Ultimately these gains are derived from micromachining's foundation in the well-established field of integrated circuit manufacturing. Batch fabrication has the potential to significantly reduce sensor cost and permits easy fabrication of sensor arrays. Among other things, arrays lend redundancy and cross-sensitivity to gas sensing, while arrays of IR sensors are an integral part of IR Focal Plane Arrays. Miniaturization has helped produce devices characterized by low power consumption, high thermal sensitivity and fast thermal response. Flexible yet precise control of device geometry combined with the capacity to choose from a wide variety of basic materials like silicon, polysilicon, silicon nitride, silicon dioxide and numerous metals, all with vastly differing thermal properties, allows the sensor designer to finely tailor the thermal characteristics of sensors and, ultimately, enhance overall device performance.

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