Understanding Thermopile Infrared Sensors

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Silicon micromachining technology has now enabled high-volume production of thermopile sensors using photolithography.

Introduction of silicon-based fabrication has made volume production of highly reliable devices cost effective and opened up new applications.

Thermopiles are particularly suited for simple fabrication of IR sensors that are generally used for noncontact measurement of surface temperature by monitoring heat radiated from the surface. There are many applications for such devices, ranging from pyrometry and gas analysis in medical and automotive equipment to temperature-controlled microwave cooking and toaster controls.

Recent advances in the production of thermopiles include introduction of silicon (Si) micromachining technology. Unlike the classical thermoelectric sensor materials - bismuth (Bi) and antimony (Sb) - silicon-based devices offer compatibility with standard semiconductor integrated-circuit (IC) fabrication processes and consequent cost-effective volume production.

Thermopile sensors

The thermocolumn or thermopile comprises a series of thermoelements, each element being a thin wire made of two materials of different thermal activity. When a temperature difference occurs between the two ends of a wire, an electrical tension thermotension, develops. Connecting several thermoelements in series adds together the thermotension of each element, producing a useful electrical output signal.

One end of each thermoelement wire is defined as hot and the other as cold. The hot junctions are concentrated on a very thin common absorbing area, while the cold junctions are located on a surrounding heat sink with high thermal mass.

Although thermopile sensors have historically been manufactured by hand in low volumes, introduction of silicon micromachining technology - based on standardized processes - has now enabled high-volume production using photolithography. Construction of a silicon-based thermocouple starts with a silicon substrate from which the middle under-part is removed by anisotropical etching to leave an approximately 1-痠 thick sandwich membrane of SiO2/Si3N4, which has low thermal conductivity (see Figure 1). Thin conductors of two different thermoelectric materials (the thermoelements) are deposited and structured onto the membrane. Both conductors have alternate junctions in the center of the membrane (hot junctions) and above the edge of the silicon substrate (cold junctions). An IR-absorbing layer covers the hot junctions.

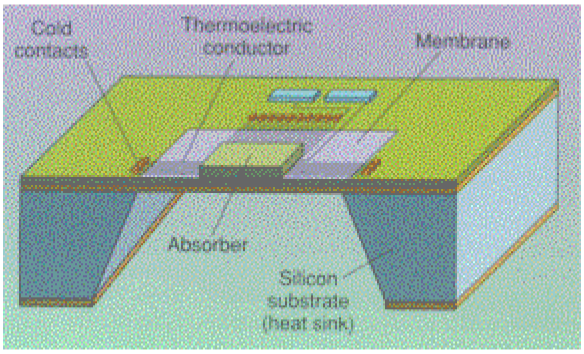

Figure 1. Standard photolithographic techniques etch a silicon substrate to create a silicon-based thermopile sensor chip. Cutaway view reveals the IR-sensing area in the middle of the substrate on a 1-痠 thick membrane of SiO2/Si3N4.

The sensor chip is mounted with good thermal contact on a TO-transistor baseplate, and a transistor cap with integral IR filter is hermetically mounted onto the base, thus sealing the sensor chip inside. Incident IR radiation is absorbed by the absorptive layer after passing through the IR filter and any focusing optics. The absorbed energy leads to a temperature difference between the hot and cold junctions, which produces a voltage difference across the detector due to the thermoelectric power of the thermocouples. Series connection of adjacent thermocouples ensures that the output voltage is measurably large. The optimum number of elements has been determined as 40 or more in series on a small absorbing area (0.5 x 0.5 mm).

Silicon as a thermoelectric material

In general, applications of thermoelectric sensors require high sensitivity and low noise. The ideal sensor would be designed with high thermoelectric coefficient (a), low thermal conductivity (l), and low volume resistivity (r). Good electrical conductors, such as gold, copper and silver, have relatively poor thermoelectric power. Metals with higher resistivity, especially bismuth and antimony, however, possess high thermoelectric power in combination with low thermal conductivity, which is why they are the best known thermoelectric materials. Doping the materials with selenium (Se) or tellurium (Te) can further improve the thermoelectric coefficient.

Exact values of thermal conductivities (l) are actually difficult to measure because thin layers often exhibit lower conductivity than bulk materials, and the parameters may vary with the deposition conditions. This usually results in a wide variation of parameters during production runs and limits thermopile use to special low-volume applications at high component costs.

Use of semiconductor materials - such as silicon (crystalline or polycrystalline) - as thermoelectric materials provides other advantages. The resistivity and thermoelectric power can be altered by changing the dopant concentration; resistivity increases faster than the square root of thermoelectric power, as does the internal resistance, *R*. Thus, the dopant concentration must be optimized for high sensitivity/noise ratios. While both silicon and polysilicon reach higher thermoelectric power, bismuth and antimony offer low thermal conductivity and resistivity. The basic advantage of silicon, therefore, is compatibility with CMOS-standard processes, with resulting high reliability and temperature stability and relatively small variations during repeated production runs.

Recent commercial products using this technology include thermopiles made with *n*-doped polysilicon and aluminum using a quasi-standard CMOS process. The membrane consists of an 800-nm sandwich of low-pressure chemical-vapor-deposited SiO_2/Si_3N_4 on top of a 400-瘘-thick silicon chip, which is anisotropically etched with potassium hydroxide at 85 蚓. The sensor chip is mounted on a TO-baseplate and fitted with a thermistor for referencing ambient temperature.

Performance specifications

Sensitivity - The sensitivity of a thermopile sensor is defined as the output voltage divided by the radiated power that reaches the sensor. The sensitivity is usually defined as responsivity in volts per watt (V/W) with test conditions specified, such as blackbody source and the spectral range of the filter. Hence

$$R = Vs/qs$$

where Vs is the effective value of output voltage, and qs is the effective value of radiation flux.

The sensitivity obtained depends on the filter transmission, the absorption of the receiving sensor area and all the thermal properties of the assembly including the sensor package. When comparing devices, it is important to consider the specifications with or without a filter. Typical values for thermopile responsivity range from 5 to 100 V/W with filter.

Noise - Within the range from 0 to 100 Hz, the noise (Vn) is determined by the thermal noise of the total internal resistance, R,

Vn = (4kTR)?/sup>

where k is Boltzmann's constant and T is temperature. The noise value is normalized to a bandwidth of 1 Hz. Typical numbers range from 10 to 50 nV/Hz?/sup> at room temperature.

Time Constant - The time constant (t) describes the duration of signal response after a change of the incident radiated power, measured when the signal has reached 63% of its final value. Typical values range from 10 to 100 ms.

Frequency Response - The frequency response of a thermopile is determined by its time constant and exhibits typical low-pass performance. The main reasons are the thermal properties of the housing, the internal construction, and the thermal conductivity of the materials used. Micromachined silicon thermopiles display a typical 1/f decrease in frequency response, starting at 5 to 10 Hz (see Figure 2).

Figure 2. Thermopiles typically exhibit a 1/*f* decrease in frequency response starting between 5 and 10 Hz; model numbers pertain to micromachined

silicon devices.

Environmental Influences

The output signal of a thermopile depends on the amount of energy reaching the sensor. Often, however, incident radiation affects not only the sensing area, but also the sensor housing; if the housing heats up as a result, the output signal is affected. The most accurate temperature sensing is obtained, therefore, when incident thermal radiation is focussed onto the sensing area.

Another factor that affects measurement accuracy is the effect of the ambient temperature level on the sensor housing - electronic temperature compensation can address this problem. Current techniques provide a temperature reference signal that tracks the temperature of the sensor housing; the reference is typically used to stabilize the electronic signal processing so it is consistent with the actual operating environment. Thermopiles with an internal thermistor or reference diode are best suited for such applications; the thermistor version is best for analog circuit design, while the diode version better suits digital signal processing.

While the variation surrounding ambient temperatures and its effect on thermopile output signals can be compensated for as described, it is more difficult to compensate for temperature coefficients of the sensor, especially when high measurement accuracy is required. Thermopiles typically show sensitivity temperature coefficients between 0.1% and 0.5%/K.

At PerkinElmer Optoelectronics (Wiesbaden, Germany), we have produced two new thermopile designs using the micromachined-wafer-batch processes with polysilicon and aluminum as thermoelectric materials. This technology typically outperforms other conventional thermopile designs due to its low temperature coefficients of sensitivity as low as 0.01%/K (see Figure 3). The first product introduced (TPS 408) has now been upgraded to a new series, the TPS 424 and the TPS 434, which has a built-in temperature reference. An enlarged sensitive area (1.8 x 1.8 mm) is also available in the TPS 624 and 634 series.

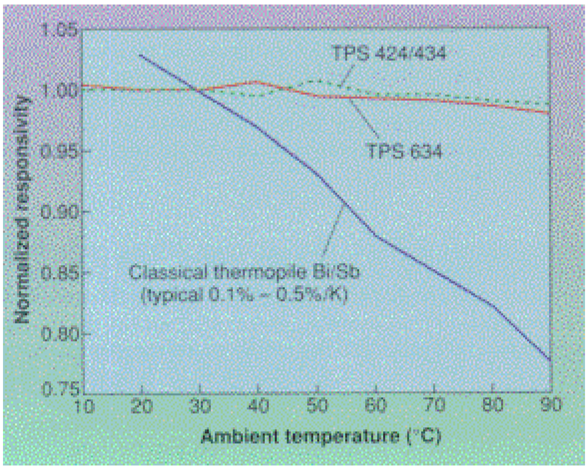

Figure 3. Thermopiles made using polysilicon and aluminum as thermoelectric materials exhibit low temperature-dependency sensitivity when compared to conventional Bi/Sb devices.

Improved performance and reliability together with the reduced cost associated with micromachined silicon thermopile sensors open the door to many high-volume sensor applications, including automotive-exhaust emission controls and medical-monitor instrumentation.