MICROMECHANICAL TEMPERATURE SENSOR

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There are several possibilities for creating temperature sensors. Different principles and technological processes and sequences could be used.

One of the simplest constructions is that, using thermocouples. In this case, different contact materials could be used. The choice is made by estimation of the chosen technology, the availability of technological equipment and materials, the application of the device, the parameters obtained by the sensor.

In this case, a semiconductor sensor is designed. One of the materials, participated in the thermocouple is silicon (Si) of the base wafer. The second contact material is aluminum – Al, deposited as a metal layer. By serial connecting of several thermocouples (thermocouple sensor battery), it is possible to improve the efficiency of the device and to increase the output signal.

Because of the necessity to have a big temperature difference between the hot and cold parts of the thermocouple, the designers have to reject the temperature conductivity alongside the device. This is the reason to choose so called micromechanical temperature sensor, the case in which, the sensing device is made on the top of very thin semiconductor epitaxial layer, made like a microbeam. Then, the temperature resistance R_{th} alongside the element is very high, and the temperature at the free end of the beam is much higher, than that at the frame of the structure. This fact gives many advantages like higher sensitivity, low temperature capacitance, fast response etc., due to the big temperature difference – ΔT.

Keywords: MEMS, Si-Al Termocouple, Thermocouple sensor battery, Sensitivity

INTRODUCTION

The Microsystemtechnics include a development and production of a miniature MicroElectroMechanicalSystems (MEMS), whose elements and components typically have dimensions in the micrometric range. For their fabrication, the conventional technological processes and sequences, typical for microelectronics, could be used. The same methods, which are used for the manufacturing of semiconductor or hybrid devices, could be used for making microsystems. This fact is very important, because, the sensing and actuating parts of the systems could be fabricated at the same time and processes, with the microelectronic devices from the data-processing part of the unit. In this way, so called intelligent, smart sensors could be designed and built.

In recent years, the miniature temperature sensors have played a big role in many areas of human life, starting from the huge automotive production, passing through some industrial and scientific applications, medical care, domestic appliances etc. and finishing with ink-jet printing heads. This large market needs very large number of different types of temperature sensors. There are many phenomena and constructions used in the contemporary temperature sensors. Normally, they are divided in several groups, as follows: resistance temperature detectors (RTD), thermoelements (thermocouples), thermistors, temperature sensors with p-n-junction(s) etc. Because of its simplicity, thermocouples are the most widely used, at a lowest price and simple construction.

For implementation of their functions, in microcomponents different physical effects are used. They have to carry out an immediate and direct transformation of the energy, where at least one of the energy forma should be the electrical. By temperature sensors, some of the following transformations of energy are performed:

Thermal energy ⇔ Electrical energy;
Thermal energy ⇔ Radiant energy;
Radiant energy ⇔ Thermal energy ⇔ Electrical energy;

In general, there are two big categories of functional principles for transformation of not electrical quantity in electrical signal.

1. Physical effects, by which, a not electrical quantity of energy is transformed in electrical signal – so called active transmitters.

2. Control of electrical flow through electrical or electronic device. In this case, non electrical quantity determinates parameters of the constructive elements, and by this means, the quantity modulate an electrical signal - so called passive temperature sensors.

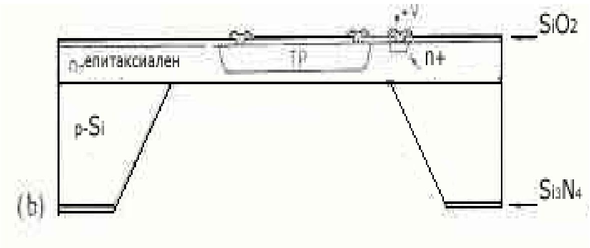

Fig. 1

Design of the thermopile

The temperature sensors could be included in some of the following categories: thermocouples, thermopiles, thermoelements and others. The thermocouples have played a big role, because they have a simple construction.

The thermocouples, as temperature sensors, are based on thermo-electrical effects. They are divided in two fundamental groups - the Seebeck effect and the Peltie effect. They belong to contact temperature sensors. For MEMS construction, several microstructures like closed membrane, cantilever beam, microbridge or floating membrane could be used.

A temperature sensor as a thermopile was designed. Because of the necessity of big difference in temperatures between the two ends of thermocouples, it was designed like a microbeam, placed over a well in semiconductor wafer (Fig. 1). In such a case, a very big heat resistance (very low thermal conductivity) could be reached. One end of the thermocouple, which is placed at the frame of the structure, will be at the low (room) temperature of the case, but the other end will be at measured temperature. Some part, at the end of the microbeam will be covered with a dark-colored material, in order to absorb the thermal energy, passed through, like infrared illumination and heated it. The sensitivity of the thermal sensor could be increased by using a number of thermocouples, in serial connection.

For making the thermal microsensor, one of the standard semiconductor technologies – CMOS was chosen. In such a case, the sensor element could be made without big changes in a typical CMOS technological process. At the end of the sequence, some additional microengineering steps, like an anisotropic etching with electrochemical etch-stop will be added. In this way, it is possible to build the sensor part and the data-processing part of the microsystem in the same technological procedure. One of the possibilities for making a micromechanical device, bulk micromachining, was chosen.

The thermocouples should be built by using some of the materials, available in CMOS technology. The choice was made, and silicon – Si, and aluminum – Al was chosen. The best way to make the microbeam, was to use the n-type Si-epitaxial layer, with its fixed thickness, and the possibility, during the anisotropic etching, this layer to be used as an etch-stopper. In the volume of this epilayer, the first part of the thermocouple should be done. A p-type diffusion Si-area was chosen. In order to increase the sensitivity of the thermosensor, several p-type areas were serially connected as thermobattery (Fig. 2). The connection lines were used as a second material for the thermocouples.

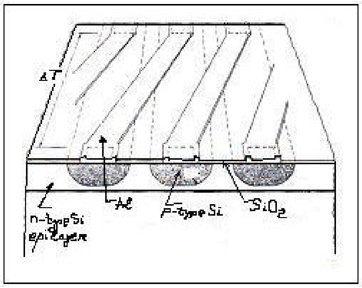

Fig. 2

Finally, the thermopile was composite from five p-type silicon thermocouples, formed in an n-type epilayer microbeam, placed over a well (Fig, 3).

The total length of the cantilever beam is L_{gr} = 300 μm and the width of the beam is W_{gr}= 180 μm, the thickness - D_{gr}=10 μm. Each of the Silicon thermocouples has the size: width – W = 20 μm, length – L = 150 μm, and the thickness is D=6 μm. The distance between them was chosen to be 10 μm.

Very important parameter is the thermal capacity (C_{th}) of the structure. Its value depends on the change of the accumulated heat, alongside of the beam and could be estimated by the following equation:

$C_{th} = dQ/dT = m_{gr} \, . \, c$; [J/K]

where m_{gr} - weight of the cantilever beam [g];
$c = 0{,}71$ - specific heat capacitance [J/g.K];

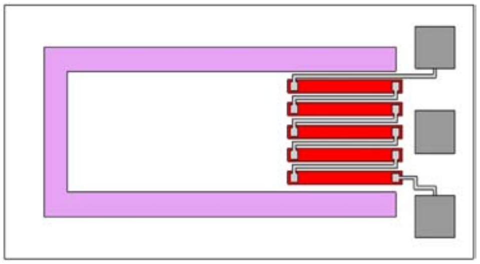

Fig. 3

The weight of the cantilever beam could be found by formulas:

$m_{gr} = V_{gr} \, . \, \rho_0$; [g]

$V_{gr} = L_{gr} \, . W_{gr} \, . \, D_{gr},$

where: $\rho_o = 2.33$ g/cm^3 is the density of Silicon;
V_{gr} - the volume of cantilever beam [cm^3];

$V_{gr} = 300.10^{-4} \, . \, 180.10^{-4} \, . \, 10.10^{-4} = 54.10^{-8}$ cm^3;
$m_{gr} = 54.10^{-8} \, . \, 2{,}33 = 0{,}13.10^{-5}$ g;
$C_{th} = 0{,}13.10^{-5} \, . \, 0{,}71 = 0{,}09.10^{-5}$ J/g.K;

The thermal (heat) resistance of cantilever beam depends on the distance of propagation and on the heat conductivity of semiconductor material.

$$R_{th} = \frac{L}{\lambda . A} \; ; \; [K/W]$$

where: A - the cross section area of the cantilever beam [cm^2];
λ – the heat conductivity of semiconductor material ($\lambda = 1.57$ W/cm.K);

$A = D_{gr} \, . \, W_{gr} = 10.10^{-4} \, . \, 180.10^{-4} = 0{,}18.10^{-4}$ cm^2;

$$R_{th} = \frac{150.10^{-4}}{1{,}57 \, . \, 0{,}18.10^{-4}} = 535 \; ^oC/W;$$

By the change of a width and a thickness of the cantilever beam, the heat resistance could be changed (Table 1). The better parameters would be obtained by a higher heat resistance of the cantilever, but it is necessary to find some optimal proportion between dimensions of the beam and the thermocouples.

Table 1

W_{gr}, µm	90	110	140	180
L, µm	150	150	150	150
D_{gr}, µm	6	7	8	10
R_{th}, ^{o}C/W	1765	1240	882	535

The thermoelectromotive voltage is the most important parameter of the sensor. It depends on the materials and the temperature difference ΔT, between cold and hot points of the thermocouple. This voltage could be found by:

$$\Delta U_{AB} = (\alpha_A - \alpha_B).\Delta T;$$

where: α_A - the Seebeck coefficient for p-silicon;
α_B - the Seebeck coefficient for aluminum.

The temperature of the cold point of the thermocouple is constant and its value is 30^0C. The temperature of the hot point is varying from 50^0C to 150^0C. The Seebeck coefficient α_A can change from 500 to 700 μV/K, and α_B - from 3.8 to 4.2 μV/K.

The general Seebeck coefficient for this thermocouple α_S could be found by:

$$\alpha_S = \alpha_A - \alpha_B = 700 - 4{,}2 = 695{,}8\ \mu V/K \approx 696\ \mu V/K;$$

Table 2 shows the dependence of the thermoelectromotive voltage on the temperature difference.

Table 2

T1,°C	30					
T2, °C	50	70	90	110	130	150
ΔT, °C	20	40	60	80	100	120
ΔUab ,mV	13.9	27.8	41.8	55.7	69.6	83.5

The sensitivity of the thermopile S, depends on the number of serial connected thermocouples. In this particular case, the number is n = 5.

$$S = n \,.\, \alpha_S = 5 \,.\, 696.10^{-6} = 3{,}4\ mV/^oC;$$

The quality factor of the thermocouple Z, depends on specific heat conductivity λ and on electrical resistivity ρ:

$$Z = \alpha_S \frac{1}{\lambda \,.\, \rho} \quad ,$$

where λ = 1.57 W/cm.K;

$$\rho_{pSi} = \frac{1}{q \,.\, p \,.\, \mu_p} = \frac{1}{1{,}6.10^{-19} \,.\, 1{,}5.10^{18} \,.\, 500} \ ; \quad \rho_{pSi} = 8{,}3.10^{-3}\ \Omega.sm;$$

$$Z = \frac{(696.10^{-6})^2}{1{,}57 \,.\, 8{,}3.10^{-3}} = 36{,}9.10^{-6}\ K^{-1};$$

The cantilever beam is fixed to the frame of the semiconductor chip. This frame plays a role of a radiator. At the same end of the cantilever, the thermopiles are created. The basic technological procedure for fabrication of the microsensor is as follows:

1. Oxidation of the substrate (masking for p-diffusion) - photolithography for p^+-diffusion and etching of the SiO2-layer;
2. p^+-diffusion in an n-epilayer (followed by oxidation, photolithography for n^+-diffusion and etching of SiO2-layer);
3. n^+-diffusion for a contact from the n-epilayer (followed by oxidation,);
4. Photolithography for opening the contact holes and etching of SiO2-layer;
5. Metallization with aluminum (followed by photolithography and etching of the Al layer);
6. Deposition of Si_3N_4-layer on top and back-sides of the wafer;
7. Photolithography and etching of Si_3N_4 at the back side of the wafer;
8. Anisotropic etching of Silicon wafer from the back side of the substrate for making of a membrane;
9. Forming the cantilever and the well in the structure by photolithography and etching of epitaxial layer from the front side of the substrate;

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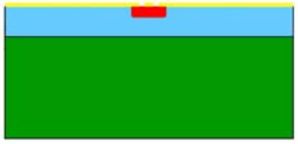

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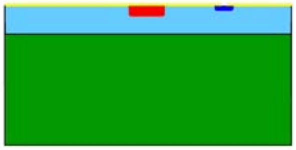

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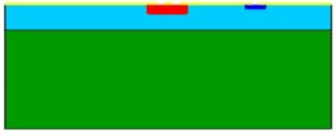

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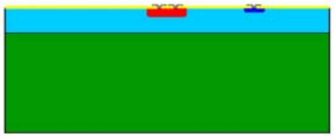

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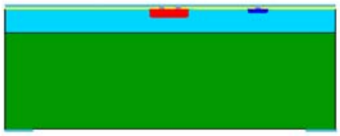

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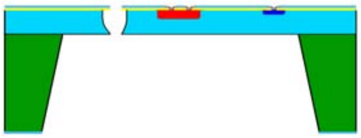

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