Study on Temperature Stability Improvement of On-Chip Reference Elements Using Integrated Peltier Coolers

Davey D. L. Wijngaards and Reinoud F. Wolffenbuttel

***Abstract*—This paper presents the concept and feasibility of a microthermostat that, besides active heating, employs active cooling by means of specially developed on-chip integrated Peltier devices. It is shown that the design for best cooling performance can be optimized through a simple criterion, i.e., the width ratio of the thermoelectric elements. Subsequently, the overall design criteria of the microthermostat are presented. System performance is shown to critically depend on the approach selected for heating, cooling, and temperature sensing.**

***Index Terms*—Microthermostat, Peltier device, thermal stabilization, thermoelectric cooler.**

I. Introduction

TEMPERATURE control is one of the most fundamental and most essential processes encountered in instrumentation and measurement. Within the context of this paper, the intended application is to establish an active control system that is capable of stabilizing the temperature of multiple specific micromachined volumes within a single chip over the largest possible temperature range. The incentive for this work results from the well-known fact that performance of a reference element is often limited by parasitic thermal effects. This especially applies to an on-chip implementation, due to the susceptibility of integrated components to absolute temperature drift as well as thermal gradients within a chip. The concept of using a microthermostat to cancel these thermal fluctuations was first demonstrated by Klaassen *et al.* [1], by stabilizing a thermally isolated bandgap reference structure at a temperature of 90 °C by means of actively heating and passively cooling it. The major problem associated with this combination of active heating and passive cooling operation at elevated temperatures only can be largely circumvented by applying active instead of passive cooling. Of the various microscale active cooling techniques available, thermoelectric coolers are favorable as these can be readily integrated with electronics, without significant fabrication and packaging constraints.

As the integrated thermoelectric cooler is the major new component of the microthermostat, the first part of this paper discusses the operation and design criteria of such elements. Thereafter, in the second part of the paper, the design constraints of the overall system are addressed. The overall system, as schematically shown in Fig. 1, consists of thermoelectric cooler(s), heating element(s), sensing element(s), and electronics for readout, signal conditioning, and driving of the heater(s) and cooler(s).

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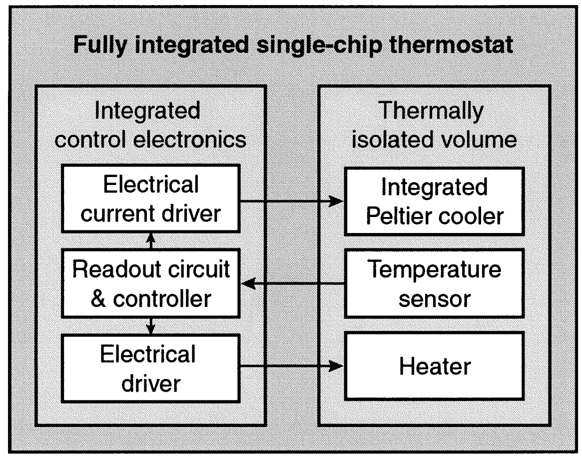

Fig. 1. Schematic diagram of the fully integrated microthermostat under investigation.

II. Peltier Cooler Performance

The (conventional) thermoelectric cooler (TEC) is gaining interest from industry as it offers low-cost, easy-to-operate, and reliable temperature control, in contrast to most other cooling techniques. In general, four characteristics stand out: localized operation, high speed, high accuracy and small size. To a very large extent, it is possible to preserve these characteristics, when miniaturizing such element for on-chip integration. Due to the small resulting dimensions (typical thermoelement lengths vary from 50 to 250 μm), response times are on the order of milliseconds only. One of the main driving forces of this work is to ensure fabrication compatibility [2], which is essential for two reasons. First, this improves the adaptation of technology by the industry. Second, it is the only way to ensure that the TEC can be co-integrated with electronics on the same chip. For this reason, polycrystalline silicon germanium (polySiGe) is preferred as the thermoelectric material, as it offers the best balance between performance and compatibility today [3].

Fig. 2 shows the schematic construction of a planar on-chip integrated TEC. The device consists of an n- and p-type thermoelement electrically connected in series, sandwiched in be-

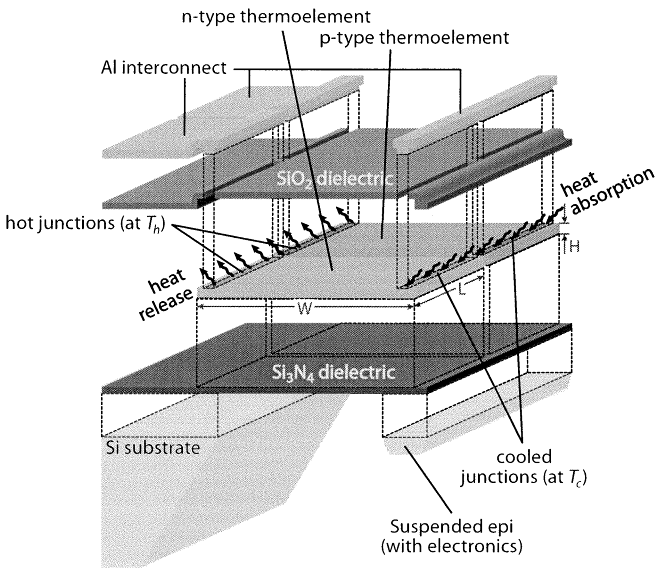

Fig. 2. Exploded view of a planar TEC.

tween two dielectric layers. Running an electrical current consecutively through the n- and p-type elements results in removal of thermal energy from the cooled (metal–semiconductor) junctions at the tip of a cantilever. This energy is released again at the hot junctions over the substrate. The primary parameter that needs to be determined is the maximum temperature reduction of the cooled junctions with respect to the temperature of hot junctions, when operating the device in cooling mode. In terms of a microthermostat, this parameter determines the lower boundary of the thermal operating range. In the macroscopic Peltier device, this $\Delta T_{\max}$ (equal to the hot junction temperature minus the cooled junction temperature, $T_h - T_c$) is

$$\Delta T_{\max} = \frac{(\alpha_p - \alpha_n)^2}{2KR} T_c^2 = \frac{1}{2} Z T_c^2 \tag{1}$$

where $K = (\lambda_n \cdot W_n \cdot H_n)/L_n + (\lambda_p \cdot W_p \cdot H_p)/L_p$, $R = (\rho_n \cdot L_n)/(W_n \cdot H_n) + (\lambda_p \cdot L_p \cdot)/(W_p \cdot H_p)$, and $Z = (\alpha_p - \alpha_n)/(KR)$. The variable α is the Seebeck coefficient, λ is the thermal conductivity, and ρ is the electrical resistivity. The subscripts n and p are used to distinguish between the n- and p-type material. The parameters L, W, and H indicate the length, width, and height of the respective thermoelements. The maximum temperature difference is obtained when applying both the optimal electrical current i_{opt} and using the proper width ratio between the n- and p-type thermoelements W_p/W_n as follows:

$$i_{\text{opt}} = \frac{KR\sqrt{KR(KR + 2(\alpha_n - \alpha_p)^2 T_h)}}{R(\alpha_n - \alpha_p)} \tag{2}$$

$$\frac{W_p}{W_n} = \frac{L_p H_n}{L_n H_p}\sqrt{\frac{\rho_p \lambda_n}{\rho_n \lambda_p}}. \tag{3}$$

Equation (2) differs from the usual expression $i_{\text{opt}} = T_c(\alpha_p - \alpha_n)/R$ [4] in that it expresses the current i_{opt} as a function of T_h rather then T_c. This is preferable, as T_c is an unknown that is to be deduced from i_{opt}. By using T_h, this mutual dependency loop between T_c and i_{opt} is avoided.

Compared to the conventional Peltier element, the integrated thin-film cooler suffers from a number of performance-limiting effects. While the macroscopic device has thermoelements in between the hot and cold junctions only, the thin-film device also has at least two dielectric layers in between, which increases the thermal leakage. Second, a thin-film device has significantly smaller junctions, so the electrical contact resistance becomes significant. These two effects can be readily integrated in (1)–(3). First a term $K' = K + K_m$ is defined, where $K_m = (\lambda_m \cdot W_m \cdot H_m)/L_m$ and identifies the thermal conduction of the additional dielectric layers. Next, the electrical contact resistance R_c is accounted for by defining $R' = R + 2R_c$. The factor 2 is required to correct for the amount of thermal energy contributing to Joule heating. The thin-film thermoelement's width ratio $(W_p/W_n)_{tf}$ now becomes

$$\left(\frac{W_p}{W_n}\right)_{tf} = \frac{H_n L_p}{H_p L_n} \times \sqrt{\frac{\left(\lambda_n L_m + \lambda_m L_n(\frac{H_m}{H_n})\right)\left(\rho_p + 2R_c W_p \frac{H_p}{L_p}\right)}{\rho_n\left(\lambda_p L_m + \lambda_m L_p(\frac{H_m}{H_p})\right)}}. \tag{4}$$

Finally, the maximum temperature difference becomes

$$\Delta T_{\max,tf} = \frac{KR}{K'R'}\left(\frac{1}{2} Z_{tf} T_c^2\right). \tag{5}$$

Here, reference is made to Z_{tf}, rather than Z, to indicate that the values found for R and K through (5) are different from those found through (3). A well-designed thin-film polySiGe TEC has an R_c on the order of a few percent of R at most, while the thermal conduction through the membrane accounts for 10%–30% of the total thermal conduction. As a result, the combined temperature decrease can be as much as 25% of $\Delta T_{\max}$. Besides K_m and R_c, other parasitic effects can play a role, like convective and radiant heat losses [5], and heating of the substrate due to the thermal load imposed by the TEC [6]. However, these effects turn out to be significantly less important.

III. Design Considerations

Besides the electronics, three major system components are distinguished: the thermoelectric coolers, the heater, and the temperature sensor. As the choice of the cooler is fixed (the TEC is the only option), the first concern becomes the selection of the type of heater and the type of sensor.

A. Choice of Heater

Looking at the materials available, two suitable heating components can be identified. The first is to integrate a resistor directly on top of the thermally stabilized region. All of the Joule heat generated by such a resistor is used to increase the temperature of that region. Within the choice of resistors, diffused resistors have the disadvantage of being process-, stress-, temperature- and voltage-dependent [7], which makes it impossible to obtain a constant nominal resistance value. Therefore, thin metal-film resistors are preferred, for two reasons. First, a thin metal-film resistor is much less process-dependent. Second, thin

TABLE I
COMPARISON OF POTENTIAL HEATING AND TEMPERATURE SENSING TECHNIQUES

Heating technique	**Characteristics**
Thin metal-film resistor	+ flexibility in shape, size and position on the area to be stabilised + zero-TCR alloys ascertain constant heat generation over entire temperature range – metal leads in parallel with the TEC significantly increase thermal leakage
Thermoelectric	+ is present by default (because of the required thermoelectric cooler) + no additional leads are required, which avoids additional thermal leakage – low efficiency – area of heat generation is less defined (i.e. also along membrane suspension)
Sensing technique	**Characteristics**
PTAT source on membrane	+ pin-pointed absolute temperature measurement on membrane – risk of self-heating due to the power dissipated in the PTAT circuit – metal leads in parallel with the TEC significantly increase thermal leakage
Thermopiles plus PTAT outside membrane	+ low offset + pin-pointed measurement – indirect absolute temperature measurement – thermopiles in parallel with the TEC moderately increase thermal leakage
TEC as thermopile plus PTAT outside membrane	+ "all-in-one" device (except for absolute temperature sensor) + low offset – indirect absolute temperature measurement – sensing is physically tied to rim of area to be stabilised (i.e., cannot be pin-pointed) – time multiplexing is required for sensing operation, which prevents a 100% cooling duty cycle and slightly reduces temperature range of operation

metal-film alloys, like $Ni_{0.45}Cr_{0.5}Si_{0.05}$ [8], have a sub-ppm temperature coefficient of resistance (TCR). This provides a near-constant power output over a very large temperature range. Even though an alloy like $Ni_{0.45}Cr_{0.5}Si_{0.05}$ is a nonstandard material in terms of IC fabrication, most thin metal films can be readily co-integrated with electronics using simple postprocessing [9]. The major limitation of heaters is the need to connect these by means of low-ohmic metal wires, which cause a significant thermal leakage between the themally stabilized region and the surrounding substrate.

The second heating technique is to use the TEC with a reversed electrical current, thus creating a thermoelectric heater. The appeal of this solution is that a single element can be used for active heating and active cooling alike. The main drawback is that the power efficiency is low: only half of the Joule heat generated within the thermoelement contributes to the temperature rise of the cantilever tip. Together with the heat transported toward the tip by means of the Peltier effect, this implies that only 60%–70% of the consumed thermal energy contributes to the temperature rise of the central membrane.

B. Choice of Sensor

Most important for the temperature sensor is the reproducibility (stability), as it determines the accuracy with which the measurement can be performed. The aim is to have an absolute accuracy of 2 K with a repeatability of 0.1 K. Furthermore, to be flexible in use, the microthermostat must be able to stabilize the designated thermal volume at any given temperature within the operating range. Therefore, the sensing component must be capable of measuring the absolute temperature of the thermally stabilized region. A proportional to absolute temperature (PTAT) circuit is ideally suited for this purpose, as it can directly measure the absolute temperature at the thermally stabilized region, when integrated in the epi-layer suspended from the cantilever (see Fig. 2). When combining the suspended PTAT circuit with advanced offset- and noise-reduction circuits in the substrate, a thermal accuracy of 0.7 K can be achieved, with a repeatability due to long-term drift of 0.1 K and a noise level equivalent to $5 \cdot 10^{-3}$ K [10].

A resistor could also be used as a temperature sensor, but the same drawbacks presented in the previous section apply. Furthermore, as the resistance of a thin metal-film resistor is comparatively small, large electrical currents are required for a good signal level. This induces significant self-heating, as the resistor is located on a thin-film membrane. Therefore, temperature sensing using resistors is not a viable solution.

The third option is the use of thermoelectric elements. This is the favorable choice, as the Seebeck effect is self-generating (and thus shows no offset) and does not exhibit self-heating. The disadvantage is the fundamental sensitivity to a temperature difference, rather than an absolute temperature. Therefore, an absolute temperature sensor, to be placed outside the microthermostat area, is required. In combination with the thermoelectric element between the microthermostat and the surrounding area, the absolute temperature at the thermostat area can be determined. The peripheral placement of the absolute temperature sensor prevents any complication in the thermal design.

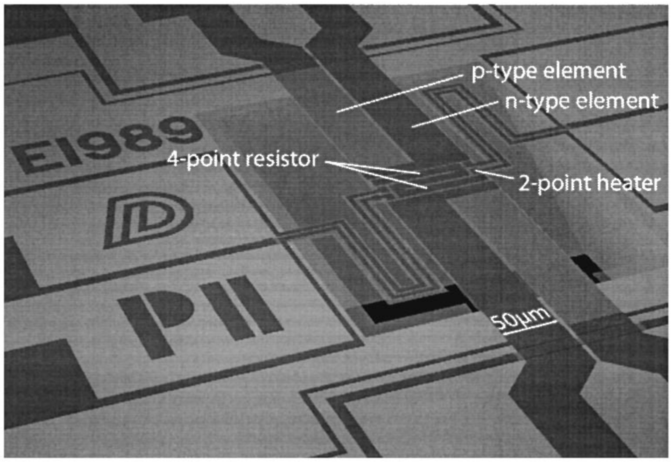

Fig. 3. View of a first-generation Peltier device.

IV. Discussion

From the above design consideration, two potential heating techniques (thermoelectric heating and thin metal-film heating) and two potential temperature-sensing techniques (PTAT circuit, thermopile) are identified. The advantages and disadvantages of each technique are listed in Table I.

The final choice of heating technique is a compromise between maximum operating range and efficiency. When using a Peltier device in heating mode, power efficiency is sacrificed at the benefit of minimized thermal leakage. Even though the metal leads to a heating resistor in parallel with the TECs are very narrow, the thermal conductivity is significantly higher. For example, the thermal conductivity of aluminum interconnects ($\sim$ 220 $\mathrm{Wm^{-1}K^{-1}}$) is approximately 35 times higher than that of polySiGe used for the Peltier devices ($\sim$ 6 $\mathrm{Wm^{-1}K^{-1}}$). In the case of the structure indicated in Fig. 3, over 70% of the thermal conduction between the heater and the substrate takes place through the metal arms that are electrically connecting the four-point and two-point resistors. In the end, the thermal leakage of the resistor outweighs the lower power efficiency of thermoelectric elements, so the latter technique is preferred.

In terms of maximizing the thermal operating range of the microthermostat, the most appealing solution is the one that uses the Peltier device for cooling, heating, and differential temperature sensing alike (complemented by an absolute temperature sensor in the substrate.) On the other hand, in most circumstances, the region to be thermally stabilised is intended to hold a circuit to be thermally stabilized. In this situation, metal wires in parallel with the TEC cannot be avoided. At that point, a PTAT circuit can be co-integrated in the thermally stabilized region. Finally, two potential microthermostat implementations are further investigated:

1) Active cooling and heating by means of a Peltier device. Absolute temperature sensing at the thermally stabilized region by means of a PTAT circuit. (See Fig. 4 for a schematic diagram.)
2) Active cooling and heating by means of a Peltier device. Differential temperature sensing using either separate thermopile or the Peltier device, in combination with an absolute temperature sensor in the substrate. This option is presented elsewhere.

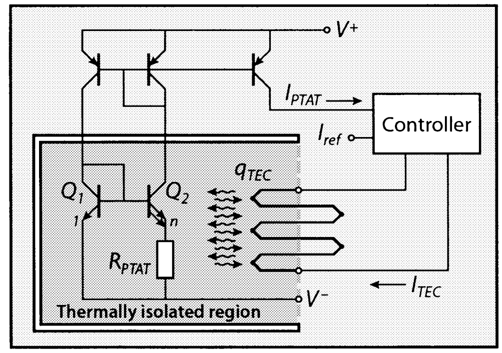

Fig. 4. Schematic diagram of the implemented microthermostat, using a PTAT circuit to sense the absolute temperature at the thermally stabilised membrane.

V. Conclusion

This paper discusses the concept of a new type of microthermostat, in which not only active heating but also active cooling is applied. For the latter function, an integrated thin-film thermoelectric cooler has been developed in an earlier phase of the project [3], [6]. The fabrication process is chosen such that fabrication compatibility with electronic processing is maintained, so that the cooler and electronics can be co-integrated in the same chip. Besides the cooler, the microthermostat requires a heater as well as an absolute temperature sensor. The different approaches available for heating and sensing techniques are compared, for achieving an optimal device configuration. Thermal leakage was found to be the most significant performance-degrading factor. Therefore, the number of interconnected leads is minimized. As a consequence, heating and cooling are best performed by means of the same Peltier device. Two sensing techniques are found to be suitable. First, a PTAT circuit can be integrated on the thermally stabilized region to provide a direct absolute temperature reading. Second, a thermopile or even the Peltier device can be used to determine the temperature difference between the thermally stabilized region and the absolute temperature sensor located in the substrate. The target specifications, an absolute temperature accuracy of 2 K with a repeatability of 0.1 K and a millisecond response time, are demonstrated to be feasible in a silicon micromachined microthermostat using active heating and cooling.

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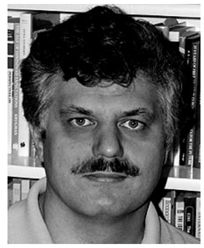

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