A novel spiral CMOS compatible micromachined thermoelectric IR microsensor

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Abstract

A novel sensing structure and realization method is proposed for complementary metal–oxide semiconductor (CMOS) compatible thermoelectric uncooled infrared microsensors. The structure enables high sensitivity and excellent thermal isolation in sensor pixels with small dimensions suitable for two-dimensional thermal imaging. Front-side dry micromachining allows fast CMOS post-processing, small pixel pitch and integration with on-chip CMOS readout. Prototype sensors with an area of $70 \times 70 \ \mu m^2$ achieved a measured noise equivalent power of $0.36 \ nW Hz^{-1/2}$ and a response time of 3 ms.

1. Introduction

Integrated micromachined thermoelectric sensors are one of the candidates for uncooled infrared (IR) thermal sensors [1–3]. Micromachined thermal sensors are revolutionizing IR imaging with uncooled thermal sensors. This is achieved by the realization of two-dimensional (2D) arrays of low-cost micromachined sensor pixels with very small thermal conductance as well as thermal capacitance that yield high sensitivity and a response fast enough for imaging [4, 5]. A comprehensive comparison between the different thermal sensors, i.e. bolometers, pyroelectric and thermoelectric sensors, is beyond the scope of this paper. However, thermocouples have some inherent advantages, including low power consumption, no $1/f$ noise and less stringent requirements for controlling the chip operating temperature [6, 7]. The thermoelectric sensors are constructed of one or more thermocouples that respond with spontaneous voltage to temperature differences induced by absorbed IR radiation. In order to allow temperature differences to develop, the ‘hot’ contact of the thermocouples has to be thermally isolated from the ‘cold’ contact heat sink. Such thermal isolation can be obtained in thin-film thermocouples fabricated on silicon substrates by the micromachining of the substrate below the ‘hot’ contacts. If complementary metal–oxide semiconductor (CMOS) circuits are realized on the same substrate, whole Microsystems can be fabricated monolithically.

Since thermoelectric sensors can be realized using standard CMOS layers, they have the best compatibility with CMOS technology and therefore have the potential of achieving low-cost uncooled imagers. Traditional designs of CMOS compatible thermoelectric sensors suffered from two main shortcomings. One disadvantage is the relatively small signal. In order to increase the signal several thermocouples are connected in series to form a thermopile [8,9]. This, however, reduces the achievable thermal resistance and thus performance. The second disadvantage is the problematic realization of 2D arrays of sensors. Using the CMOS layers as the sensor material limits processing mainly to bulk micromachining. Wet bulk micromachining can be done either from the back or from the front of the chip. Wet micromachining from the back limits the pitch of the array to values too high for 2D imaging, because of the angle of the anisotropic etch. Wet micromachining done from the front is more harmful to the CMOS circuits and to the released structures due to capillary forces and the stiction problem [13]. As opposed to traditional micromachining methods that used wet anisotropic etching processes for silicon bulk micromachining [2, 3, 6–10], this paper presents a dry micromachining technique for the release of thermally isolated thermocouples, which is new for this application. The silicon bulk is used as a sacrificial layer and structures made of CMOS processed thin films constitute the sensors. This technique allows better yield [13] and better thermal isolation in small pixels. Uncooled IR sensors have been realized, integrated in standard CMOS chips using this technique and tested.
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Figure 1. Schematic top view of a spiral thermoelectric sensor, showing (a) the micromachined cavity, (b) the spiral structure comprising a sandwich of dielectric layers (white), polysilicon (light grey) and aluminium (dark grey), (c) the hot contact, and (d) the sensor output on the unetched silicon bulk.

2. Sensor structure

The novel sensor structure, as depicted in figure 1, is based upon a spiral, which is the way of achieving the longest and yet narrowest structure in a given square area. This results in the highest thermal resistance possible and therefore the largest signal. The fact that the structure is narrow allows fast underetching using isotropic dry reactive ion etching (RIE) of the silicon bulk. In the areas around the structure, the silicon bulk is exposed during the CMOS processing. The structure is made of CMOS processed dielectric layers as well as n-poly silicon and aluminium conductors that constitute the thermocouple. Since the process is fully integrated in a CMOS chip, the voltage signal can be amplified and signal processed on-chip.

3. Analysis

If we assume that the sensor is encapsulated in moderate vacuum conditions of the order of 10 mTorr, heat conduction through gas is negligible. As long as the total length of the spiral is less than about 10 mm, the dominant heat transport is through the spiral material itself and not through radiation. In this case, the thermal balance of the structure can be modelled as a one-dimensional (1D) heat equation. Of the different sensor materials, aluminium contributes most of the thermal conductance, thickness and width, respectively, of the dielectric layer sandwich.

The dominant noise source in the sensor is the Johnson noise of the thermocouple, which limits the noise equivalent power (NEP) of the sensor to:

\[ \text{NEP} \approx \frac{v_n}{R_V} \approx \frac{2kT w^2}{FF \varepsilon_1 \alpha_1 \sqrt{\frac{4kB T_0 R_{\text{r1}} B}{w_1 L_d}}} \]

where \( R_{\text{r1}} \) and \( w_1 \) are the sheet resistance and width of the polysilicon lead and \( B \) is the bandwidth.

4. Experimental details

The process flow for the realization of the sensors showing (a) the CMOS processing, (b) the dry micromachining releasing step and (c) the gold-black deposition.

Figure 2. Process flow for the realization of the sensors showing (a) the CMOS processing, (b) the dry micromachining releasing step and (c) the gold-black deposition.
The fabricated sensors were bonded and packaged for testing in a Dewar that was then evacuated to a pressure of $8 \times 10^{-5}$ Torr. The Dewar had a ZnSe window with 70% average transmission of radiation wavelength between 0.5 and 15 $\mu$m. The sensors were characterized for their IR response using a setup comprising a black body (1000 K), a mechanical chopper and a lock-in amplifier to measure the response at different chopping frequencies. The responsivity of the sensors was evaluated by measuring the response for different radiation powers by changing the black body aperture radii and distance from the sensor. Figure 4(a) shows the power response of a $70 \times 70 \mu m^2$ pixel, with a responsivity of $18.1 V W^{-1}$. The response time was evaluated by measuring the response for different chopping frequencies and determining the cut-off frequency. Figure 4(b) shows the frequency response of the same pixel, corresponding to a response time of about 3 ms. By measuring the noise as well, the NEP of the sensor was determined to be $0.36$ nW Hz$^{-1/2}$.

5. Summary

CMOS compatible thermoelectric IR sensors with a novel structure and fabrication process have been investigated and realized. The new structure enables high thermal resistance and sensitivity in small sized pixels suitable for 2D thermal imaging. Post-processing of the sensors is conveniently done after standard CMOS processing without an additional mask using short dry processing. A $70 \times 70 \mu m^2$ pixel has been fabricated using the new design and process, showing a NEP of $0.36$ nW Hz$^{-1/2}$ and a response time of about 3 ms. Using a CMOS process with a smaller feature size and optimization of the sensor pixel will enable better performance of 2D arrays of high performance thermoelectric sensors.

References