MICROMACHINED THERMOELECTRIC ENERGY HARVESTER FABRICATION ON 6-INCH WAFER AND CHARACTERIZATION

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Abstract: In this paper, a micromachined thermoelectric energy harvester with 6μm-high thermopiles on 6-inch wafer is presented. Micromachined thermopiles are considered as a cost-effective solution for energy harvesters working at low thermal gradients and weak heat flows, typical for e.g. human body as well as machine-related waste heat. The micromachined thermoelectric generators will be used for powering autonomous wireless sensor nodes in a Body Area Network.

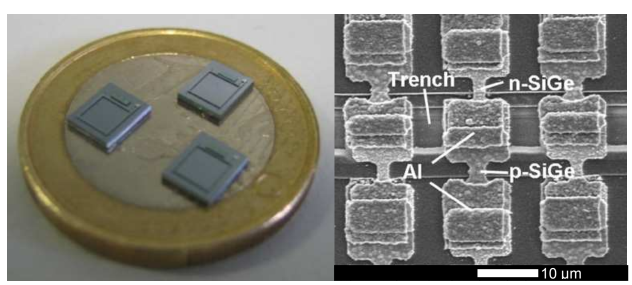
Key Words: Thermal Energy Harvester, Stepper, Large Topography, Thermocouples, Micromachining, MEMS

INTRODUCTION

Temperature differences in/on artificial objects (machinery, buildings, transport, pipelines) and on the skin of animals and man can be used to power autonomous devices. For example, the first wearable wireless sensors and medical devices (Electroencephalograph (EEG) system, an Electrocardiography System in a Shirt) fully powered by thermoelectric generators (TEG) on man have been demonstrated [1]- [3].

Thermal energy harvesters is these devices are off-the-shelf thermopiles and have high fabrication cost because of small temperature difference observed on the human body. However, the cost of energy harvesters is an important factor for their acceptance by industry and for moving them into mass production. Reduction of the cost can be achieved, e.g., by using micromachining technologies and fabricating many devices in one run. It is the subject of this paper to discuss the development of micromachined thermoelectric harvesters.

The simulation results show (Figure 2(a)), that a thermopile height of about 10-15μm allows reaching the optimal performance: a voltage of around 5V and a power of 10μW/cm^2 could be reached for thermopiles made of Bi_2Te_3 [4]. However, achieving such a height is one of the main barriers to reach the target performance of micromachined thermopiles. In this work, 6μm-high thermopiles are developed, which could offer useful performance characteristics at a contact resistance between semiconducting legs and interconnecting metal of the order of 100Ωμm^2. In a low heat flow regime, e.g., harvesting waste heat from human body, the density of thermopiles per unit surface must be as high as possible to get useful voltage output (~1-2V). The modeling shows that, at a height of 6μm, the lateral size of thermocouples fabricated using thin-film technologies must be a few micrometers, i.e., 3~10μm, and that the thermocouples should be located very close to each other, separated by the only 2~3μm. Therefore, the performance of such a thermopile is limited by photolithography. In previous work we have used contact aligner to fabricate thermocouples with 0.5μm height and 3μm width [5], which is close to the limit of contact lithography for such design (see Figure 1). In this work we have used stepper technology because it has better critical dimension at the desired large depth of focus. It has allowed reaching the 6 μm high thermocouples with the required line widths, from 3~10μm. Furthermore, stepper technology gives a smaller overlay error, which provides better alignment between layers and high yield [4].



(a) (b)

Figure 1 Previous micromachined thermopile design fabricated by contact lithography [4]. (a) Chips placed on one Euro coin (b) Close-up view.

In our design, Figure 2(b), a few thousand of thermocouples fabricated on the hot-plate Si die are connected electrically in series and thermally in parallel, and covered by another Si die that acts as a cold plate. The thermopile is made of n- and p-type of SiGe and has a height of 6µm. Aluminum is used for interconnection of semiconducting legs. A very thin layer of adhesive, which preferably must be less than 1µm thick, is used to glue the top die to the device die. Several versions of thermopile have been fabricated with a line width of 3, 7 and 10µm. The distance between adjacent thermocouples is 2µm and 3µm; and the total number of thermocouples in a thermopile varies from 1300 to 2500. The combination of parameters has been determined by taking into account values for the temperature gradient, contact resistance, total resistance, etc., while all having about the same optimized output power. In general, the total area of a single device is less than 1mm x 2.5mm.

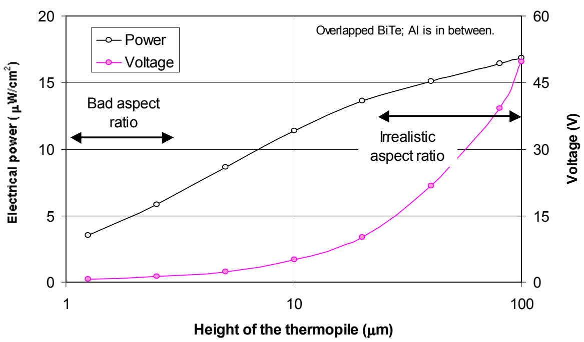


Figure 2 (a) The simulated voltage and power for the Bi_2Te_3 thermopile with an area of 27µm² per thermopile. Modeled for a wearable energy harvester with 1×1×0.5 cm³ radiator. (b) Schematic of two thermopiles in the energy harvester (cross section view).

FABRICATION

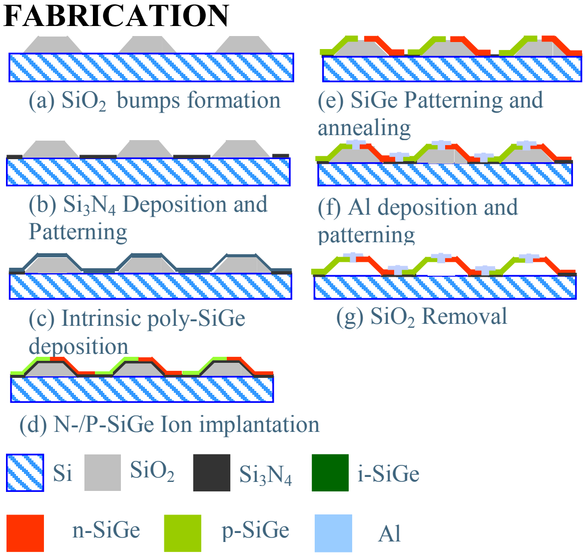


Figure 3 Process Flow of Thermopile fabrications

The process flow is sketched in Figure 3. We start with a 6µm-thick sacrificial layer. PECVD SiO_2 has been used, because it is removable and can tolerate high temperature through the process steps. Polycrystalline SiGe has been used as thermoelectric material because it is readily available for processing on 6-inch wafers. After deposition of the 6µm-thick SiO_2 and subsequent lithography, the sacrificial oxide is patterned to form bumps (see Figure 3(a)). Since it is very difficult to pattern thermopiles over a vertical wall, a certain angle is needed for the slope of SiO_2 bumps (in this work, it is 30 degrees). A layer of 150nm-thick Si_3N_4 is deposited and patterned, acting as an electrical insulator between device and substrate (Figure 3 (b)). Then, undoped SiGe is deposited (c), followed by implantation to become n- and p-type legs (d), patterning and annealing (e). The width variation of thermopile legs are less than 10% over the whole 6µm high bump, as well as on top and the bottom [4], which needed a special mask design and fabrication process (discussed in detail in [6]). Next, Al is deposited and patterned. Finally, the thermopiles are released by using Pad Etch[6].

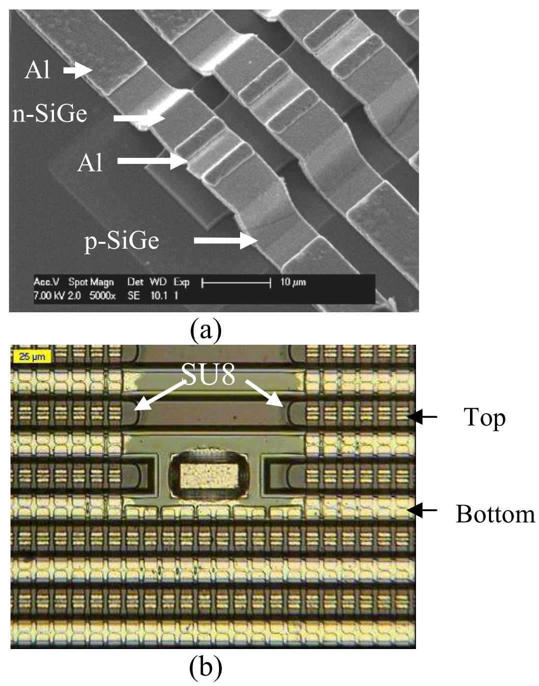


Figure 4 (a) SEM Photo of released thermocouples (b) SU8 Bonding between Pyrex and Device

In Figure 4(a), one can see freestanding thermocouples, where the thermocouple bridge is made by n-SiGe, p-SiGe and Al.

Next, the wafer is diced and the resulting die is bonded to a top die by using an adhesive. We have used SU8-2002, which is a good material for bonding, using layers less than 1µm. It has a reasonable thermal conductivity of 0.3W/mK. The result after optimization of the bonding procedure is shown in Figure 4(b) (to have a visual check, we have bonded a transparent Pyrex wafer on top). One can see the well positioned bonding between the top surface of thermocouples and the Pyrex wafer.

To quantify the effect of bonding, we have measured the output voltage of a device in two cases. In the first case, the top die is just placed on the device, without bonding (only making mechanical contact) while in the second case, the two dies are bonded to each other by the SU8. The result is plotted in Figure 5. Due to a better thermal contact, the temperature difference on the thermopile is increased thereby proportionally increasing the power output.

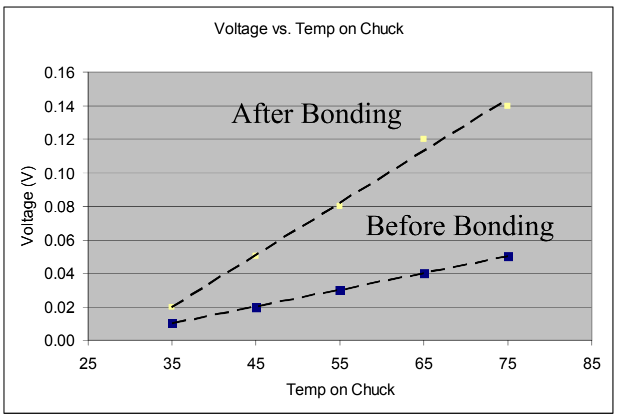
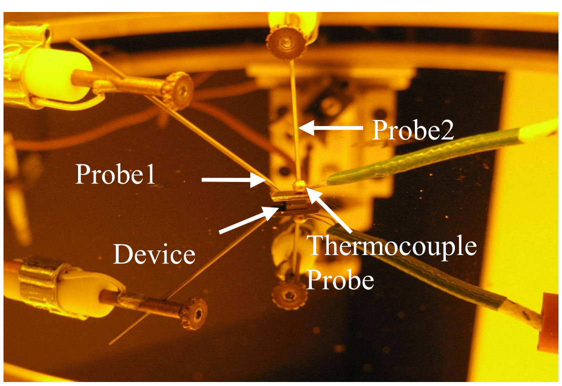
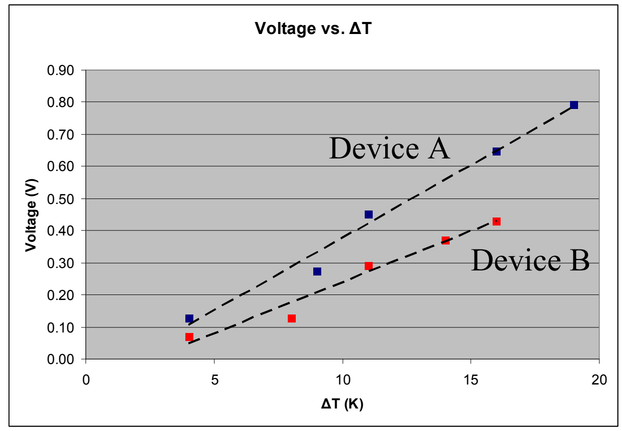


Figure 5 the voltage output before and after bonding



(a)



(b) Device A&B

Figure 6 (a) Measurement Setup (b) Voltage Output vs. Temperature difference

CHARACTERIZATION

The measurements have been performed on a heat chuck; the setup is shown in Figure 6(a). The voltage output of the device is measured by using two probes, while a thermocouple probe measures the temperature on top of the cold plate. In these initial measurements, the temperature of the hot plate is assumed to be the same as the set-point temperature of the heat chuck, which is measured by thermocouple probes located inside the chuck. The temperature difference is calculated as the difference between the hot and cold probe readings. In practice, the temperature readings are not accurate, because the thermal contact between the device and thermocouple probe on the cold plate is not perfect. Therefore our measurements are only qualitative at this point. Further measurements are planned using a setup sketched in Figure 7 to get more accurate results. Devices will be provided with thermally conductive paste for the thermal contact with metal plates. Two thermocouple probes will be inserted inside metal plates to measure the temperature of hot and cold plates.

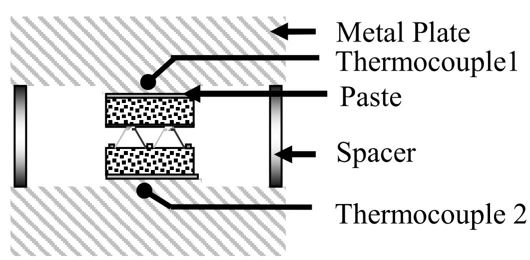


Figure 7 Schematic of the improved measurement setup.

A voltage versus temperature difference for two devices is plotted in Figure 6. For both devices, the voltage output increases linearly as the temperature difference increases, which proves both devices are functional. For device 'A', 1776 thermocouples made of SiGe are connected in series. The width of each thermocouple is 10µm and the distance between adjacent thermocouples is 2µm. Device 'B' has the same width of thermocouples as Device 'A', but 1664 thermocouples in series and the distance between adjacent thermocouples is increased to 3µm. However, the large difference in output voltage is not expected from our modeling, indicating the need for a more accurate temperature measurement.

We have not yet been able to achieve a reasonable power output. The reason is that a very high internal electrical resistance is observed after fabrication, being around 20MΩ. This is found to be due to a very high contact resistance between n-SiGe and Al. Further research is ongoing to decrease this resistance.

CONCLUSIONS

In this paper, a functional SiGe thermoelectric energy harvester is fabricated and measured. A voltage can be generated which is a function of temperature, showing the functionality of the device. The high contact resistance disturbed to obtain the useful power. The technological study is ongoing to decrease the contact resistance. In future, we will look for other materials that show better thermoelectric properties than poly-SiGe [7], e.g., BiTe, superlattices.

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