SELF-SUPPORTED AND MEMBRANE-SUPPORTED BULK-MICROMACHINED THERMOPILES FOR ENERGY SCAVENGERS

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ABSTRACT

Designs for a film-based thermopile are discussed, which are well suited for a microelectronic industry. In the first one, thermocouples form bridges between two Si bars. In the second one, the thermopile represents a set of film-based thermal shunts located thermally in series with either membrane-supported thermopiles or self-supported ones. The designs allow decoupling of the parasitic heat conduction through air between Si bars from the length of thermocouples. The modeling has been performed for wearable and implantable thermoelectric generators (TEGs). The fabrication of poly-Si structures has been completed to verify feasibility of both the technological process and the thermopiles.

1. INTRODUCTION

There are only two basic designs for a film-based thermopile, which are well suited for energy scavenging on low-temperature heat sources, namely the thermopile on a polymer tape [1, 2] and the micromachined one on a micromachined pillar [3, 4]. The third, in-plane design is discussed in this paper, which can be fabricated in standard Si wafers. There are two feasible design versions for a film thermopile on a membrane. Such membrane can be fabricated, e.g., of Si_3N_4 or SiO_2 layer on Si wafers with etched window in Si under the membrane. The latter must be relatively large, from several millimeters to a few centimeters in size. In the first design, the hot junctions must be on a Si frame, while the cold ones must be close to the center of membrane, or vice versa [5]. In energy scavengers, the ambient air cools down such membrane therefore a temperature difference appears in between the Si frame and the center of a membrane. However, the convective heat transfer from the membrane is not good enough to reach top performance of energy scavengers. It is because the membrane area is not large enough and, furthermore, it is located in the convection layer formed around the heat source. In energy scavengers, the measures of performance of a thermopile are the voltage and power generated under conditions of high thermal resistance of the environment, e.g., 1000 cm^2K/W, and of weak heat flow such as 10 mW/cm^2. At these conditions, the temperature difference between the cold and hot junctions strongly depends on the environment and is typically small resulting in poor performance characteristics of such thermopiles.

Another design is discussed in this paper. According to fabrication process, upon mounting the thermopile die in between the hot and cold plates of a TEG, it represents two bars of silicon and a thermopile in between them, Fig. 1. It is obvious that such thermopile is mechanically completely unstable because the total thickness of the layers is a few or several micrometers only, so an external

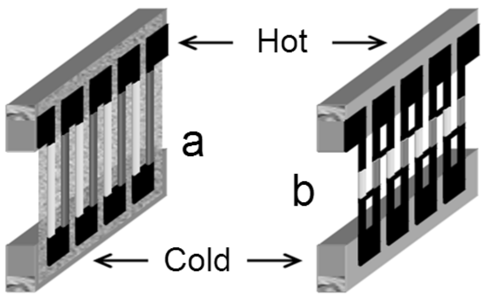

Fig. 1. Dies with a film-based thermopile on a membrane (a, see Section 2) and with thin film thermal shunts (b, see Section 3).

support and certain technological tricks must be done in order to protect such "impossible" dies. All the structures discussed below are optimized for wearable TEGs to give a numerical example of their dimensions and performance characteristics, while for the other applications, some redesign could be required.

2. THERMOPILES ON A MEMBRANE AND SELF-SUPPORTED ONES

An example of the thermopile die is shown in Fig. 2a. The sides of Si frame are removed (Fig. 2b) only after installing the die(s) in the TEG and providing an external support with thermally isolating holders, Fig. 2c. Optimization of such structure at typical thermal conditions in vicinity of a wearable device ($T_{still\ air}$=22°C and variable thermal resistance of a human being $R_{th\ b}$=250…400 cm^2K/W, depending on heat flow) is performed in this work for a 3×3 cm^2 TEG, at 1 cm distance in between the hot plate and pin-featured radiator with its effective surface of 12 cm^2. The optimal length of thermocouples is several hundred micrometers, however, typical thickness of layers in microelectronic processes is about 1 μm, so the thermopiles have too high thermal resistance. The largest power in a watch-size TEG then can be obtained if several dies are mounted in the TEG.

The results of modeling performed for 10 dies, each 28 mm-long, are shown in Fig. 3. For modeling, we assumed that the etch of Si is anisotropic (wet) offering slope of the etched frame as in Fig. 2c. (In Fig. 2a, b, the profile of Si frame after DRIE process is shown instead.) In this idealized

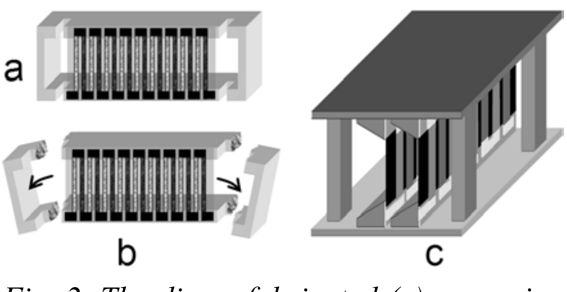

Fig. 2. The die as fabricated (a), removing the sides of Si frame (b), and (c) two dies installed in between the plates of a TEG.

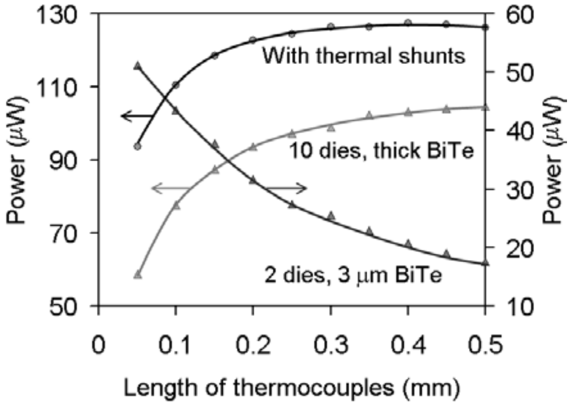

Fig. 3. Calculated power of a TEG featuring the dies with no and with thermal shunts (fixed or variable number of dies).

calculation, the best available BiTe material with a ZT of 0.9 has been utilized; a good, but realistic electrical contact resistance of 100 Ω μm^2 has been assumed at the interface of BiTe and Al. It was also supposed that (i) a thick-film process could be used and (ii) the thickness of photoresist could not exceed the minimal feature size. The length of a thermocouple is equal to the length of a SiO_2 membrane. The latter is usually thin (less than 1 μm), it isolates the thermocouples from Si and does not affect the characteristics of optimal thermopiles. Therefore, the results are valid for both membrane-supported and membrane-free thermopiles. At the device level, it was supposed that for effective using the power when T_{air} is close to T_{skin}, the TEG must produce not less than 5 V on the matched load at 22 °C. Accounting for thermal matching of a TEG [6], which is needed for maximizing the power generation, the required thickness of BiTe grows together with the length of legs, e.g., from 6 to 14 μm in Fig. 3. It is worth mentioning that over 100 μW offered by the TEG is about half of the power generated by watch-size wearable TEGs with commercial thermopiles. Looking further for low-cost solutions, the number of dies could be effectively decreased with no proportional drop of power, furthermore, the thickness of BiTe could be decreased in practical applications. The corresponding result for a TEG with only two dies filled with self-supported 3 μm-thin thermopiles is also shown in Fig. 3, wherein the amount of BiTe is decreased by a factor of 23, while the power production is only halved as compared with maximal power obtained with 10 dies in previous example.

3. THERMOPILES WITH FILM-BASED THERMAL SHUNTS

The Si wafers are thick, e.g., a thickness of 725 μm is used in this set of calculations. As a result, the air in between the hot and cold frame sides of several dies inside the TEG represents a bypass for a heat (parallel to thermopiles) thereby decreasing the power, especially with short thermopiles. The ways of decreasing this parasitic heat flow is wafer thinning or wafer transfer technology, however, these are not cost-effective solutions. This task can be solved much easier through introducing thin film metal strips located thermally in series with short thermocouples, Fig. 1b (black lines). The average distance in between the cold and hot sides of the TEG is kept large, while thermocouples can be much shorter, with lower resistance than in the design described in previous section. The resulting temperature gradient on thermocouples increases, while the temperature difference on them remains practically the same.

The heat conduction between the hot and cold ends of metal strips still effectively takes place through the air in their area proximal to thermocouples. Therefore, it is thermally beneficial to couple neighbor dies face-to-face. Furthermore, such coupling is useful if the optimization of the p- and n-type materials requires mutually contradictory technological regimes, i.e., not compatible with each other. In such case, one die with p-type material is to be coupled with the n-type die, while the interconnection of the thermocouple legs in two dies can be performed using standard flip-chip technology.

The TEG with thermopile dies featuring film-based thermal shunts, Fig. 1b, has been modeled at a 2 mm-wide air gap between the frame sides, and assuming 4 μm-thick Al interconnects. The other conditions were the same as in the calculations above. The power offered by optimized thermopiles with Al interconnects is also shown in Fig. 3. Comparing the results with the ones for 10 dies of BiTe (0.5 mm-long, 14 μm-thick legs), one can see that, e.g., at a length of thermocouples of 100 μm, the thermopiles with Al shunts offer more power (with only 8 dies and 4 μm-thick BiTe required). The maximum of power generation calculated for the thermopiles with Al interconnects approaches the power obtained with the thermopiles purchased on the market [4].

For low-cost solutions for a TEG, the number of dies could be decreased. For example, with 50 μm-long thermocouples, six dies are optimal for reaching about 90 μW, Fig. 3. However, the thermopiles optimized for the case of two dies should demonstrate only 30% loss in power.

Large efforts are spent around the globe on development of nanostructured thermo-electric materials with the major goal of decreasing their thermal conductivity. The effect of its possible reduction on power in the designs discussed in this paper has been modeled, too. If the thermal conductivity is reduced by a factor of two, the 2 dies offer, in the best case, less than 50% increase of power. However, a decrease in thermal conductivity, as expected, should be accompanied by some increase in electrical resistivity, therefore, the application of nanostructured materials in the thermopiles discussed above would not offer a profound increase of power, while the fabrication cost is expected to rise.

To verify the feasibility of thermopiles discussed in this paper, the process flow has been designed for 1 μm-thick poly-SiGe thermopiles. The calculations show that a power up to 14 μW can be obtained using 6 dies with 50–100 μm-long thermocouples, Fig. 4. It is worth mentioning that a contact resistance of, e.g., 1 kΩ μm^2 does not affect dramatically the generated power. The fabrication process has been verified using undoped poly-Si, Fig. 5. The fabrication of large SiO_2 membranes is not trivial. Due to

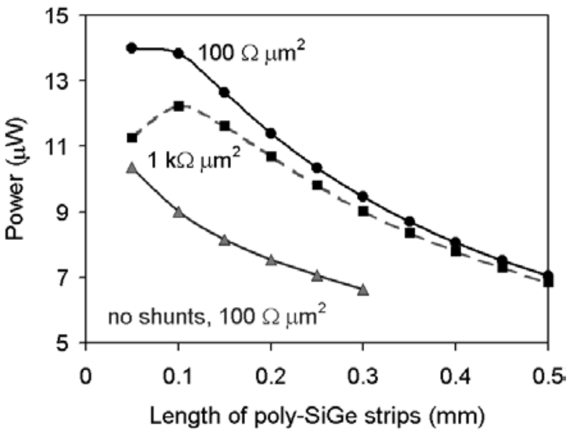

Fig. 4. Power calculated for 1 μm-thick poly-SiGe thermopiles of different designs.

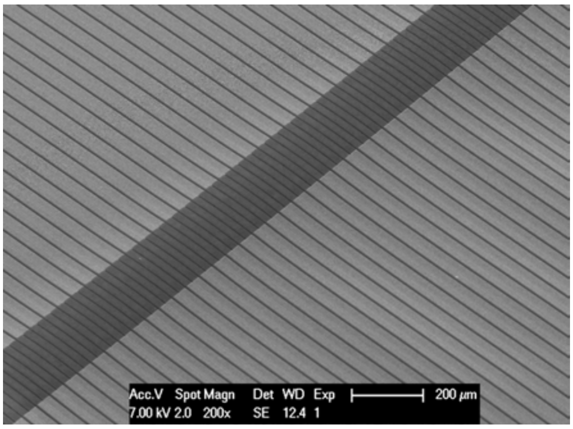

Fig. 5. SEM image of released 1 μm-thin undoped poly-Si lines (dark) with Al interconnects (bright lines) on SiO_2 membrane.

large internal stress, the membranes with no other layers on them break during fabrication. However, with thermopiles and metal lines on top of 0.5 μm-thick SiO_2, the membranes are curved but stay intact. Fabrication of first poly-SiGe thermopiles with thermal shunts is ongoing.

4. THERMOPILES FOR IMPLANTS AND THIN WEARABLE DEVICES

A plurality of implantable devices such as cardiac pacemakers, drug delivery devices, and health-monitoring ones have a serious drawback, i.e., the necessity of periodical replacement of batteries accompanied by a (minor) surgery. Existing methods of their non-contact recharging, in general, have not been widely accepted by patients.

Preliminary modeling of implanted TEGs performed 2 years ago (unpublished), has indicated that despite less power per square centimeter of the skin than in wearable TEGs, they could produce power quite satisfactory for most of implantable devices, thereby offering the possibility of lifetime implants. To keep the surgery at minimal level it would be also beneficial to have thin TEGs, thinner than the examples discussed above. One of the solutions is illustrated in Fig. 6. Of course, such thinning of the TEG can be performed only on cost of some loss in generated power.

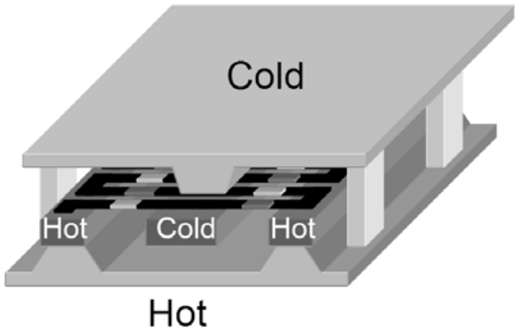

Fig. 6. TEG with a thermopile parallel to hot and cold plates for watches or implants.

5. CONCLUSION

Film-based thermopiles, which can be used in wearable and implantable devices such as watches or cardiac pacemakers are modeled. They offer over 60% of power obtainable with commercial thermopiles, but at lower cost. They simplify thermal matching with the heat source and sink, they are resistant to shocks, and able to generate much higher voltage.

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