STEPPER LITHOGRAPHY ON LARGE-TOPOGRAPHY MICROSTRUCTURES FOR THERMOELECTRIC ENERGY SCAVENGERS

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Abstract: This paper describes the development of the lithography process over a large topographic step (up to 6μm), an essential part for the fabrication of micromachined thermopiles. Micromachined thermopiles are considered as a cost-effective breakthrough solution for energy scavengers working at low thermal gradients and weak heat flows, typical for e.g. human body and some types of machine-related waste heat. The thermoelectric generators will be used, in the first instance, for autonomous wireless sensor nodes in a Body Area Network.

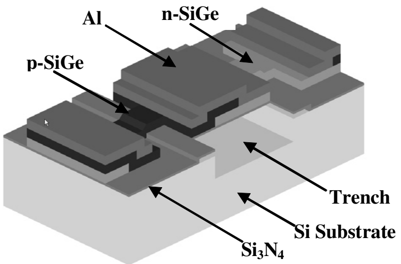
Key Words: Thermal Scavenger, Stepper, Large Topography, Resist Coating, DOF

1. INTRODUCTION

Temperature differences available in nature and in/on artificial objects (machinery, buildings, transport, pipelines) can be used to power autonomous devices. This paper discusses thermoelectric converters on living beings as an example of possible applications. Wearable wireless sensors and the first medical device, battery-less wireless pulse oximeter, fully powered by thermoelectric generators (TEGs) on man have been recently demonstrated [1]-[2]. The developed TEGs and systems will be used, in first instance, in a human body area network (BAN) being under development at the Holst Centre [3]. In our previous work we have presented devices using smallest commercial thermopiles. However, micromachined thermopiles theoretically may reach the same performance as commercial ones [4], so the target of this research is to reach this goal using surface micromachining. Calculations performed in [1] have shown that at 22 °C ambient temperature, the thermopiles made of BiTe film with a figure-of-merit ZT of 1 allow reaching 30μW in a TEG occupying 1 cm^2 of skin, while using less exotic (for the microelectronics) and more extensively developed poly-SiGe one may only obtain about 4μW/cm^2.

There is, however, one barrier which still does not permit reaching the target performance. Ideally, the thermocouple fabricated on a rim or on a pillar, must be of several micrometers in height, i.e. 5 – 15μm depending on critical dimensions of lithography and electrical contact resistance at the interface between the semi conducting thermopile legs and the metal interconnecting p- and n-type legs. The contact aligner does not allow fabrication of 3μm-tall thermocouples at a critical dimension (CD) of 1μm. With a stepper, however, this becomes possible, due to its large depth of focus.

Large depth of focus not only allows



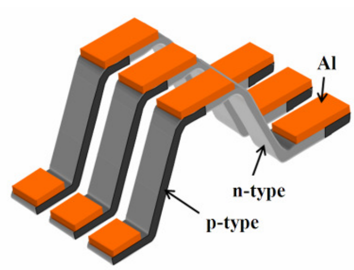


Figure 1 Comparative size and shape of the micromachined thermocouple according to [7] (left) and arcade thermocouples (three thermocouples are shown) discussed in this paper (right).

quantitative improvements in performance of micromachined thermopiles, but also offers new design opportunities largely affecting their optimal design and, thereby, affords reaching near-theoretical performance of energy scavengers and dramatically simplifies the fabrication and assembling technologies.

Other benefits for migrating from contact aligner to stepper lithography for fabricating micro thermopile devices are [4]:

1. Higher productivity (more wafers per day) enables large volume production
2. Much higher yield because of necessity of serial electrical interconnection of thousands thermocouples in series
3. IC-compatible fabrication process enabling the integration of IC and MEMS fabrication
4. Extendibility in imaging technology, so that a sub-micron imaging is possible which is important for future MEMS thermopiles.
5. The overall cost per device is to go down significantly.

2. THE DEPTH OF FOCUS AND THE CRITICAL DIMENSION OF A STEPPER LITHOGRPAHY

We have simulated the depth-of-focus (DOF) of PAS5500/100, an i-line stepper system, at given critical dimension and critical dimension uniformity (CDU) requirements (See Figure 11 in [5]). Different partial coherence settings are considered at given NA of the projection optics (i.e., the degree of partial coherence varies within the 0.32 – 0.56 range). Given the relaxed CD requirements and the large DOF requirements, a lowest NA of 0.48 that is available for this system has been chosen for the modeling and thermopile fabrication. A ±5-15 % CDU was taken into account. From the simulation results, one observation is that at a feature size of 3µm the DOF is as high as about 10µm.

With the simulated data, we have designed and modeled a TEG at topography of 6 µm. The details of modeling process are described elsewhere [4], here we only show the major results for thermopiles on a human being thermally matched to the environment at 22 °C [5] at a practically obtained minimal spacing in between the lines of 1.8 µm. In Figure 2, the dependence of the voltage on a matched load and the generated power is shown for a case of a polycrystalline SiGe arcade thermopile having the electrical contact resistance of 70 Ω µm^2 versus the line width at a slope of 30 deg (left) and versus the slope at a line width of 5µm (middle). The calculated points are obtained for thermally matched thermopiles; therefore, to obey thermal matching conditions [5] thereby reaching the maximal power, the number of thermopiles must be changed while varying the line width or the slope of the lines. The material characteristics used in the modeling are taken from the measurement results obtained on SiGe thermopiles [6]. The designing is performed for a person sitting indoor and wearing the TEG on the radial artery at a body thermal resistance of 200cm^{2}K/W. An output voltage of 4 V and more

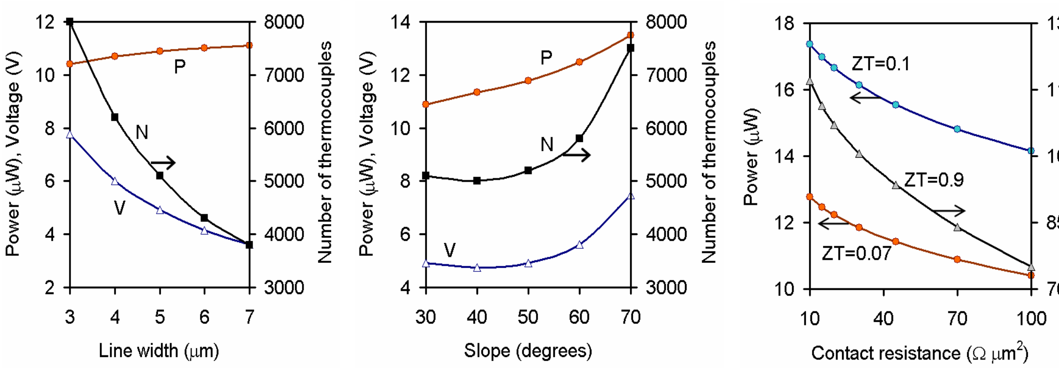


Figure 2. Dependence of the voltage on the matched load, the power and the number of thermocouples on the line width (left) and on the line slope (middle) calculated for a 6 µm-tall poly-SiGe thermopiles placed in the watch-size TEG with a pin-featured radiator of 3×3×0.5 cm^2 size, and dependence of the average power obtainable on human beings with such device at 22 °C with poly-SiGe thermopile at a ZT of 0.075 obtained in the previous run [6], at a ZT of 0.1 feasible with poly-SiGe, and for BiTe thermopile at a line width of 8 µm and a ZT of 0.9 (right).

is chosen to make sure that at 30 °C the TEG still can transfer more than 1.5 V into the matched load. In Figure 2, right, the dependence of the power on electrical contact resistance is shown for poly-SiGe and BiTe thermopiles at a slope of 30 deg. The corresponding voltages are 4.9 V at a ZT of 0.075, and 5.7 V at a ZT of 0.1 for poly-SiGe, and 5.2 V for BiTe thermopile. Comparing the two materials, we have to mention, that the power is not proportional to commonly quoted figure-of-merit ZT which reflects the side effect of the thermal matching performed in process of modeling the energy scavenger. The replacement of poly-SiGe with BiTe would allow in future reaching, as follows from Figure 2, right, 13μW/cm^2 which is 50% of the theoretical limit at a ZT of 0.9. The power exceeding 20 μW/cm^2 can be obtained only with taller thermopiles, thicker films, lower contact resistance, or at ZT>1. Then one may reach the same power as has been already obtained in our previous work when using commercial thermopiles at a cost of 100-1000 times less.

3. PROCESS DEVELOPMENT

To develop this thermal scavenger, the lithography on 6μm topography with small features (3~5μm) is the key point. Thus, three different ways of resist coating technique are studied. They are spin coating, spray coating and electro-deposition.

3.1 Spin Coating

With spin coating, the photoresist thickness is determined by the spin speed and the viscosity of photoresist.

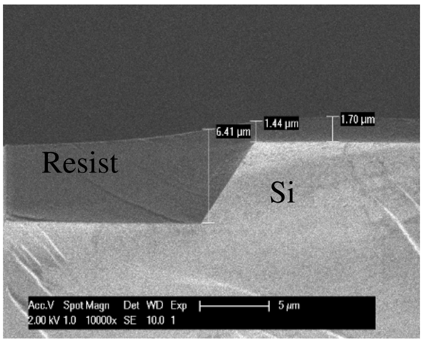


Figure 3 SEM pictures of spin-coated resist on 6μm topography

Thus, the Photoresist will not see the topography during spin coating. If the photoresist thickness is the same as or larger than the dimension of topography, the topography will be covered with a thin layer on the top surface (hill) of topography and a thicker layer on the bottom surface (valley) of topography (Figure 3), otherwise, there is little photoresist on the top surface of topography.

3.2 Spray Coating

Spray coating is a relatively new technology to coat photoresist, especially on substrate surface with high topography [9]. For our application, we want a thin resist layer, on up to 10μm topography. AZ4562, which has a 40% solid content, is a photoresist used for spin coating thick photoresist layers. In order to spray a thin layer, the photoresist is diluted to 2%, by MEK (Methyl ethyl ketone) (AZ4562: MEK=1:19). We find that already on a flat wafer, the resist thickness is not homogeneous, the variation being more than 10%. We have coated a wafer with 3μm topography by the same procedure (Figure 4).

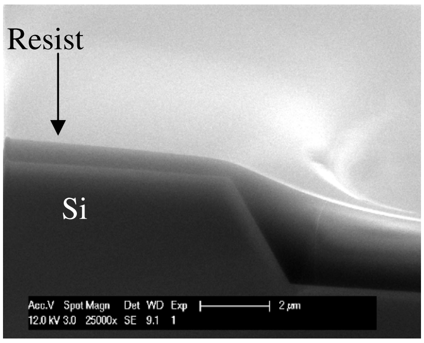
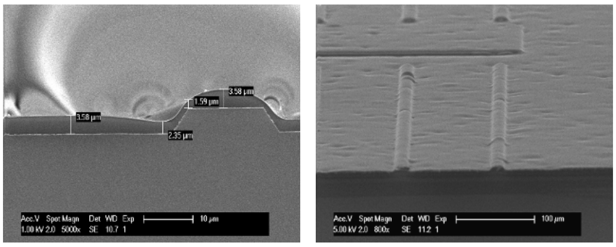


Figure 4 SEM picture of Spray coated resist over 3μm topography

We see that the results resemble very much the spinning result (Figure 3). This is due to the large dilution needed, meaning the substance will behave very much as a liquid and, the photoresist accumulates at the bottom corner and less photoresist is deposited on the top corner.

3.3 The Technique of Electro-deposition (ED)

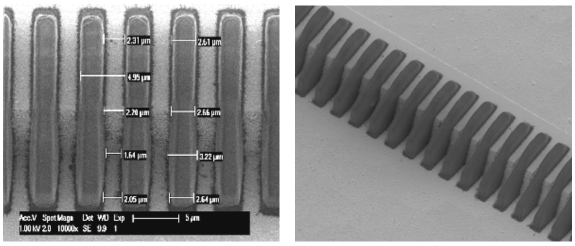
The resist coating process is based on the electro-deposition of a negative organic acrylate-type photoresist onto a cathode polarized conductive substrate [10]. We have optimized electro-deposition to get a 3.5μm thick resist on flat wafer with Eagle 2005ED resist and applied the recipe to 6µm topography. The cross-section view is showed in Figure 5. The layer is more conformal than those in the other deposition techniques, but still the surface of resist is rough. Overall, however, the best result is reached with electro-deposition.



(a)Cross Section (b) Overview

Figure 5 SEM pictures of ED on topography

In a next experiment, we have done exposure by PAS5500/100 of the resist over the 6 µm Topography. The result is shown in Figure 6.



(a) Top view (b) Side View

Figure 6 SEM picture of a pattern over 6µm topography

After developing, the line width is measured by SEM (Figure 6). We have reached an average line-width of 2.78±0.29µm.

4. CONCLUSION

Using electro-deposition, we have been able to pattern resist feature over 6µm topography, using a stepper for the exposure. The stepper has a very large depth of focus, enabling to reach this result. We are currently developing a method to pattern over 10µm topography.

We have designed a scavenger over a large topography, and the simulations show that output energy levels of 10 and 100 µW can be reached, using SiGe and BiTe material, respectively.

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