PROCESS DEVELOPMENT ON LARGE-TOPOGRAPHY MICROSTRUCTURES FOR THERMOELECTRIC ENERGY HARVESTERS

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Abstract: This paper describes the successful development of fabricating thermopile structures with 6µm height. Micromachined thermocouples are considered as a cost-effective breakthrough solution for energy harvesters 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 first an instantiation, for autonomous wireless sensor nodes in a Body Area Network.

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

I. 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. The first wearable wireless sensors and medical devices (wireless pulse oximeter, EEG system) fully powered by thermoelectric generators (TEG) on man have been recently demonstrated [1]-[4]. The developed TEGs and systems are supposed to be used, in first instance, in a human body area network (BAN) being under development at the Holst Centre [5].

There is, however, one barrier which still does not permit reaching the target performance in micromachined thermopiles. The height of thermocouples must be as large as possible, i.e. a height of about 10-15µm allows reaching the near theoretical performance, while 6µm, developed in this work, could offer a practically useful performance characteristics at a contact resistance between semiconducting legs and interconnecting metal of the order of 100 Ωµm². In a low heat flow regime, the density of thermocouples per unit surface must be as large as possible to get the useful voltage output, which means the lateral size of thermocouples must be a few micrometers. Therefore, the thermopile performance is limited by photolithography. In order to reach good performance characteristics a gap between the neighbor thermocouple legs must be about 2µm or even smaller on topography with a height of 6-10µm.

In general, contact aligners are perceived to have better DOF (Depth of Focus) than the stepper and scanners. However this is true at large features. For example, the resolution of contact aligner is 4µm when the DOF is 0µm and increases to 8µm when the DOF is 100µm as described in [6]. The minimum feature size of contact aligner is limited to a few microns, which restricts further scaling down of the device. On the other hand, I-line steppers and scanners allow effective device scaling down to sub-micro pattern. Moreover, the stress introduced by 6µm thick silicon oxide deposit by PECVD makes the wafer bow with 38µm. Due to the bow, the area in the centre will have higher resolution compared to that on the edge by using contact mask to expose the whole substrate. In contrary, die to die exposure in I-line steppers and scanners enables different level tuning with respect to each die. Another advantage of I-line steppers and scanners is the higher alignment accuracy, which is important for aligning metal interconnects to thermoelectric legs. The features size we fabricated could not be done on a contact aligner, as the metal contacts would touch the adjacent legs.

Figure 1 Arcade thermocouples (three thermocouples are shown) processed in this paper [7](right).

Concluding, benefits for migrating from contact aligner to stepper (ASML PAS5500 System) lithography for fabricating micro thermopile devices are:
a. Higher productivity (more wafers per day) enables large volume production
b. Much higher yield because of necessity of serial electrical interconnection of thousands thermocouples in series
c. IC-compatible fabrication process enabling the integration of IC and MEMS fabrication
d. Extendibility in imaging technology, so that a sub-micron imaging is possible which is important for future MEMS thermocouples.
e. The overall cost per device is to go down dramatically.

In this paper, we have show the progress in the process development needed for the fabrication of thermopiles based on stepper lithography, enabling to make 6µm high thermocouple structures with a critical dimension (CD) of 3µm, which verified the simulation results in [7].

II. PROCESS DEVELOPMENT

1. Poly-Si Patterning over 6µm Topography

After the fabrication of the 6µm high sacrificial silicon oxide layer (see the SEM picture of Figure 2), 150nm Silicon Nitride and 1µm poly-Si are deposited.

Three photoresist coating methods, particularly spin coating, spray coating and electro-deposition, have been the subject of previous work [8]. As discussed in this paper, the electro-deposition process performed really well, obtaining the most homogeneous resist coverage over a large step and thus enabling to pattern very high resolution features into the resist. However, the electrodeposition process is quite complex and not IC compatible. Moreover, when the CD is not very critical (CD> 2 µm), spin coating combined with a clever mask design will suffice as we will show in this paper. In case of spin coating over topography (hills and valleys), the photoresist on the hills is much thinner than that on the valleys (as discussed in [8]). Due to this photoresist thickness difference, the exposure energy sufficient to define a resist structure in the valley, will lead to overexpose of the resist on the hill. The difference can be compensated for by varying the width of the features on the mask, as shown in Figure 3. The width of the mask lines which are to be exposed on the hill are larger than the ones appearing in the valley. At the same time, the line width on the slope can be tuned as well.

Figure 3 Schematic drawing of the mask compensation structure (green) being exposed over a topography (grey) (Top view)

To optimize the photoresist line profile, a Focus Energy Matrix (FEM) is applied [9]. In order to find the best image over the topography, especially on the slope, a specification of the line width is defined in below:
1) The line width on slope corresponds to the active area of the final thermocouples. Therefore these lines should have a variation, but smaller than 10%.
2) The lines on the hills and in the valley are the contact areas. It is preferred that both to have the same line width and preferably the same value as the width on the slope.

Figure 4 Description of position ’a’, ’b’, ’c’ and ’d’

With these requirements in mind, the resulting line width have been measured at four parts on the structure, giving value ’a’ to ’d’ (Value ’a’ measures
line width on hill, ‘b’ and ‘c’ measure the max and min line width on slope, and ‘d’ measures the line width at valley, shown in Figure 4.

- Alfa is related to line width variation on the slope and is defined as \( \alpha = \frac{(\max(b,c)-\min(b,c))}{\text{average}(b,c)} \)
- Parameter Beta compares average line width on slope with line width on top surface of topography. \( \beta = \text{average}(b,c) / a. \) Optimum value equals 1.
- Parameter Gamma, compares line width on slope with line width on bottom. \( \gamma = \text{average}(b,c) / d. \)

The results for a structure with 4\( \mu \)m resist line width on hill, 2\( \mu \)m gap between photoresist lines and 3\( \mu \)m wide photoresist lines on valley, are shown in Figure 5 (a)-(c), where \( \alpha, \beta, \) and \( \gamma \) are plotted vs. different focus setting of the stepper for different exposure energy settings. Apart from the ideal values for \( \alpha, \beta, \) and \( \gamma, \) there is another effect that has to taken into account, namely the spread in parameter values between the different energy settings. As can be seen from Figure 5, there is no ideal point and an optimum has to be found. An image with focus at 0\( \mu \)m and energy at 440mJ, gave the best results. Furthermore, for our application, with a CD of 3.0\( \pm \) 0.3\( \mu \)m wide lines over a 6\( \mu \)m step, optimized spin-coating in combination with a clever mask design suffices.

After exposure, the pattern is transferred into the poly-Si by means of dry etching (see Figure 6).

![Figure 6 SEM Photo after poly-Si Etching](image)

2. Aluminum Patterning Over 6\( \mu \)m Topography

A metal contact layer, e.g. Aluminum, is needed to connect all thermocouples in series. To facilitate the study of the Al processing on topography, the same mask as for poly-Si processing is used. Hence, a same FEM study is preceded and the best image, when energy is 340mJ and focus is 0\( \mu \)m, is found, see Figure 7.

![Figure 7](image)
3. Removal of (Sacrificial) Silicon Oxide

The final release of a thermopile like structure has been studied. We have therefore fabricated poly-Si lines, completely covered by Al lines (again, using two times the same mask and with the settings found in the previous experiments). This structure was subsequently wet etched. The resulting structure is shown in Figure 8.

IV. References: