MICROMACHINED MEMBRANE-BASED HEAT ENGINE AS AN ELECTROSTATIC POWER GENERATOR

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Abstract: The design concept of a microfabricated heat engine, conceived as an electrostatic power generator, along with the fabrication and characterization of its prototype is described. Its main part is a closed chamber placed between a heat source and a cold sink and filled with a liquid-gas mixture. The thermal energy flowing through the chamber causes the pressure changes according the cycles of the heat engine and thus cyclically moves the flexible chamber's wall. This wall is a part of a parallel-plate capacitor, which movement changes the plate separation and thus the energy, stored in the internal electric field. The fabricated prototype represents the heat engine without the cold sink. In the course of the experiment it was brought to vibration, simulating the engine's cycles, with the frequency of 10 Hz and corresponding amplitude of 5 µm.

Keywords: heat engine, membrane, variable capacitor, liquid gas phase transition, micromachined

INTRODUCTION

A lot of contemporary applications such as wear-out and high-loaded parts of a car motor or a wind power station need the preventive detection of a possible failure, which would enable the on-demand change or repair measures thus reducing the maintenance costs. Such prognosis could be obtained from the constant monitoring of the device's condition and the environmental parameters, which subsequently presumes the implication of some energy-harvesting devices [1]. The energy demand, required for permanent measurements, could be covered, due to the relatively high effectiveness, by solar cells, but their applicability is severe limited by the working conditions. At the same time the above mentioned application by their very nature, due to heavy mechanical load associated with them, demonstrate high temperature gradients between their structural parts. Such environment provides ideal conditions for the implementation of thermogenerators (TG), but the common Seebeck-effect-based TGs often cannot offer sufficient effectiveness, which is negatively affected by their relatively high thermal conductivity (TC). This issue becomes especially aggravating when, due to the high level of the needed power output, the size of the TGs is already comparable with the structures providing the thermal gradient, which are not longer able to provide the sufficient thermal flow through the TG.

The possible solution could be the implementation of a TG based on the heat engine (HE) design, whose TC is determinate by the properties of the working substance. In case of the at least partly gaseous working substance comparatively minor TC could be achieved. The design proposal of such HE is already described [2], but it presents an attempt to directly transfer the conventional HE with all the corresponding mechanical parts (turbine, pumps, bearings etc.) into the MEMS-device. Due to too complex structure this design was not implemented in practice.

The design of a micromachined TG, proposed in this paper, is based on the membrane-based HE with the gas-liquid working substance and offers the facile manufacturing within the implementation field of the common silicon-micromachining technology.

The proposed design of the heat-engine-based TG along with the fabrication and characterization of its prototype is the subject of the paper.

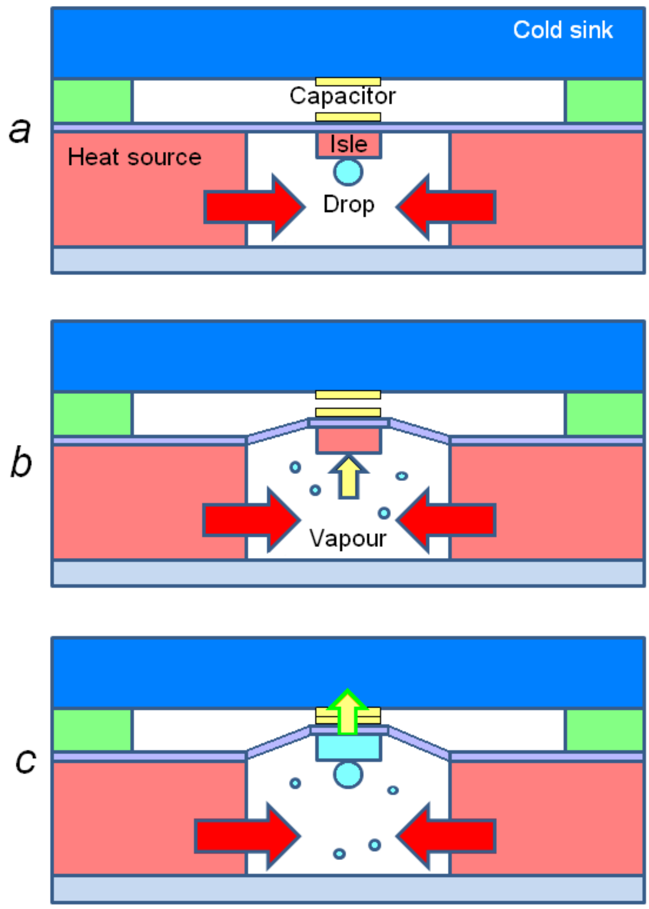

Fig. 1: TG's design and working principle:
(a) the working liquid-gas mixture is heated up, (b) the rising pressure pushes up the isle, (c) the isle is cooled down by the cold sink, the working gas condenses.

DESIGN

Figure 1 depicts the proposed TG's design and illustrates its working principle. The TG consists principal of a closed chamber with a drop of the working liquid in it. Some of the chamber's walls represent the heat source of the heat engine, whose temperature is higher as the phase transition point of the implemented liquid. From one side the chamber is enclosed by a flexible membrane.

The membrane has a rigid and flat "isle" in its middle. When the fluid's evaporation raises the inner pressure, the isle will be pushed up till it contacts the cold sink and grows cold. The following condensation on its surface causes the pressure drop and the returning of the isle to its initial position, thus closing the cycle. Thus the working cycle of the heat engine consists of three phases (see fig.2): heat addition + expansion (polytrophic), heat rejection (isochoric) and heat addition + compression (polytrophic). The temperature of the working substance drops during the third phase despite the occurred heat addition. The additional energy is consumed by the isle, which was cooled down during the second phase.

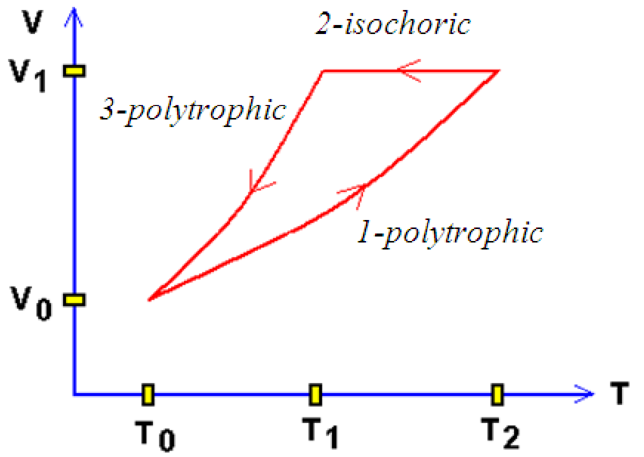

Fig. 2: Working cycle of the heat engine.

The conductive plates with dielectric isolation on the isle and the cold sink build together a variable capacitor, which would be used to obtain the electrical power. The power generator based on the variable-capacitor-design with comb-shaped electrodes is already described [3], but its efficiency was affected by big plate separation (ca. 3 µm) and small variation of the capacity. The proposed design, as it is shown below, will solve this problem.

The manufactured prototype consists from the chamber with the membrane and the isle (fig. 3), which purpose is to demonstrate the feasibility and the mechanical properties of the HE. The prototype lacks the cold reservoir therefore the temperature gradient is induced by the heater placed on the isle.

FABRICATION TECHNIQUE

The fabrication is based on the well-established silicon micromachining technique. The fabrication steps

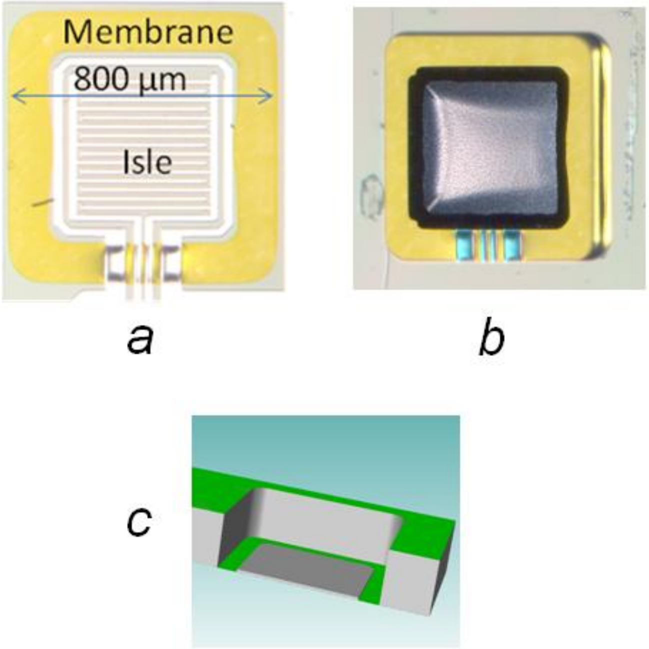

Fig. 3: Unsealed TG's prototype:
(a) photo of the front side, (b) photo of the back side,
(c) the cross section of the structure.

of the prototype are shown in figure 4. The four represented stadiums include three photolithography steps. In sequence:

- a) a silicon wafer with a dielectric stack of the silicon dioxide (500 nm) and the silicon nitride (300 nm) layers was prepared. The Pt-heater was formed on the top. As an adherent layer between the silicon nitride and platinum the aluminum oxide was chosen
- b) the isle was formed on the back surface. Initially the dielectric stack was removed around the isle, to form the channel surrounding the isle. Then the next photolithography step opened the channel once more together with the isle, which stays protected by the dielectric stack though. The deep reactive-ion etching (DRIE) formed the isle. The dielectric stack on the isle was subsequently removed.
- c) the second DRIE-step exposed the dielectric membrane in the channel, thus segregating the isle from the silicon substrate.
- d) drop of the working liquid was placed into the chamber and then sealed.

Although the prototype includes deep relief structures, all photolithography steps are made on the flat surface, thus profoundly facilitating the manufacture process.

CHARACTERIZATION

The goal of the prototype's characterization was to bring its membrane with the isle to vibration. Since the prototype misses the cold sink, the heater was supplied with pulsing potential difference, thus causing the temperature oscillations of the isle and simulating the heat outflow to mimic the cold sink. Approximately

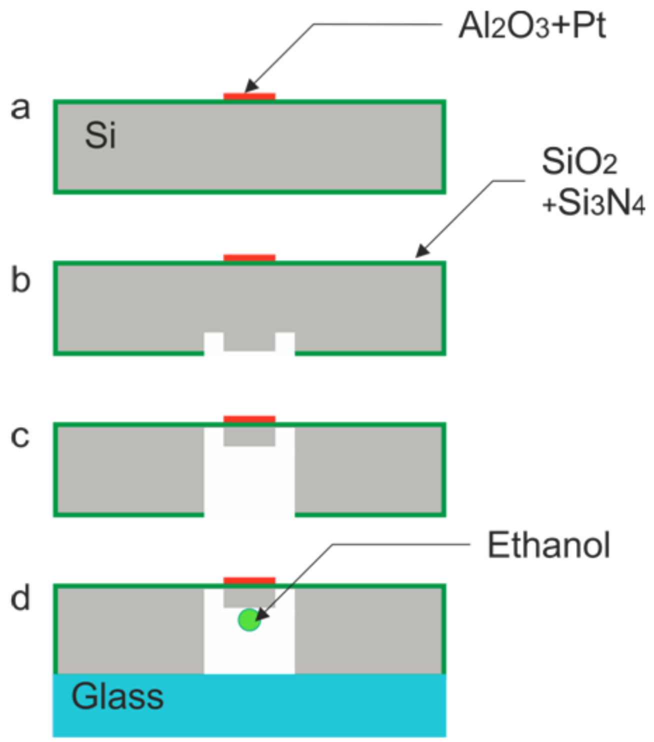

Fig. 4: Fabrication of the TG's prototype:
(a) oxidized Si-wafer with silicon nitride and the heater, (b) isle's definition on the back side, (c) DRIE-fabrication of isle, (d) deposition of fluid's drop and chamber sealing.

10% of the chamber's volume was filled with ethanol in the experimental chip. The vibration's amplitude of the membrane was measured from the deflection of a laser beam, reflected from it (fig. 5).

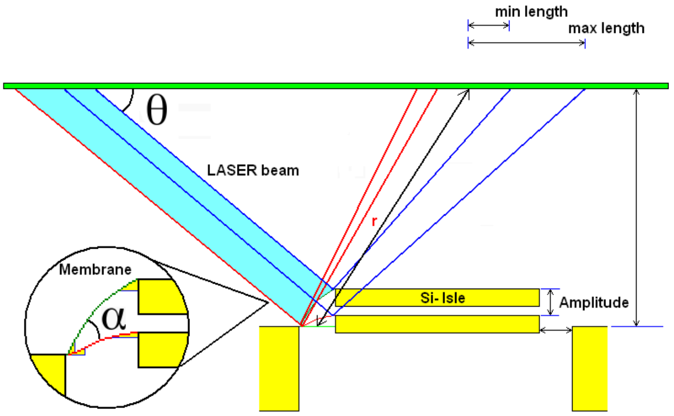

Fig. 5. Schematic of the experimental set-up

The experiment results are shown in figure 6, which includes three pictures, representing three projections of the laser beam on the opaque screen. The first projection is generated by the chip with inert membrane and has the maximum, which represents the reflection from the whole chip (total reflection). The second and the third projections are created by the beam, reflected from the chip with the membrane oscillating at the frequency of 10 Hz. They represent respectively the minimal and maximal deflection. In addition to the central reflection maximum they contain also the pulsing horizontal line, whose length depends on the membrane's bending.

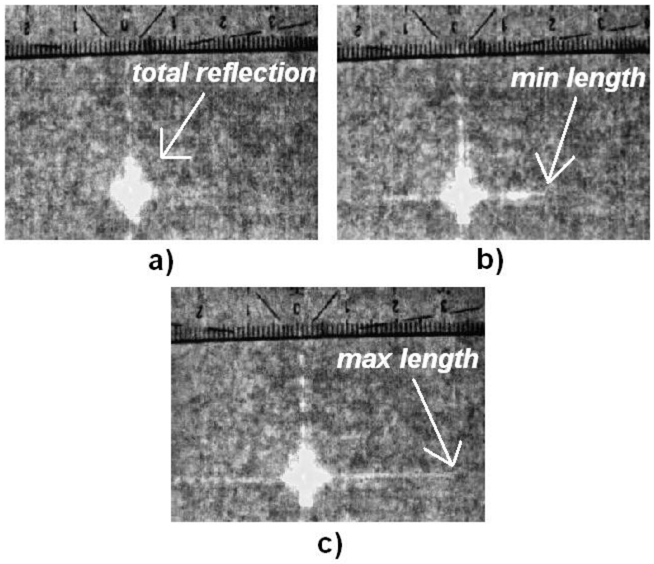

Fig. 6. Projections of the reflected laser beam: (a) inert memnbrane, (b) minimal deflection, (c) maximal deflection.

Thus the end positions of the line on the second and the third pictures define the maximal and minimal vertical deflection of the isle during the oscillation.

The characterization has shown, that the isle can be brought to vibration, which amplitude depends on its frequency (fig. 7). In order to verify the results of the laser experiment the supplemental tests with microscope was made. In this case the membrane's deflection was measured from the depth of sharpness with high magnification. Though this method is less exact, it validates the obtained results. Figure 8 shows the membrane oscillating with the frequency of 1 Hz in low and high positions as it is viewed in a microscope. This method also shows that at higher frequencies the oscillation takes place around the point of the isle's maximal vertical deflection. The same result is obtained from the figure 6: the presence of the horizontal reflection line on the second picture means, that the membrane is not flat, when the isle is moved down maximally.

DISCUSSION

The prototype, manufactured within the frame of this work, demonstrates the plausibility of the introduced HE's concept. The next suggestive research step would the fabrication of the full-function HE with the integrated cold sink, which would be able to act as the electrostatic TG, based on the variable capacitor principle. Such variable capacitor can be considered as an alternating current source, which sends practically the whole charge stored in it into the outer circuit during the discharge phase. This phase is associated with the minimal capacity and maximal energy, stored in capacitor, and happens, when the isle is maximally removed from the cold sink. During the charge phase, when the isle goes upwards, the electrical current change its direction. The energy, stored in such capacitor, would be mostly determined by its maximal capacity at membrane's high position. The plate

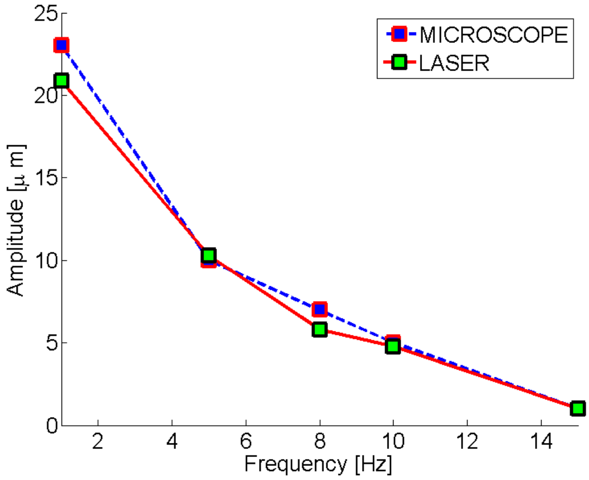

Fig. 7. Experimental points for the vibration amplitude versus its frequency.

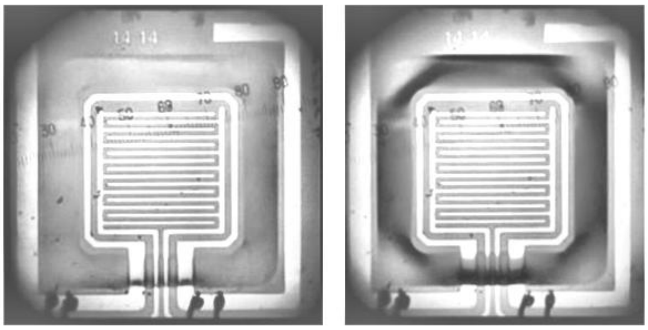

Fig.8. Vibrating membrane in low and high positions. The membrane deflection is 22µm.

separation would be in this case equal to the thickness on the isolation layer, placed for example atop of the metallization layer on the cold sink. The implementation of an effective dielectric such as Ta_2O_5 [4], could reduce this thickness to circa 100 nm. Therefore the low-amplitude high-frequency working regime of the HE would be preferred (e.g. 5 µm - 10 Hz – see fig. 7). That corresponds to the 50-times capacity variation. The calculation shows, that at such circumstances the energy stored during each pulse in the electric field reaches the 1 mJ mark, thus giving the theoretical limit of 10 mW on the possible power output. But the real power output would be heavily dependent on the impedance of the energy collecting circuit, which, because of the limited carrier number, should be extremely high-ohmic. This circuit could include for example some electrostatic actuator, which would connect the capacitor to the energy consuming device only when the maximal potential difference is reached. In this case despite of the low current, which is limited by the stored charge, high power output could be achieved. The maximal potential difference can reach some hundred volts, thus hampering the application of some electronic switch. Another actuator's advantage is its practically zero power consumption.

CONCLUSION

The novel design of a TG, based on a variable capacitor, whose plate separation is cyclically changed by a micromachined HE, is introduced. The prototype of the TG was fabricated using the silicon-micromechanics-technique. Despite of the prototype's complex structure, the corresponding technical process does not require the deep-relief photolithography, thus facilitating the fabrication and ensuring adequate miniaturization.

The prototype's working membrane was brought to vibration, thus simulating the working cycle of the HE and affirming the introduced TG's design. According to its characterization, the whole functioning TG would be able to function in the 10-Hz-cycles regime with the 5µm isle's deflection. That gives the theoretical limit of 10 mW on the possible power output. Although the real power output will be heavily dependent on the nature of the power consumption unit. The limited carrier number, stored in the TG's capacitor, makes it necessary to discharge only when the maximal potential difference is achieved. One possible solution could be the application of an electrostatic actuator, which would work as a switch between the TG and electronic circuits.

The development of the appropriate actuator along with the construction of the whole functioning TG will be the subject of further researches.

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