PERFORMANCE IMPROVEMENT OF A MICRO THERMOMECHANICAL GENERATOR BY INCORPORATING GALINSTAN® MICRO DROPLET ARRAYS

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Abstract: In previous research we have developed a pyroelectric energy harvester based on a micro thermomechanical generator (µTMG). This device uses a bistable thermal switch to move a thermal mass between a hot and a cold side, thus generating a temporal thermal gradient over pyroelectric material in between. A major parameter affecting its operational frequency, hence the power output, is the thermal contact resistance (TCR) present at the mating regions of thermal mass, hot and cold side. We have investigated the fabrication of an array of Galinstan droplets to reduce the TCR. With such an array incorporated into a µTMG the device's operational frequency is increased by at least 50 %.

Keywords: Galinstan, liquid metal array, heat engine, dynamic thermal interface, energy harvesting

INTRODUCTION

Micro thermomechanical generators (µTMGs) in combination with pyroelectric materials are proven to generate electrical power from ambient thermal gradients [1]. The operation of such a micro energy harvester is illustrated in Figure 1. The engine chamber is heated up in the down state from the heat source. Consequently the air inside the sealed cavity also gets heated up and the pressure inside the chamber rises. When this pressure exceeds a threshold, the bistable membrane flips. The engine chamber moves up and comes in contact with the heat sink. Now, heat is transferred out of the engine chamber. As a consequence, the air inside the chamber is cooling down. When the pressure inside the chamber drops below a threshold, the membrane flips back and the engine chamber moves down. The whole process continues in a self-regulated fashion, ensuring a periodic heating up and cooling down of a sheet of pyroelectric material, attached to the engine chamber. This pyroelectric generator (PEG), by virtue of its inherent pyroelectric nature, converts the thermal transients into electrical energy. The electrical power generated by such a harvester is directly proportional to its operational frequency [1]. To increase the operational frequency of the harvester, the various thermal capacitances and resistances present in the system have to be reduced if not eliminated. Among those influencing parameters, the thermal contact resistances (TCRs) between the mating surfaces play a major role in the heat transfer into and out of the engine chamber. These thermal contact resistances have to be reduced as far as possible, to improve the heat transfer rate and thereby the operational frequency of the harvester. The very fact that the interface is dynamic adds to the complexity of the situation.

THEORY

Higher thermal contact resistances arise primarily from the fact that the real area of contact is only a fraction of the apparent area of contact. At the microscopic level, only a few protruding spots are in contact [2]. To increase the number of contact spots, Cho *et al* have proposed a thermal interface based on a liquid metal droplet array [3]. Mercury, a toxic liquid metal, has been used to fabricate the liquid metal

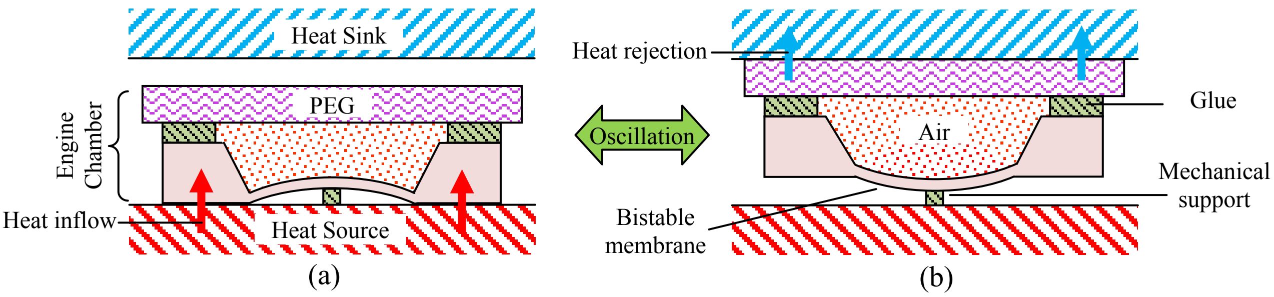

Figure 1. Schematic of a micro energy harvester showing its operation.(a) shows the down state of the harvester and (b) shows its up state.

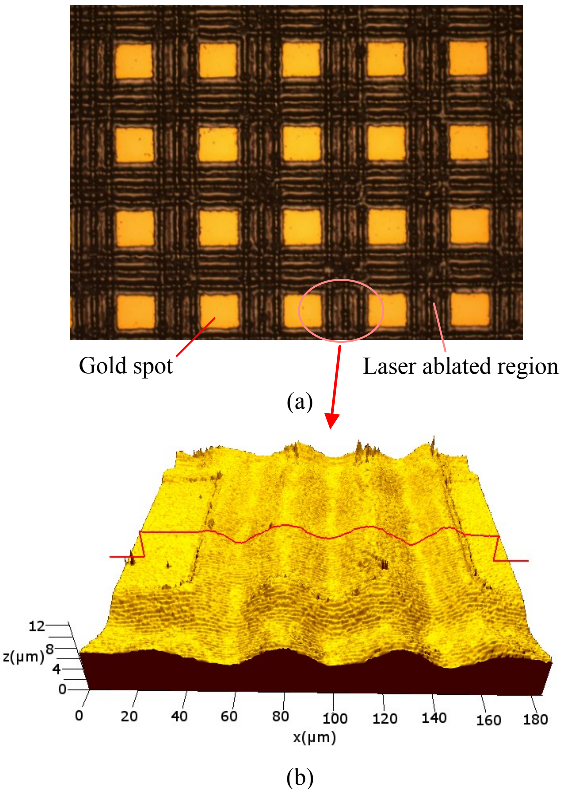

Figure 2: a) Optical micrograph of a part of the gold coated silicon chip after lasering. A typical chip consists has 1600 spots / cm^2.b) shows the Laser Scanning Microscope (LSM) image of the surface of a typical laser ablated region with sub micron features, using a Zeiss LSM 5 Pascal microscope.

droplet array. Mercury droplets are deposited onto selected and pretreated spots using a vapor deposition technique. Each anchored droplet is surrounded by a thin layer of non-wetting coating. This layer prevents the droplets from rolling over and coalescing. However, the setup used in [3] is complicated, as toxic material is deposited onto specially tailored surfaces at high temperature. To overcome these difficulties we propose the utilization of another liquid metal - Galinstan, an alloy of Gallium, Indium and Tin with a melting point of -19 °C. In comparison to Mercury, Galinstan is non-toxic. However, unlike mercury, Galinstan wets nearly all materials that could be used for a good thermal interface, especially silicon and various metals. This makes the utilization of Galinstan as a replacement for mercury challenging. A detailed treatise on MEMS devices incorporating Galinstan and associated challenges can be found in [4]. The excellent wetting behavior of Galinstan on gold surface is exploited here, to fabricate the anchoring spots for the micro droplets. Baldacchini *et al* have proposed the surface modification of a silicon wafer using femto second pulsed lasers to generate superhydrophobic surfaces [5]. In line with this, we have decided to fabricate the non-wetting region by surface profile modification via laser micromachining, however, by using a much simpler concept and equipment compared to those utilized in [3].

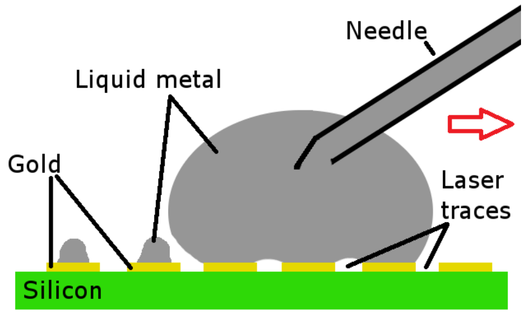

Figure 3: Deposition of Galinstan droplets by rolling a small droplet of Galinstan on the fabricated array of gold spots.

FABRICATION

A 525 μm thick <100> Silicon wafer is coated with a 10 μm/ 100 μm Cr/Au layer. The wafer is then diced into 20 mm × 20 mm sized chips. These chips form the substrate for the Galinstan micro droplet array. A Nd:YAG laser micro-machines the gold-coated side to create an array of gold spots, as shown in Figure 2a. Each chip consists of 3600 anchoring gold spots of 100 μm × 100 μm size and a pitch of 250 μm. The surface profile of a selected region, measured with *Zeiss LSM5 Pascal* microscope is shown in Figure 2b. The flat regions seen to the left and to the right of the center scan line are anchoring spots. They are surrounded by the laser micro-machined regions which exhibit sub micron features. It turned out in a large number of experiments that Galinstan does not wet these regions, preferably due to a Lotus like effect [6]. To deposit the Galinstan droplets, a small drop of Galinstan is dispensed onto the tip of a syringe. This droplet is then slowly rolled over the fabricated chip, as shown in Figure 3. Owing to its wettability on gold surface, Galinstan adheres to the gold spots. As the big droplet is rolled over, a very small portion of the Galinstan droplet detaches and stays on the gold spot. A fabricated array of liquid metal droplets is shown in Figure 4. A histogram showing the droplet diameter against the number of droplets is shown in Figure 5. More than 75 % of the droplets have a diameter of more than 30 μm, which is essential for thermal contact points. Hence, the deposition yield is also 75%.

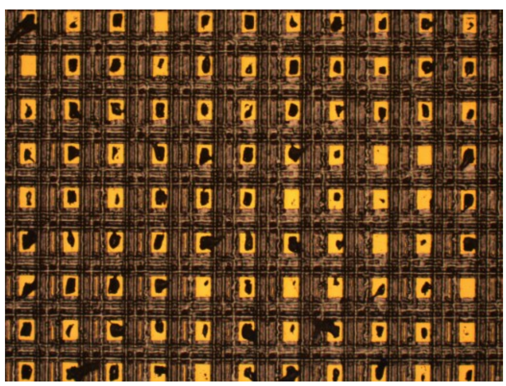

Figure 4: Optical micrograph of a Galinstan droplet array on a chip.

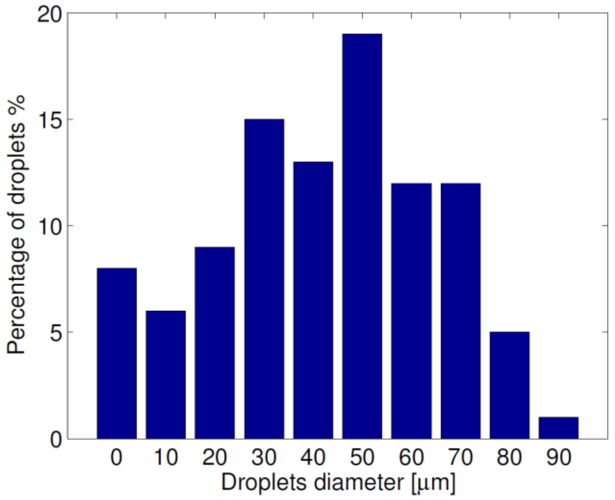

Figure 5: Histogram showing the distribution of droplet diameter on a chip consisting of 3600 anchoring spots. The measured mean diameter of the droplets is approximately 50 µm.

CHARACTERIZATION

A schematic of the test setup used to measure the TCR is shown in Figure 6. The thermal chuck is fixed on a XYZ-stage. The temperature of the chuck is set to the required value using a *Labview 8.2* based interface. The thermal capacitance of the chuck is so large that its temperature remains nearly uniform everywhere, once the steady state is reached. A thermal mass suspended on the top of a force sensor forms the critical part of the test setup. The force sensor is used to measure the contact force and thereby the contact pressure. A thermocouple attached to the thermal mass is used to record its temperature over time.

A thin film of a thermal paste used in the experiment is dispensed onto the thermal mass. The thermal chuck is heated up to 60 °C. Once the temperature reaches steady state, the Z stage is adjusted to bring the chuck in contact with the thermal mass via the film of thermal paste. The contact force is monitored via the force sensor and a read out circuit. While it heats up, its temperature profile is recorded with a *Tektronix TDS2002* oscilloscope. Due to thermal expansion the contact force increases. The contact force is kept constant at the initial value by manually adjusting the Z stage.

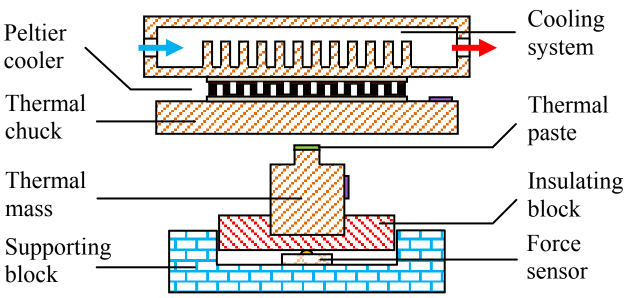

Figure 6: Test setup for measuring TCR. The thermal chuck is moved down and mated with the thermal mass during measurement.

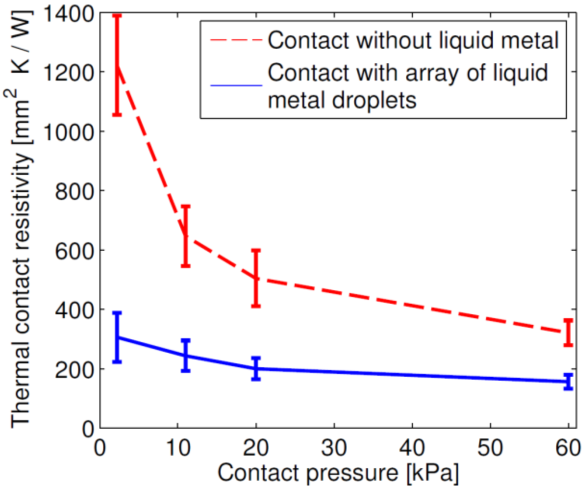

Figure 7: Variation of TCR with contact pressure. As expected, the TCR is reduced drastically when the liquid metal array is incorporated.

A *COMSOL* model of the whole test setup with the thermal paste is built up with the TCR at the thermal paste-Cu interface as a variable parameter. The model is simulated by setting the TCR to different values. The temperature profile of the thermal mass obtained from simulation is compared to the recorded profile. The TCR which gives a profile nearest to the measured one is chosen as the thermal contact resistance at the thermal paste - copper interface. The whole experiment is repeated to determine the TCR at different contact pressures. Similarly, the TCRs at different interfaces like silicon-heat paste, PZT-heat paste etc. for different contact pressures are measured. In another experiment, the thermal mass is modified by soldering a 10 mm × 10 mm sized PZT sheet onto its top surface. The thermal resistance at the Cu-Solder-PZT joint is also measured with the same test setup, using heat paste as interface material.

A gold-coated silicon chip, which is not micro-machined, is attached to the bottom surface of the thermal chuck using heat paste. The thermal chuck is heated to 60 °C. Once the temperature reaches steady state, the chuck is mated with the modified thermal mass. The temperature profile of thermal mass is recorded, keeping the contact pressure constant. With the help of the modified *COMSOL* model and the calculated TCR at Si-heat paste, heat paste-Cu interfaces etc., the thermal contact resistance at the gold coated silicon-PZT interface is calculated. The TCR is calculated for contact pressures varying from 2.2 kPa to 60 kPa. Similarly, the TCR at the gold coated silicon with Galinstan droplet array – PZT interface is calculated for varying contact pressures.

A comparison of the TCR with and without liquid metal droplet array is shown in Figure 7. The TCR at the interface reduces from 1223 ± 167 mm^2KW^{-1} to 306 ± 83 mm^2KW^{-1} at a contact pressure of 2.2 kPa, i.e. with a factor of nearly ¼. The thermal contact resistance decreases rapidly with the increasing contact pressure and saturates thereafter. This steep reduction

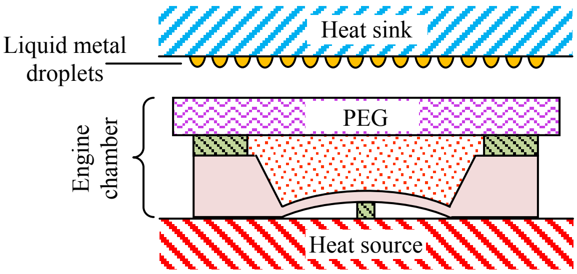

Figure 8: µTMG-PEG combination with integrated liquid metal droplet array.

is attributed to the increasing number of formed contacts and microscopic deformations in the initial phase. However, a further increase in contact pressure does not result in the creation of a proportional number of contact points, leading to saturation.

INTEGRATION

An illustration of the modified harvester is shown in Figure 8. The silicon chip with its liquid metal array replaces the heat sink of the energy harvester. The harvester is sandwiched between a hot reservoir and cold reservoir. The gap between the reservoirs is adjusted to get the device running. The temperature between the hot and cold reservoirs (ΔT) is measured along with the operational frequency of the device. A detailed account of the characterization of a similar device without an improved thermal interface can be found in [1]. The engine is operated at temperature differences (ΔT) varying from approximately 60 to 90 K. The whole experiment is repeated with the normal heat sink as well. A comparison of the variation of the operational frequency of the device with ΔT, with and without the Galinstan micro droplet array is shown in Figure 9. The measurements clearly show that the operational frequency increases by approximately 50 % after the introduction of liquid metal droplet array at the top contact interface.

CONCLUSION

A novel method to fabricate an array of liquid metal droplets has been developed. The laser micromachining process eliminates the need for a conventional coating layer which repels liquid metal droplets [3]. Moreover, the liquid metal droplet deposition process is quite simple and can be carried out in the lab at room temperature rather than via an expensive clean room process at high temperature. The developed arrays have been characterized using a novel and simple test setup. Further, the fabricated liquid metal array has been integrated into an energy harvester to evaluate its impact. Additionally, the non-wetting behavior of Galinstan on laser micro-machined copper and brass surfaces has been verified. Hence, the process is useful to create Galinstan repellent surfaces on different material surfaces or even create liquid metal arrays on varied material surfaces. Such arrays could also find applications in the energy harvesters proposed by Krupenkin *et al* [7].

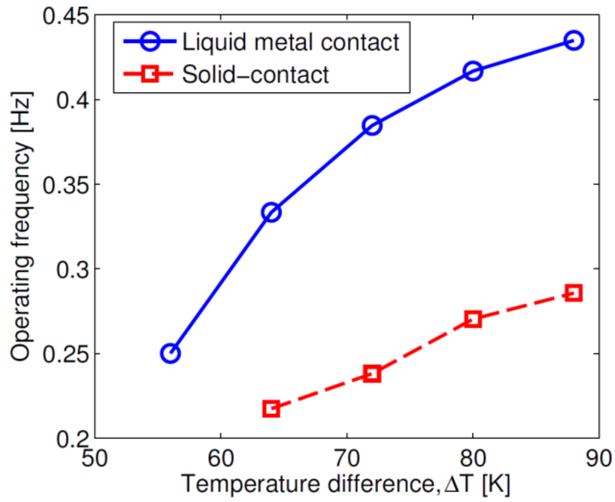

Figure 9: Variation of the engine operating frequency with the temperature difference between heat source and heat sink (ΔT).

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