Micromachined Thermogenerator Directly Integrated into Metal Parts: Technological Aspects of the Embedding Process

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Summary: The goal of the research is to demonstrate feasibility of the incorporating of semiconductor (sc) devices into metal workpieces during their forming form the melt. Alongside with the mechanical and thermal stability of the sc-device itself preparations to the embedding process are important to the overall success. The preparation stage is the focus of this paper and includes manufacturing of the adequate framework and fixing of the sc-devices in it. Frameworks were manufactured from polycarbonate and the thermogenerators, which were chosen as demonstrators, were fixed in them using plugs from vacuum rubber.

The frameworks were subsequently placed into the casting mould and a high pressure die casting process with liquid aluminium was performed. After the mechanical removing of the protective plastic cover and plugs, the thermogenerators were laid open. The subsequent functionality test gave a percent yield of 28%. The failure analyse shows the need of further development of the framework.

Keywords: Aluminum, Casting, Energy Harvesting.

1. Requirements and demonstrator's choice

Bringing functional elements directly into metal workpieces can be advantageous in two different ways: on one hand the direct contact with the substrate under load improves the sensibility of embedded sensors, on the other hand the enclosure of electronic parts into robust metal casing can play protective role against mechanical stress and environmental influence. Several attempts were undertaken in order to achieve this goal.
The first solution, which was probed on the example of RFID-chips [1-2], uses some relatively thick protective layer in order to avoid the exposure of such sensitive electronic device to the extreme temperature of the casting process. But this decoupling from working body makes this method practically unusable for sensing elements. Another possibility, used for embedding thin-film strain sensors [3-4], implements a steel substrate and thus is incompatible with common semiconductor technology and strictly limits the complexity of applied devices.

The main goal of this work is to close the gap between those approaches and to demonstrate the possibility of embedding of semiconductor (sc) structures into a metal workpiece during its forming from the melt.

The "proof-of-concept"-example of a sc-device should be chosen on the first realization step. On the one hand, in order to concentrate the research on the questions, associated with the embedding process itself, this device should not be too complex. On the other hand its functionality should be later useful for more complex second-generation devices and its set-up should include structural elements, which would be required during this second stage.

A Seebeck-effect based thermogenerator (TG) was chosen as such a demonstrator [5]. Figure 1 depicts the TG which consists primarily of a borosilicate glass (BSG) body with Si-metal-thermopiles on its surface. The amorphous structure of the BSG-substrate and the wavy form of the thermopiles dampen the thermomechanical stress associated with the casting process. The Al_2O_3-isolation protects thermopiles from short circuits.

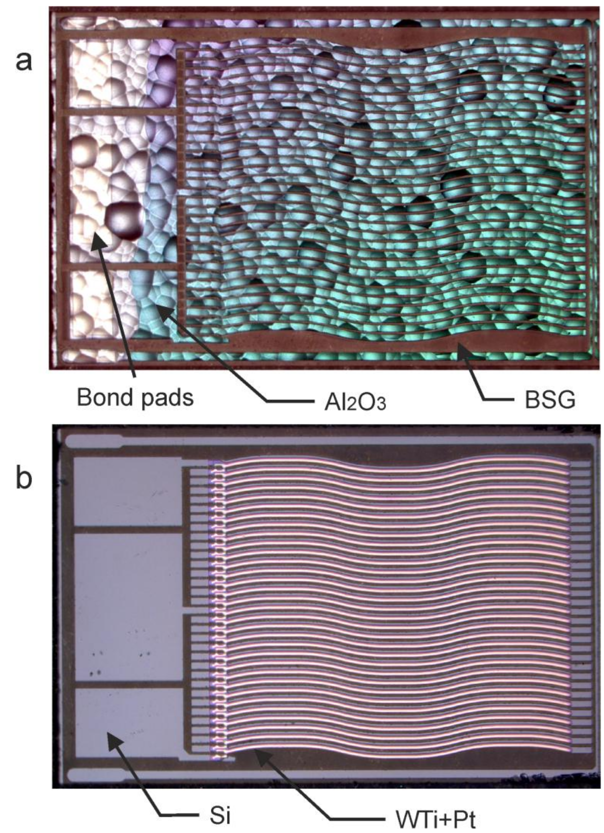

Figure 1. Thermogenerator: (a) view from the structured side, (b) view through the transparent BSG-substrate.

2. Technological aspects of the embedding process

The first experiment was to put the TG into a brass form filled with molten tin. It showed, that the TG was not damaged during the procedure (see fig. 2), thus demonstrating the concept reliability at least up to the tin's melting point (232°C). The most important result of this experiment is the absence of the short circuit between the metal and TG, which means that the Al_2O_3 isolating layer does not have cracks or pinholes. The next experimental step was the approbation of the high pressure die casting (HPDC) process.

Although the chip should be fully placed in the cast form during the HPDC-process, it should be only partially embedded into aluminium: the ends with radiators and contact pads should remain free. Therefore, it is necessary to cover the chip's ends primarily with plastic (see fig. 3 - step 1). After that the central parts of the TGs should be embedded into the molten metal (see fig. 3 - step 2). The plastic protective layer should be subsequently stripped off (either chemically dissolved or removed mechanically - see step 3 in fig. 3). The special puncheon for the initial partial embedding of the TGs into the plastic protective framework was produced (see fig. 4). This component would be subsequently used as a mounting for the casting process.

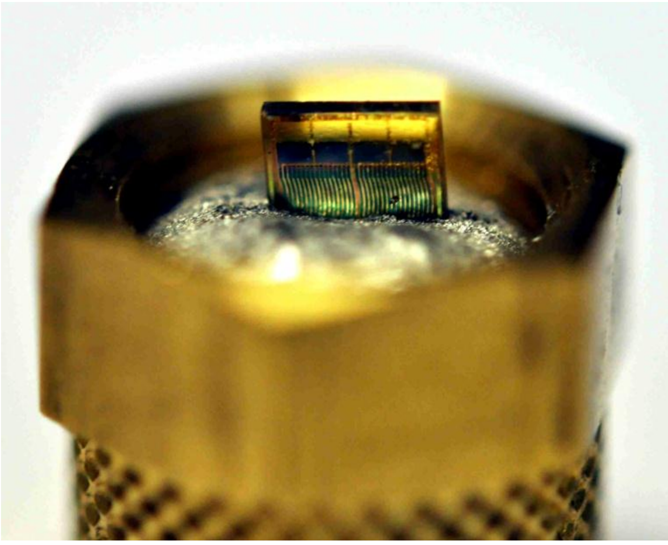

Figure 2. TG embedded into tin.

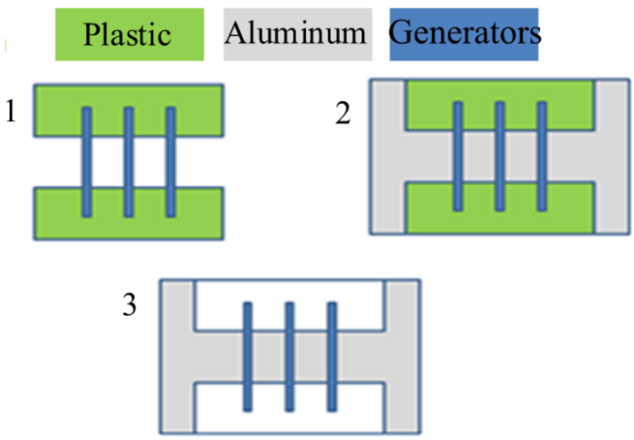

Figure 3. Schematic of the embedding process with a removable plastic protection.

In the middle of the working volume this puncheon has two butted partition-walls with eight vertical slots for the TGs in one of them. When the plastic detail is formed, these two walls would be disengaged leaving the middle parts of the TGs free. But the transacted tests showed that during the disengagement it is difficult to maintain the proper alignment between the detached partial-wall and the plastic detail with embedded TGs. This misalignment causes the mechanical destruction of the chips. The attempted effort to lubricate the chips before the process with silicone oil did not solve the problem. It was decided to build in the TGs into the plastic after the forming. This required the implementation of additional plugs, which were produced from thermally stable vacuum rubber.

In the protective plastic mounting the 5-mm holes were drilled in which the fabricated TGs were fixed using the plugs from the high-temperature resin (see fig. 5). Beforehand for additional safety the second passivation layer of 40µm glass (Heraeus IP9025ST) is deposited as a paste on the chips and annealed at 430°C.

Along with the standard TG there were specimens consisted from the TG and an additional BSG-die fixed by the same glass paste on the BSG-side of the TG's, thus making the assembly

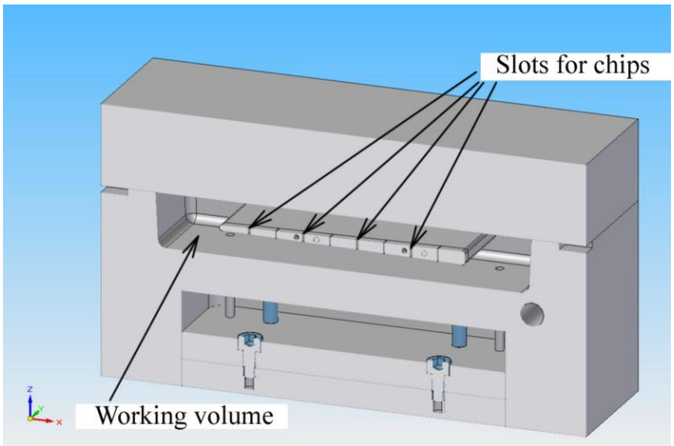

Figure 4. Section of the puncheon for the initial embedding into the plastic component.

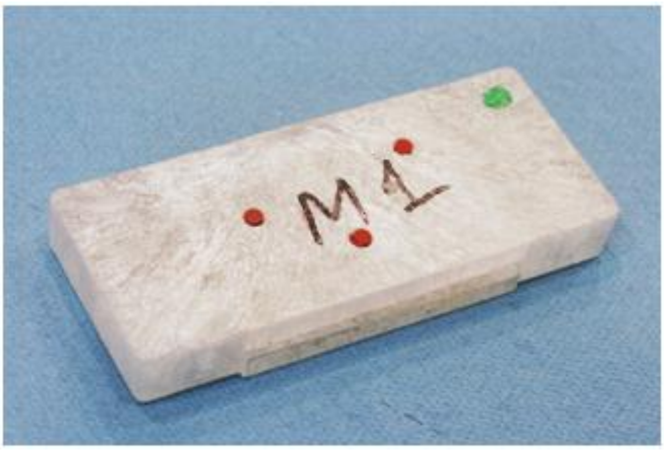

Figure 5. Plastic mounting with three TGs fixed in it using resin plugs.

Figure 6. Mounting with three TG embedded in cast aluminium.

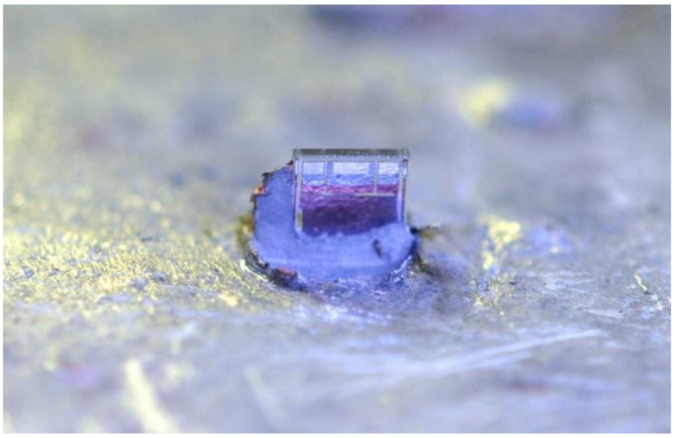

Figure 7. Half embedded TG after removing protective plastic.

more mechanically stable but not impeding the thermal contact between the TG and its environment. Also some TGs were winded around with a 0.2-mm wire. Although the molten metal will penetrate under the pressure of the HPDC-process practically any cavity and fill the gap between the wire and the TG, this measure could be able to mitigate the initial shock. Finally, the devices were placed into the casting mould and a HPDC process with liquid aluminium is performed. For the HPDC process a casting unit 'BÜHLER SCN/66' was used. As molten metal an aluminium alloy type AlSi9Cu3 (Al plus 8-11% Si plus 2-4% copper) was teemed by 700 °C, plunger speed of 0,6 m/s and a redensification of 300 bar. Figures 6 and 7 show subsequently photos of the mounting after embedding into molten aluminium and of the device itself after removing the protective plastic. Initially the framework's plastic parts were supposed to be dissolved in organic solvent (e.g. acetone or methylbenzol), but tests showed, that it is more convenient to strip them off mechanically directly after the embedding, when the plastic is still hot and soft.

Fourteen out of the fifty embedded TG were functional after the embedding. The failure analysis showed no significant difference between the standard TG and the exemplars with additional protection (BSG-die or wire). The main cause of the cracks, aroused in the failed TGs, is probably the deformation of the cast metal part itself. The 55-mm long aluminium wall with embedded TGs is mechanically the weakest point of the whole assembly and has to be reinforced. In many cases, when its bending exceeded 4 mm, no TGs survived the process independent of the protective measures applied (see fig. 8). The problem of the mechanical stability of the final aluminium detail can be solved by implementation of an improved framework and will be addressed in future works.

Figure 8. Deformation of an aluminum casting part.

3. Conclusions

The feasibility of direct incorporation of semiconductor devices into metal structural parts during their casting from a molten mass was demonstrated. As an example a thermogenerator (TG) was embedded into tin and aluminum. This thermally and mechanically stable MEMS-structure was tested up to 730°C and did not lose its functionality. An important role of the TG's preparation to the embedding process including manufacturing of the corresponding frameworks and fixing the chips in them should not be underestimated.

Possible application fields of the developed TG can also include its embedding in other metals such as magnesium, brass and bronze, glass or ceramic components during their manufacturing (e.g. casting process), what will be the subject of further researches, which additionally have to include further development of the preparation stage with corresponding customizations to each application. The possibility of other MEMS-implementation of the introduced technology will be also considered.

Acknowledgements

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