

A CONCEPT OF AN ELECTRET POWER GENERATOR INTEGRATED WITH A RECTIFIER

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Abstract: We propose, and experimentally support, a concept of a monolithic electret power generator integrated with a rectifier. The entire device is fabricated by exploiting MEMS-specific processes such as DRIE to provide electrical device isolation for the rectifier. Firstly, we summarize the advantages of integrating a rectifier to a micro-power generator. Secondly, we present a relatively simple micro-fabrication process to integrate a rectifier to a mechanical microstructure. Thirdly, we report on fabrication results as well as problems encountered. We end with some speculations as to how the process might be improved.

Keywords: vibration energy, electret, rectifier

INTRODUCTION

The field of micro-energy harvesting strives to find a means to power small electrical units, in particular network nodes of a sensor network [1]. One of the energy resources that is considered viable is vibration energy [2]. In this paper we focus on vibration energy harvesting and in particular ones in which electrostatic energy conversion principles are employed [3].

While until recently attention of the community seemed to focus rather predominantly on the electromechanical energy conversion itself, the attention is now also being directed towards the issue of efficient use of generated electrical power. On a larger scale, there has indeed been interesting results already, regarding efficient rectification of the generated electrical current [4, 5]. Here we describe an approach that is about device fabrication processes, rather than improvements at the systems-level. Our approach attempts to integrate a rectifier to minimize stray capacitance associated with the rectifier circuit, which would be detrimental to rectification efficiency. We note that a recent study [6] go towards this direction, although monolithic integration is yet to be achieved.

ELECTROSTATIC TRANSDUCER

It is always, of course, good to make devices small. However, in this particular case of electrostatic micro power-generation, there is a stronger reason to do so – that is, to minimize associated stray capacitance.

Electrostatic electromechanical energy transducers has output charge as a function of positions of its mechanical elements. In the case of piezoelectric materials, the charge depends on deformation, while in the case of electret-based

devices the charge depends on the position of the electret relative to the associated electrodes because the electret always induces counter charge on nearby metal. When the configuration of the electromechanical transducer is changed, the output charge changes in time, inducing an electric current. In an electret-based transducer where the electret moves in parallel with the nearby metallic surfaces (henceforth referred to as ‘work electrodes’), the situation is as shown in Fig. 1.

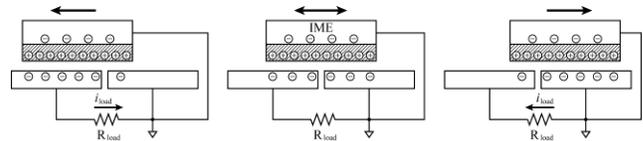


Fig. 1: An electromechanical transducer using an electret. IME stands for internal mass element of a power generator.

In Fig. 1., the induced counter charge simply follows the motion of the electret, thus producing an electric current. The ‘slit’ between the two work electrodes helps us to ‘take’ the induced current out to be fed to the load. Note that the produced charge depends only on the surface charge density σ of the electret and the geometry, regardless of dynamics. In the case of micro-sized transducers, this charge tends to be rather small. A ballpark estimation would be $q \sim 10^{-8}$ C, if we use values of $\sigma \sim 10^{-4}$ C/m² (for a good electret) and typical length scale of $l \sim 10$ mm.

MOTIVATION FOR MINIATURIZATION FROM THE CIRCUIT POINT OF VIEW

In view of the above estimation, it is important to minimize any associated stray capacitance. Figure 2 (a) and (b) show simple half-wave and full-wave

rectifiers, respectively. In these figures, we took an electret-based vibration energy harvester as an example, in which the work electrodes rather than the electret moves horizontally. (Only the relative motion matters.) In a micro-scale power generators, half-wave rectification circuit could be of some use, because the size of the output charge is so small that the associated voltage may not exceed the threshold voltage of the full-wave circuit (that is roughly twice the forward-voltage-drop V_g of the diode). Note that, in both the half-wave and full-wave rectifiers, a sub-circuit element shown in Fig. 2 (c) is involved.

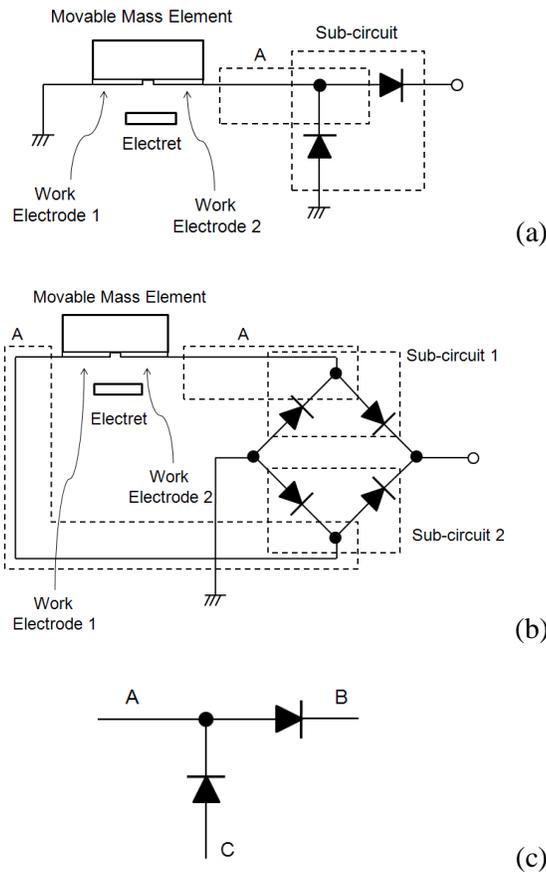


Fig. 2: Rectification circuit for a micro-sized electrostatic electromechanical transducer. (a) A half-wave rectifier. (b) A full-wave rectifier. (c) A common sub-circuit. The part shown as ‘A’ is where we want to minimize stray capacitance.

The portion indicated as ‘A’ in the sub-circuit of Fig. 2 (c) is connected to one of the work electrodes (that will henceforth be referred to as the ‘output’ work electrode) of the electromechanical energy converter. The entire connection is shown in Fig. 2 (a) and (b). These parts are crucial in that the ‘swept’ electric charge Q accumulates there and should subsequently go through the rectifying diodes.

Therefore, we need to minimize the associated stray capacitance C_S between the portion ‘A’ and the ground because we do not want the voltage $V = Q/C_S$ to be smaller than the threshold voltage V_{th} of the rectifier. (The voltage V_{th} would be approximately V_g and $2V_g$ for the half-wave and full-wave rectifiers, respectively.)

As far as the initial stage of rectification is concerned, we do *not* have to minimize stray capacitance of other part of the circuit. However, there may well be following circuit that, for example, would double the voltage output in the case of micro-sized power generators. In such cases, those other parts (such as the parts indicated as ‘B’ and ‘C’ in Fig. 2 (c)) may have to be designed carefully as well.

The simplest and effective way of minimizing the stray capacitance C_S is to fabricate the circuit physically small. Therefore, performing micro-fabrication to produce a monolithically integrated device makes sense. We now turn our attention to fabrication processes to produce such a device.

FABRICATION PROCESS

As there have already been fabrication methods for MEMS structures as well as semiconductor circuits, it is matter of how to combine these processes. For example, the ‘post-processing’ methods are used to produce MEMS devices by using integrated circuit devices as the starting material.

Here we propose a means of simplification, which may be of interest depending on the application at hand. Ordinarily bipolar device fabrication processes are quite complicated (when compared to, for example, the MOS processes) in part because the bipolar devices must be properly isolated electrically. Such device isolation is usually done by providing reverse-biased p-n junctions where necessary. However, this conventional method includes a number of dopant diffusion processes and silicon-dioxide layer formation processes, among others, to the fabrication process. One aspect we could exploit in our situation is that we are necessarily fabricating a device involving mechanical structures. Therefore, we provide device isolation simply by removing required part of material of the silicon substrate, when we fabricate MEMS structures by deep reactive ion etching (DRIE). In this case, the stray capacitance may not be as small as what the conventional method would achieve. This is because the isolated portion of the circuit still contains the whole thickness of the silicon substrate whereas the isolated circuit would be localized on the surface of the silicon wafer if we employed a more conventional approach.

Nevertheless, the size of the stray capacitance made possible by our method would be much smaller than values that would be obtained by using a discrete rectifier connected to an MEMS transducer by electrical wires.

Figure 3 shows our fabrication process. First of all, we thermally oxidized (at 1100 degree Celsius, for 3.5 hours) an N-type (100) silicon wafer “A” that had electrical resistivity of nominal 5~8 Ω cm (Fig. 3 (a)). An appropriate value is desired because if too much dopant was present it would be difficult to reverse the polarity by diffusing a P-type dopant and if too little dopant was present the electrical conductivity would simply be not good enough. The SiO₂ layer B is then etched by buffered HF. Subsequently, boron atoms were diffused into the substrate (at 1160 degree Celsius, for 2 hours) to form p-n junctions C (Fig. 3 (b)). Another set of ‘windows’ D were subsequently opened in the SiO₂ layer to provide electrical access to the N-type part of the silicon substrate (Fig. 3 (c)). Metallic electrodes E, F were then formed by first sputtering aluminum, that contains 5% silicon, and then patterning by photo-lithography using negative photoresist OFPR-800 by Tokyo Ohka Kogyo (Fig. 3 (d)). The silicon component in aluminum prevents the silicon in the wafer from diffusing into the electrode (and thus protecting the p-n junction) in a later annealing process, that is performed for 30 minutes at 375 degree Celsius. Subsequently, we define portions where the silicon substrate is removed by DRIE to provide both MEMS structures and electrical device isolation. This is performed again by standard photo-lithography process combined with buffered-HF etching. Then, to provide mechanical strength for the later stages of fabrication, we glue the whole device to another silicon wafer by using OFPR-800 photoresist. The DRIE (Bosch) process resulted in a structure shown in Fig. 3 (e) because the etching stops essentially at the SiO₂ layer on the other side. Importantly, the same process was also used to fabricate MEMS structures. Before chemically removing the device from the large ‘supporting’ wafer, we injected CYTOP (CTL-809M, Asahi Glass Co.) polymer into the device-isolation-groove G just produced, which was followed by a vacuum degassing process and a thermal curing process at 150 degree Celsius for 1 hour. Finally, the whole device was removed from the supporting wafer by using the ‘Stripper 502A’ (Tokyo Ohka Kogyo). The thin SiO₂ layer at the MEMS structure part naturally disappeared.

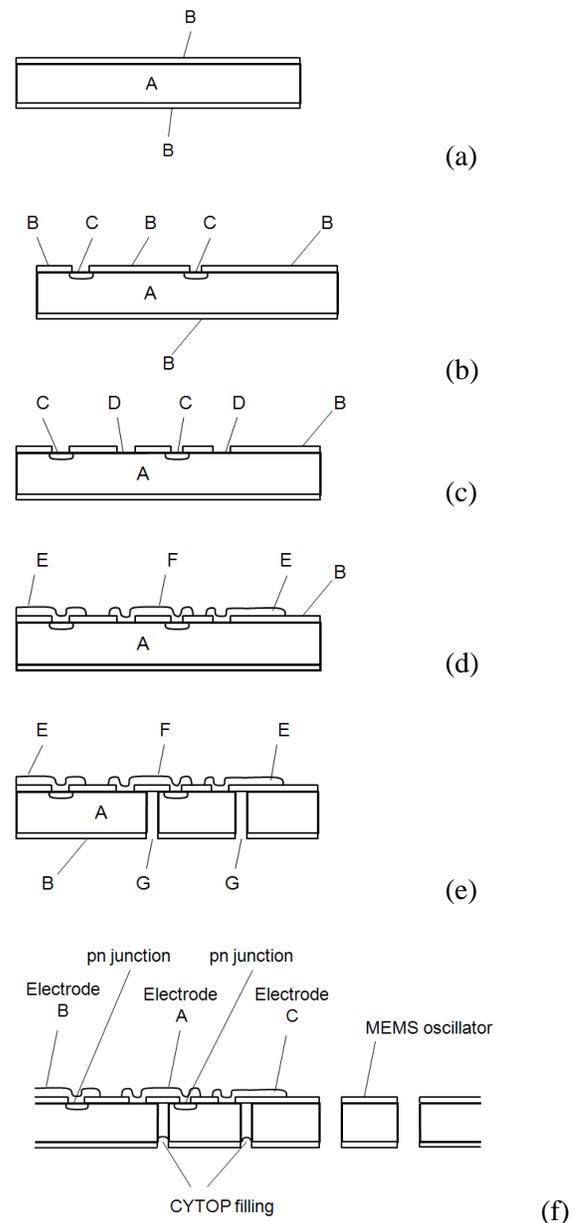
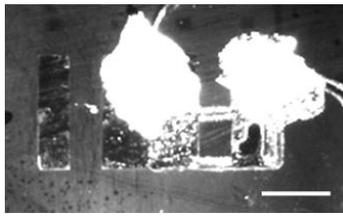


Fig. 3: The fabrication process. See text.

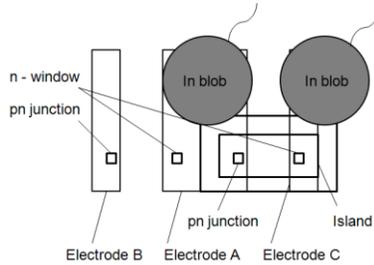
A schematics of the final structure is shown in Fig. 3 (f).

RESULTS AND DISCUSSION

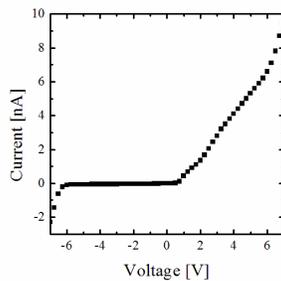
Figure 4 (a) shows a picture of a resultant device, while Fig. 4 (b) explains which part of the picture corresponds to what element. The characteristic of one of the diode produced is shown in Fig. 4 (c). At the present stage of development, the diode characteristic is not as good as it should be *after* the MEMS process (e. g., involving a rather large reverse leakage current), and the precise reasons are currently under investigation.



(a)



(b)



(c)

Fig. 4: (a) An image of a device. Scale bar: 1 mm. (b) Schematics. (c) An IV curve of a fabricated diode.

CONCLUSION AND OUTLOOK

We presented a method to produce an integrated micro-sized, vibration-driven energy harvester that includes both an electromechanical energy transducer and a semiconductor rectifier. We argued that such an integration makes sense not only because compact devices can be fabricated, but also because one can minimize the associated stray capacitance in order to increase rectification efficiency. We presented a fabrication method to make such an integrated device, that would be, at least for some situations, much simpler than a more conventional approach. The fabrication method realizes electronic device isolation simply by removing part of the substrate silicon, rather than by providing with inversely-biased p-n junctions. The fabrication test results have been presented, and some problems to be solved have been identified. That is, we still have problems regarding the quality of semiconducting diodes that appear to arise when the diode fabrication process is combined with MEMS processes. Looking ahead, however, we would argue that the process could eventually be combined with our recent finding [7] that the use of ‘free-standing’ electret, or variant of it, would help optimizing the overall vibration-driven micro energy

harvester even further.

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