RECTIFIER OF VIBRATION-DRIVEN MICRO ENERGY HARVESTING SYSTEM

Kuni Tsuji[1], Hiroshi Okamoto[2], Sumito Nagasawa[1], Hiroki Kuwano[1]
[1]Department of Nanomechanics, Tohoku University, Sendai, Japan
[2] Faculty of Systems Science and Technology, Akita Prefectural University, Yurihonjo, Japan
*Presenting Author: tsuji@nanosys.mech.tohoku.ac.jp

Abstract: In this paper, two types of rectification methods, mechanical rectification and semiconductor rectification, for micro energy harvesting systems are proposed and evaluated. Both the rectification methods have been developed in view of enabling integration with micro energy harvesting devices on the same wafer. The mechanical rectifier converts the alternating current (AC) to a direct current (DC) using a set of needles and contact electrodes under external vibration, which is also used for energy generation. An anisotropic etching was employed to fabricate the needles. T We also study the more traditional rectification method based on semiconductor diodes. Electrical isolation of these diodes was realized by a simple MEMS process that also allowed us to reduce the parasitic capacitance.

Keywords: energy harvesting, mechanical rectifier, semiconducting rectifier

INTRODUCTION

In recent years, society has established a highly-networked information infrastructure, with increased demand for wireless sensor networks for medical services, industrial monitoring, environment monitoring and so on. To satisfy this demand, a number of maintenance-free sensors are needed for the realization of wireless sensor networks. These sensors require electric power. In view of the cost of replacing the batteries of these sensors, the idea of harvesting energy from the environment has been attracting attention [1]. The energy sources for the harvesting are light, thermal gradient, wind, and vibration, et al. In this paper, we focus on mechanical vibration energy systems which can be used in many places. Vibration-driven energy harvesters always contain mechanical components to convert vibration energy to electricity. Hence micro electromechanical systems (MEMS) processes are needed for the fabrication of micro-sized energy harvesters.

Most studies of vibration-driven micro energy harvesters use electromechanical power converters such as piezoelectric elements, electrets and ferromagnetic materials [2-4]. These power converters generate alternating current (AC) output. However, most micro sensors and actuators need direct current (DC) input. Furthermore energy from vibration-driven energy harvesters becomes intermittent because vibration sources do not always vibrate. Therefore we need to store the energy to operate devices in need. Ways to rectify and store are already suggested by using electronic circuit with CMOS devices [5], however, if the energy harvesters are made through MEMS processes together with the rectifiers and capacitors, entire process may be simplified.

In this paper, we suggest a micro energy system. The focus is mainly on proposing and demonstrating methods to fabricate rectifiers of micro energy systems using MEMS processes.

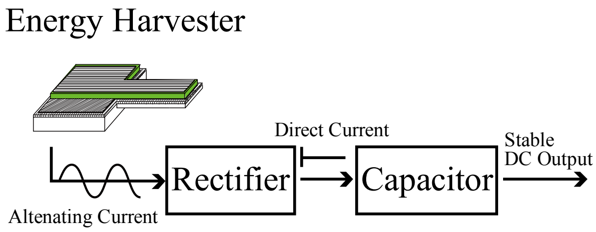

Fig. 1 Composition of the micro energy system

DESIGN OF THE MICRO ENERGY HARVESTING SYSTEM

The micro energy system is composed of an energy harvester, a rectifier and a capacitor which are on the same wafer. In this paper, we suggest the design of this micro energy system which uses two different types of vibration-driven micro energy harvesters. Fig. 1 shows the components of the micro energy system. Vibration-driven micro energy harvesters generate AC because of electric polarity reversal by vibration. However, the energy from a vibration-driven energy harvester becomes intermittent because vibration sources do not always vibrate. Hence it is difficult to operate micro sensors and actuators. To solve this problem, the micro energy system works as flows. Firstly, a vibration-driven micro energy harvester generates AC and a rectifier converts the AC power into DC power. Secondly, a capacitor stores the DC power. Finally, when enough energy is stored to operate a micro sensor or a micro actuator, the DC power is provided from the capacitor. In the following, we investigate a rectifier which is mounted into a micro energy harvester. We consider two rectifiers: a mechanical rectifier and a semiconductor rectifier.

MECHANICAL RECTIFIER

Fig.2 shows the design of the mechanical rectifier. The adopted energy harvester is a cantilever structure which is a popular type in energy harvesters. The

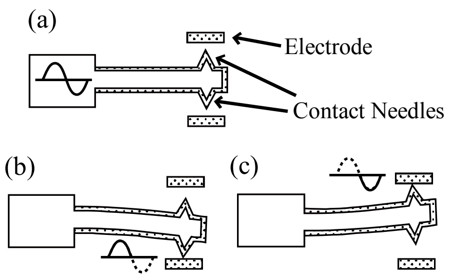

Fig. 2 Schematic diagram of the mechanical rectifier

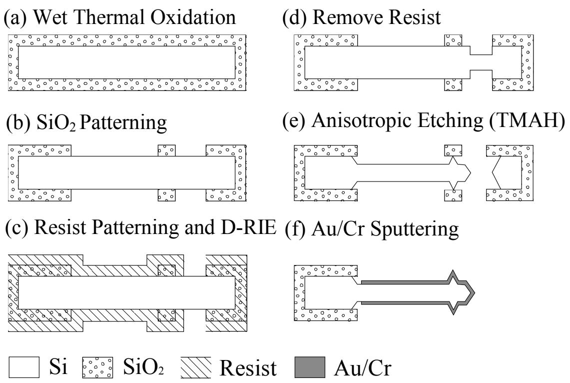

Fig. 3 Fabrication process for the mechanical rectifier

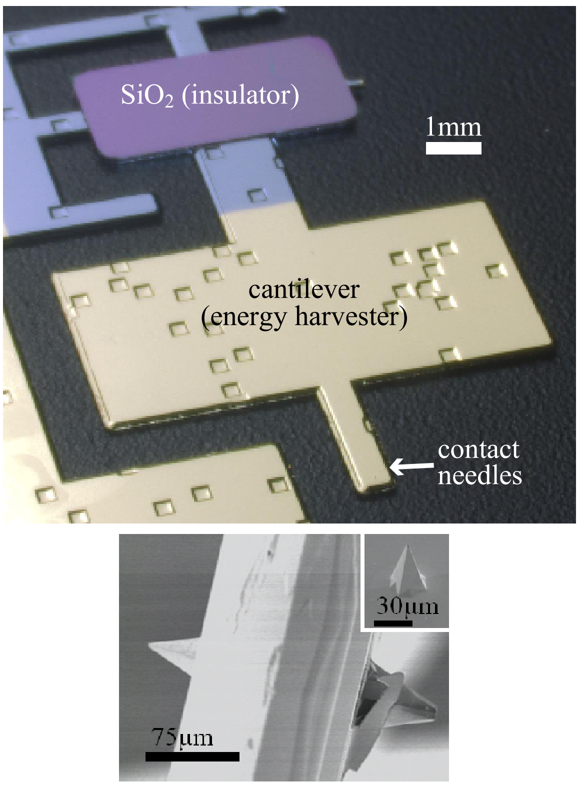

Fig. 4 A photo of the cantilever (top) and a SEM image of the micro needles (down)

cantilever of the micro energy harvester has two needles at the tip. And two counter electrodes are arranged, on both sides of the cantilever tip as shown in (a). When the cantilever is bended downward by vibration, the needle touches the lower counter electrode, through which the positive charge generated is transferred (b). When it is bended upward, the negative charge is transferred through the upper counter electrode for the other needle (c).

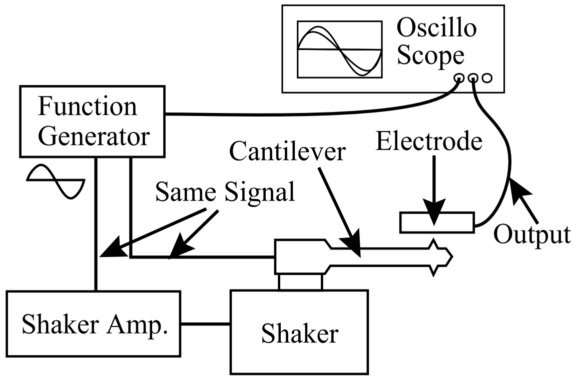

Fig. 5 Measurement setup for the mechanical rectifier

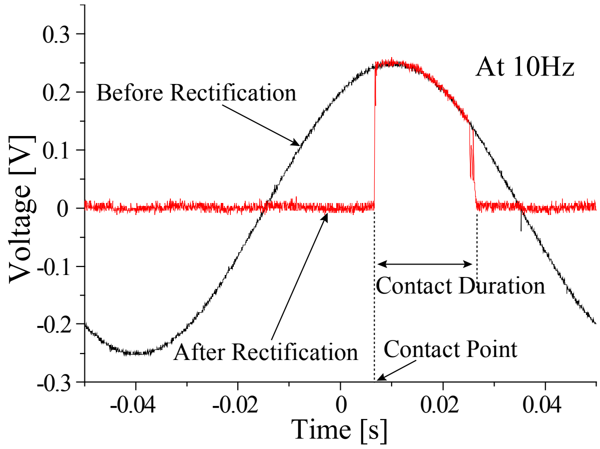

Fig. 6 The result of the mechanical rectifier (half-wave rectification)

Fabrication process of the mechanical rectifier

Fig.3 shows the fabrication process of the mechanical rectifier. Two needles and a cantilever are formed by anisotropic wet etching and deep reactive ion etching (D-RIE). We used a 250µm thick, (100) Si wafer. The Si wafer was thermally oxidized (a) and SiO_2 was patterned with buffered HF (b). The remaining SiO_2 was used as an anisotropic etching mask. After patterning the resist, Si was etched using D-RIE (85µm in depth, both sides) (c). The resist was removed (d). Then the needles were formed by anisotropic wet etching (TMAH) until a cantilever was released from a base silicon wafer (e). At the end of the process, Au/Cr film was deposited by sputtering (f). As shown in Fig. 4, successful formation of the cantilever and the micro needles were confirmed by a photograph (top) and a SEM image (bottom).

Evaluation of the mechanical rectifier

Fig.5 shows a setup of the rectifying experiment. The purpose of this experiment is to evaluate the rectification capability of the mechanical rectifier with cantilevers and needles. In normal case, a cantilever generates energy by using electromechanical power converters such as piezoelectric materials, electrets and ferromagnetic materials. However the purpose of this experiment is to evaluate the rectification capability. Therefore, instead of rectifying the output of the

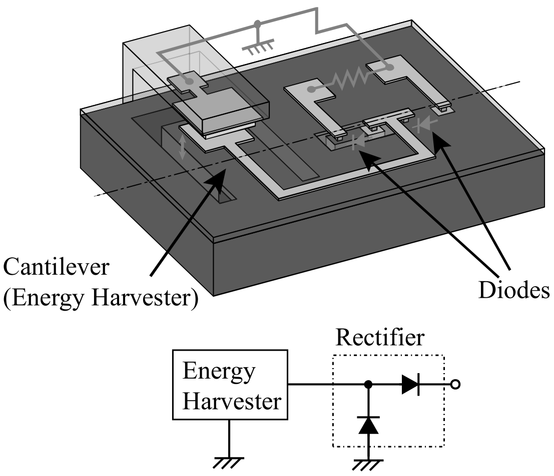

Fig. 7 The design of a semiconductor rectifier

cantilever, we input AC in it. The frequency and phase were the same as the shaker's. And we observed the waveforms (input and output).

Fig.6 shows the experimental result. The input frequency was 10 Hz. In this examination, we used one electrode for half-wave rectification. Before rectification the waveform included both positive and negative voltage. In contrast, after rectification only positive voltage was observed. This result shows that it is possible to rectify using such a mechanical rectifier.

The benefits of this mechanical rectifier are that it is easy to fabricate this rectifier using MEMS process and that there is no switching loss compared with semiconductors. However we don't consider a switching timing relevant to whole system loss in this paper.

The problems are, firstly, the physical strength of the needles, since the needles touch the electrodes repeatedly. Secondly, we cannot get any power if the amplitude of vibration is too small for the needles to touch the electrodes. Consequently it is best to use this mechanical rectifier in the place where the amplitude of vibration is known in advance.

SEMICONDUCTING RECTIFIER

Semiconducting rectification have already been widespread. In order to use such rectification for sensor networks, CMOS devices are usually considered. In this paper, we propose to integrate a rectification circuit with an MEMS energy harvester (Fig. 7). By integrating it, it is possible to make smaller devices. While a similar study has been reported earlier [7], in the present work we have obtained pn junctions with improved characteristics. When fabricating a micro energy harvester (cantilever), D-RIE is used to electrically isolate it from the semiconductor diodes. By separating semiconductors, it is possible to decrease the leak current and parasitic capacitance and to simplify the entire fabrication process. Furthermore by integrating the components on the same wafer, the wiring length can be shorter and the resistance can be smaller.

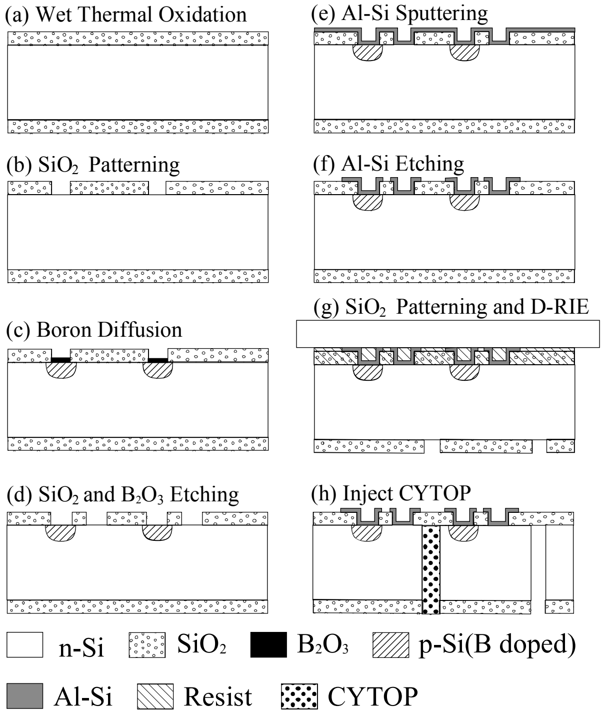

Fig. 8 The fabrication process for p-n diodes and an energy harvester

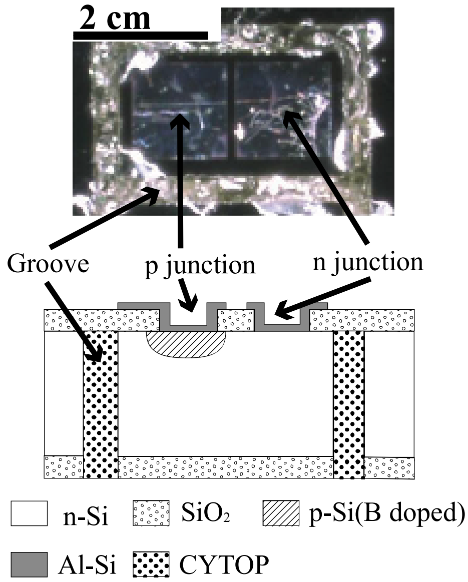

Fig. 9 A photo of fabricated diode (top) and cross-section diagram (down)

Fabrication process of the semiconducting rectifier

Fig.8 shows the fabrication process for diodes and an energy harvester. As a substrate, we used a 400μm thick, (100) silicon wafer, which was doped with N-type dopant to have nominally 5~8 Ωcm resistivity. The N-type silicon wafer was thermally oxidized over a thickness of 1μm of SiO_2 (a). And then, as p-junctions, windows were opened in the SiO_2 layer with buffered HF (b). Subsequently, boron atoms were diffused at 1125 °C for 2 hours to obtain p-type regions (c). The depth of the p-type regions was calculated to reach 2.95μm. After photolithography, B_2O_3 and SiO_2 were etched simultaneously using buffered HF (d). In doing so, the B_2O_3 place was made into p-junction windows by boron diffusion; while the

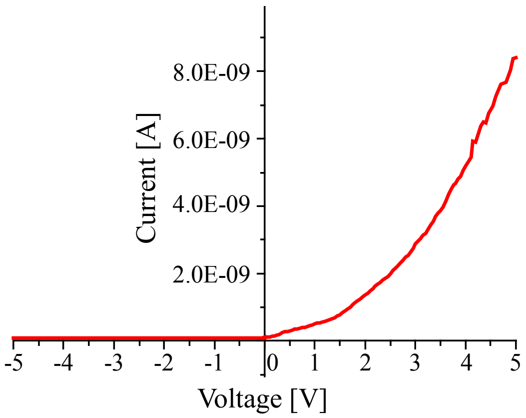

Fig. 10 Current-voltage characteristics of the fabricated diode

SiO_2 place was etched into n-junction windows. A 75nm thick Al-Si (5%) layer was deposited by sputtering (e). To form the electrodes, Al-Si was then patterned (f). After fabricating the aluminum electrodes, the SiO_2 on the other side was partially removed to define the regions where the Si is to be removed, and the device was attached to a 'dummy wafer' for D-RIE using positive resist (g). By D-RIE, Si is etched throughout the entire thickness to isolate the diodes, and at the same time structures cantilever structures for vibration-driven micro-energy harvesting can be fabricated. To prevent mechanical breakdown, we injected amorphous fluorocarbon polymer CYTOP (Asahi Glass, CO.) into the isolating groove surrounding the diodes (h). Thus, the diode structure is mechanically well-supported before the wafer is removed from the supporting wafer. Fig. 9 shows an image of the fabricated diode. The diode is surrounded by a groove.

Evaluation of the semiconducting rectifier

Fig.10 shows the current-voltage curve of a diode produced. The curve was measured after the D-RIE process. This result shows the normal behavior of the p-n junctions. This means that it is possible to use this diode as a rectifier.

CONCLUSION

In this paper, we suggest the design a micro energy system with two different types of vibration-driven micro energy harvesters, in order to supply energy for sensors in wireless sensor networks. This system is fabricated on the same wafer. In order to realize this micro energy system, we consider a rectifier, which is one of the components consisting of the micro energy system. Two different types of rectifiers have been demonstrated to work: a mechanical rectifier and a semiconducting rectifier. The mechanical rectifier consists of needles and electrodes. The semiconducting rectifier uses diodes. Both the mechanical and semiconducting rectifiers were fabricated using MEMS processes, and we confirmed that both types can rectify the voltage and/or current. The mechanical rectifier may find a better use in places where the vibration amplitudes are known in advance. The fabricated diodes for the semiconducting rectifier successfully showed diode characteristics after the MEMS-specific processes.

ACKNOWLEDGMENTS

This work is funded by scientific research funds (Grant-in-Aid for Creative Scientific Research No.18GS0203). We would like to thank the Ministry of Education, Culture, Sports, Science & Technology JAPAN.

REFERENCES

[1] Ivo N. Ayala, Dibin Zhu, Michael J. Tudor, and Steve P. Beeby, AUTONOMOUS TUNABLE ENERGY HARVESTER, *Technical Digest PowerMEMS 2009, (Washington DC, USA, December 1-4 2009)* 49-52

[2] M. Ferrari, V. Ferrari, M. Guizzettia, B. Andòb, S. Bagliob, C. Trigonab, Improved energy harvesting from wideband vibrations by nonlinear piezoelectric converters, *Sensors and Actuators* **A: Physical** *(2010)*

[3] Ibrahim Sari, Tuna Balkan, Haluk Kulah, An electromagnetic micro power generator for wideband environmental vibrations, *Sensors and Actuators* **A** *145–146 (2008) 405–413*

[4] K. Mori, T. Suzuki, S. Nagasawa, H. Okamoto, , and H. Kuwano, ENERGY HARVESTING USING MICRO ELECTROSTATIC GENERATOR WITH BOTH ENDS BUILD-IN H-BEAM STRUCTURE, *Technical Digest PowerMEMS 2008+ microEMS2008, Sendai, Japan, November 9-12 (2008) 273-276*

[5] D. Maurath, Y. Manoli, CMOS-INTEGRATED ADAPTIVE LOAD MATCHING INTERFACE WITH AN INTEGRATED LOAD MATCHING DETECTOR, *Technical Digest PowerMEMS 2009, Washington DC, USA, December 1-4 (2009)* 217-220

[6] S. Nagasawa, T. Suzuki, Y. Takayama, K. Tsuji, and H. Kuwano, MECHANICAL RECTIFIER FOR MICRO ELECTRIC GENERATORS, *MEMS 2008, (Tucson, Arizona, USA, January 13-17 2008)* 992-995

[7] H. Okamoto, T. Suzuki, K. Mori, and H. Kuwano, A CONSEPT OF AN ELECTRET POWER GENERATOR INTEGRATED WITH A RECTIFIER, *Technical Digest PowerMEMS 2009, (Washington DC, USA, December 1-4 2009)* 292-295

[8] Marcin Marzencki, Yasser Ammar, Skandar Basrour, Integrated power harvesting system including a MEMS generator and a power management circuit, *Sensors and Actuators* **A** *(2008)* 363-370