Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp681-682

PS-2-05

High Efficiency MOSFET Bridge Rectifier for AlN MEMS Cantilever Vibration Energy Harvester

Ryohei Takei[1], Hironao Okada[1], Daiji Noda[2], Ryo Ohta[2], Toshihiro Takeshita[1], Toshihiro Itoh[3] and Takeshi Kobayashi[1]

[1] National Institute of Advanced Industrial Science and Technology
Research Center for Ubiquitous MEMS and Micro Engineering
1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan
Phone: +81-29-861-7100 E-mail: r.takei@aist.go.jp
[2] Micromachine Center
MicroNano Open Innovation Center
67 Kandasakumagashi, Chiyoda, Tokyo 101-0026, Japan
[3] Univ. of Tokyo
Graduate School of Frontier Sciences
5-1-5 Kashiwanoha, Kashiwa, Chiba, 227-8563, Japan

Abstract

We demonstrated a high efficiency bridge rectifier circuit consisting of four pMOSFETs for an AlN MEMS cantilever energy harvester. Three types of the rectifier circuit configurations were simulated and the output was maximized for a device width. Our rectifier exhibited most efficient AC-DC conversion compared to commercial available rectifier circuits.

1. Introduction

A dramatic reduction in size and power consumption of microelectronics chips is strongly driving research and development of an autonomous power supply [1-3]. Among the various autonomous power supply technologies, a vibration energy harvester (VEH) is promising because vibrations widely exist in the environment. The environment vibration is always generated from human activities, moving cars, operating machines, and so on.

However, these vibrations are faint, thus mechanical resonance phenomenon is suitable to obtain valid electrical power. The VEH generates alternating current (AC) power. Therefore, a rectifier circuit is indispensable to supply direct current (DC) power to electronics. A high efficiency rectifier circuit together with low power electronics is a key technology because the obtainable power is very weak.

In this work, we demonstrate a high efficiency rectifier circuit consisting of four p channel metal oxide semiconductor field effect transistors (pMOSFETs) for an aluminum nitride (AlN) micro electro mechanical systems (MEMS) cantilever VEH. We derived an equivalent circuit of the VEH at the resonant frequency by measuring its output voltage dependence on a load resistance. By installing the equivalent circuit into a circuit simulator, the rectifier circuit was designed to maximize an efficiency of the rectifier. The designed rectifier was fabricated by a fab and experimentally evaluated.

2. Circuit simulation

First, we determined the equivalent circuit of the AlN MEMS VEH, which was fabricated on 8-in. silicon on insulator (SOI) wafer with 10 μm-thick Si top layer and 1 μm-thick buried oxide (BOX) layer. The fabrication procedure is described below. On the initial SOI wafer, a thermal oxide serving as an electrical isolation was formed. A piezoelectric material AlN sandwiched by Pt electrodes was deposited on the oxide using DC magnetron sputtering. The multilayer was processed to make a MEMS cantilever using a standard semiconductor MEMS process. The fabricated cantilever was mounted in a ceramic package.

An output voltage of the fabricated VEH was characterized as shown in Fig. 1. A harmonic vibration with a peak acceleration of 1.5 m/s^2 was applied to the VEH at a frequency of 98.8 Hz which is around a resonant frequency. The output voltage was measured using an oscilloscope with changing a load resistance. The VEH is electrically represented by a combination of an ideal current source, a capacity, and a resistance as shown in the inset of Fig. 1. The dash line shows a fitting curve of the output voltage where I_p=3.1μA, C_p=0.66nF, and R_i=4.1MΩ.

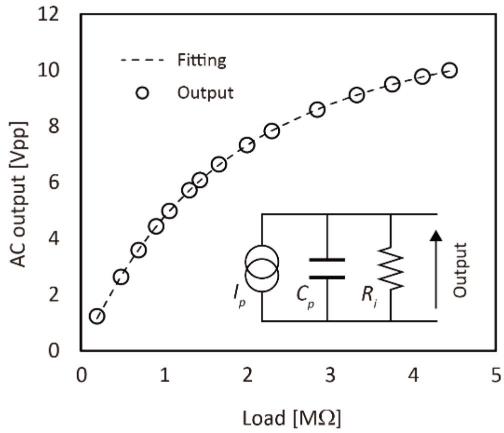

Fig. 1 AC output voltage of the fabricated AlN MEMS cantilever VEH as a function of a load resistance.

Next, we simulated three types of rectifier circuits. The pn junction diode bridge as shown in Fig. 2(a) is a typical rectifier. On the other hand, the bridge rectifiers shown in Fig. 2(b) and (c) consist of four pMOSFETs. The MOSFET rectifier can be enhance the rectifier efficiency because a threshold of a MOSFET can be reduced to less than that of a pn junction diode. In addition, an applied voltage to the gate in pMOSFET bridge 2 is higher than that in pMOSFET bridge 1, resulting in a low leak current.

For the simulation, a 1 μF storage capacitor was connected at the output of the rectifier and a 1 μA current load was also connected in parallel of the smoothing capacitor. The Silterra's 0.18 μm high voltage technology is selected for fabrication of the rectifier circuit chip, Figure 3 shows the calculated DC output voltage for each rectifier with changing a device width where I_p=3μA, C_p=1nF, and R_i=4MΩ, indicating that the pMOSFET bridge 2 is more efficient than pn the junction diode bridge and the pMOSFET bridge 1. The output voltage is saturated above a device width of 1500 μm (for MOSFET, a device width corresponds to a gate width).

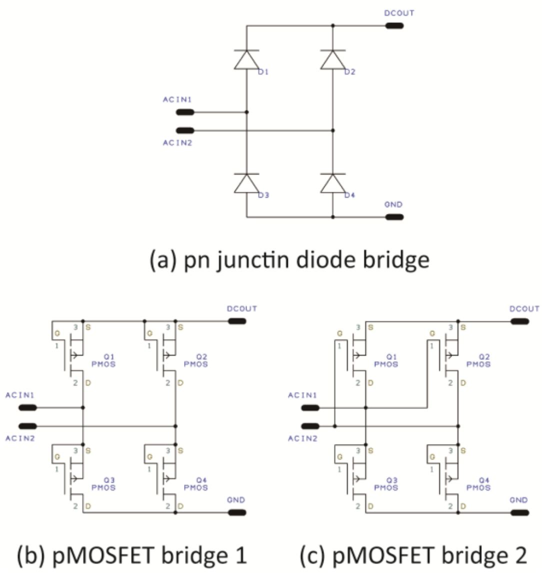

Fig. 2 Three types of rectifier circuit diagrams.

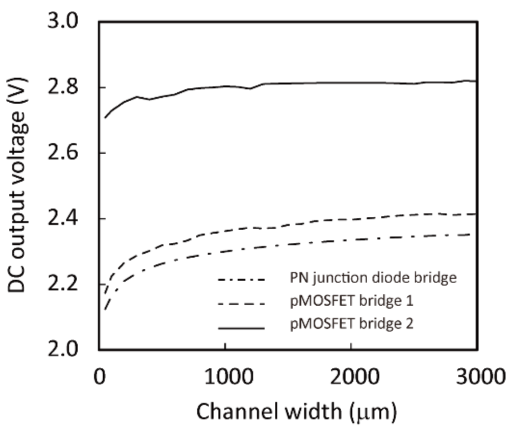

Fig. 3. Simulated DC output voltage as a function of a device width.

3. Measurement and Results

We fabricated the pMOSFET bridge 2 by a commercial available foundry (Silterra, Malaysia) by the 0.18 μm high voltage technology. The DC output voltage was measured with a setup depicted in Fig. 4. The smoothing capacitor has a capacitance of 100 nF, and the digital multi meter (DMM) was set to be in a high impedance mode (>10 GΩ), meaning that an open output voltage was measured. A vibration with a peak acceleration of 0.5 m/s^2 was input to the AlN MEMS cantilever VEH at a frequency of 46.6 Hz. The device geometry of the VEH in this measurement is different from that of the VEH used in the circuit simulation. Table I shows the measured DC voltage with various rectifier circuits. LTC3588 is a commercial available power management IC for piezoelectric energy harvesters manufactured by Linear Technology. A bridge rectifier circuit is integrated in LTC3588. SSM3K116TU is a discreet n channel MOSFET for power electronics application manufactured from Toshiba. Four SSM3K116TUs configure a bridge rectifier similar to pMOSFET bridge 2 as shown in Fig. 3(c). The measured open DC voltages are summarized in Table I, showing that our rectifier has a highest DC output voltage compared to other rectifier.

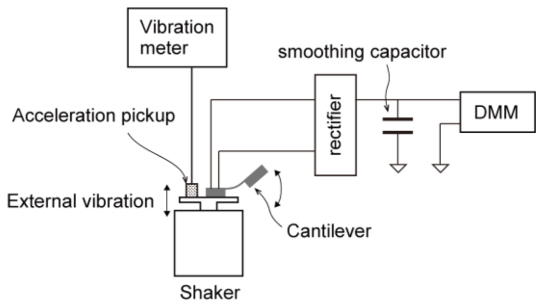

Fig. 4. Measurement setup.

Table I DC output voltage

Rectifier	DC output (V)
This work	3.01
LTC3588	1.25
SSM3K116TU	2.72

4. Conclusion

In this work, we demonstrated a high efficiency rectifier for AlN MEMS cantilever VEH. Since our rectifier is promising for autonomous operating wireless sensor network module, we believe that it helps to realize sustainable and safe society.

Acknowledgements

This work is partly supported by New Energy and Industrial Technology Development Organization (NEDO).

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