

Characteristics of Thermoelectric and Vibrational Devices for Integrated MEMS Power Generator

Norio Sato, Hiromu Ishii, Kei Kuwabara, Tomomi Sakata, Jun Terada, Hiorki Morimura,
Kazuhisa Kudou*, Toshikazu Kamei*, Masaki Yano* and Katsuyuki Machida

NTT Microsystem Integration Laboratories, NTT Corporation
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0198, Japan
Tel +81-46-240-2284, Fax +81-46-240-4321, E-mail nsato@aecl.ntt.co.jp
*NTT Advanced Technology Corporation
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0198, Japan

Abstract

This paper describes a novel concept of a MEMS power generator where thermoelectric and vibrational devices are monolithically integrated. The characteristics of the thermoelectric and vibrational devices were clarified by measurement systems. The thermoelectric devices showed that a series of thermocouples outputs a voltage correlating with temperature difference. By applying a driving voltage, the movable plates in the vibrational devices were ascertained to move. Moreover, the vibrational devices were demonstrated to vibrate in resonance with external vibrations. These results confirmed that the devices actually harvest the thermal and vibrational energy in their surroundings.

Keywords: energy harvesting, thermoelectricity, vibration, integration

1 INTRODUCTION

Energy harvesting is a promising technology for a ubiquitously sensor-networked society. A large number of small electric appliances are needed as sensor nodes. Accordingly, the size of power sources should also get smaller. It is preferable that the maintenance and reimbursement of energy source are reduced. In order to meet these requirements, various ways of converting environmental and human energy have been investigated, such as thermal, vibrational, and kinetic energy

conversions [1-6]. However, they are based on a single-type of energy conversion, which leads to small amount of power and limits applicability for various environmental and human situations. Some prototypes are rather large and require further miniaturization by MEMS fabrication process. There are few reports that demonstrate successful extraction of electrical signals and energy from movable MEMS structures. Materials used in the power generators should also have low environmental loads, considering that a large number of power generators in these electric appliances may be distributed over a wide area.

2 CONCEPT

We propose to integrate different kinds of energy conversion techniques monolithically on a Si substrate using MEMS technology. Different kinds of devices have different electrical characteristics. By combining the advantages of these devices, we can fully utilize the harvested energy with high efficiency and suitability to various surrounding environments. MEMS technology also contributes to a reduction in their size. Figure 1 shows an integrated power generator with thermoelectric and vibrational devices. In order to integrate these two types of devices, a capacitive type of vibrational device is selected rather than a piezoelectric type, because the latter requires special materials and complicated fabrication processes for integration. The thermoelectric device as a power supply and vibrational device as a variable capacitor can generate and boost an electrical voltage with appropriate switching.

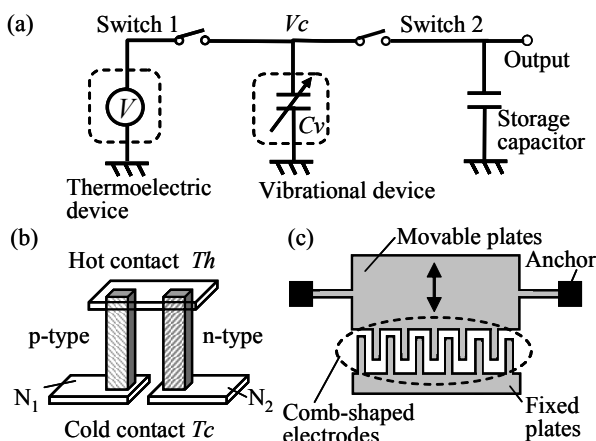


Fig. 1. (a) Power generator with integrated (b) thermoelectric and (c) vibrational devices. A unit of thermoelectric device as shown in (b) produces a voltage proportional to the temperature difference ($T_h - T_c$) between nodes N_1 and N_2 . In the vibrational device shown in (c), external vibrational force varies the capacitance between the movable and fixed plates, which induces charge transfer.

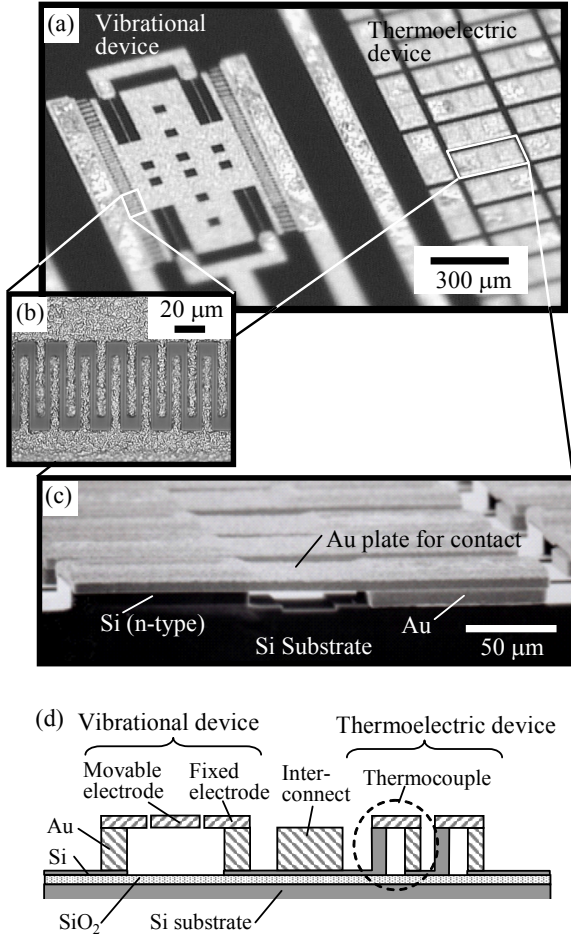


Fig. 2. (a) Optical-microscope image of the integrated power generator, (b) magnified image of the comb-shaped electrodes of the vibrational device, (c) magnified SEM image of the thermoelectric device, and (d) schematic view of a cross-section of the integrated device.

The purpose of this study is to prove that the monolithically-integrated MEMS power generator converts thermal and vibrational energies into electrical energy; the thermoelectric devices produce an output voltage from thermal energy and the vibrational devices produce current due to their movement in resonance with external vibration.

3 INTEGRATED MEMS POWER GENERATOR

The concept was realized as the monolithically integrated device shown in Fig. 2, based on seamless integration technology [7]. The details of the fabrication process are described in our previous paper [8]. The vibrational device on the left in Fig. 2(a) has comb-shaped movable electrodes made of gold (Fig. 2(b)). The high density and low Young's modulus of gold enable a low resonant frequency, on the order of 1 kHz. The thermoelectric devices on the right in Fig. 2(a) and Fig. 2(c) are composed of thermocouples of gold and highly doped n-type silicon. These materials have low environmental loads. The fabrication process with gold electroplating and deep RIE of a SOI layer 15 μm thick achieved the integration of the thick structures as shown in Fig. 2(d).

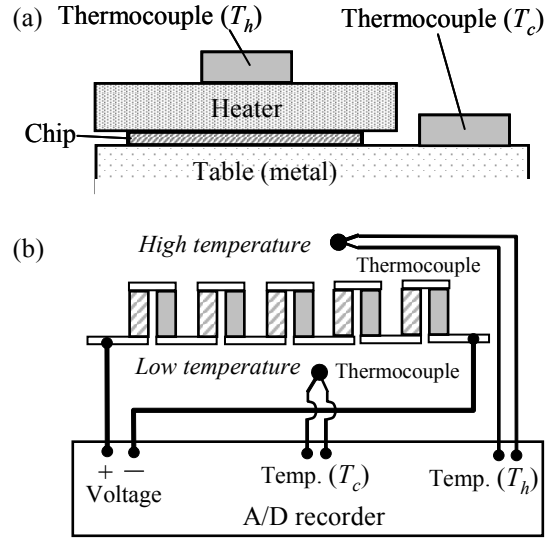


Fig. 3. (a) Schematic view and (b) block diagram of the measurement setup for the thermoelectric devices.

4 EXPERIMENTAL

We used a heater and commercial thermocouples for the evaluation of the thermoelectric devices. The measured temperatures with the thermocouples and the output voltage from the fabricated thermoelectric devices were simultaneously obtained by an analog-to-digital recorder.

Unlike the thermoelectric devices, the vibrational devices have movable plates. First, it should be checked whether the fabricated vibrational devices are movable or not. Next, the vibrational devices should be vibrated by external vibration. Thus, in the measurements of the vibrational devices, we selected two driving method: electrostatic force and external vibration. In order to drive the movable plates, a high ac/dc voltage source from 0 to 150V was used. The movement was observed by an optical microscope and quantified by an impedance analyzer that measured capacitance change. For external vibration, we used a shaker and a lock-in-amplifier to detect small electrical signals.

5 EVALUATION

5.1 Thermoelectric Device

In the measurement setup, the surface of the fabricated chip was heated with a heater (Fig. 3(a)). The back of the chip was cooled on a metal table with sufficient heat capacity. An analog-to-digital recorder measured the output voltage and temperatures at the surface and back of the chip simultaneously as shown in Fig. 3(b). The output voltage V due to thermoelectricity is expressed as

$$V = \alpha(T_h - T_c), \quad (1)$$

where α is the Seebeck coefficient, T_h is the temperature at the hot contacts, and T_c is the temperature at the cold contacts. The correlation of the output voltage and temperature difference was examined in order to ascertain the thermoelectric effect.

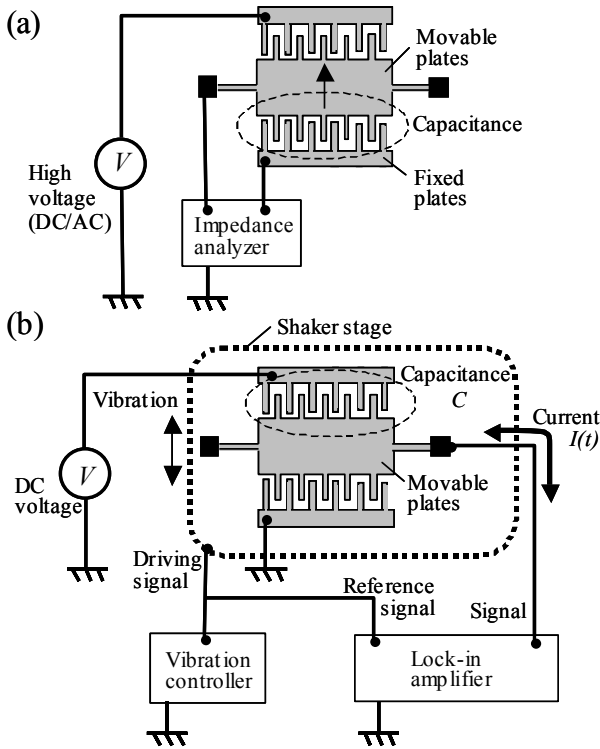


Fig. 4. Schematic views of the measurement setups for the vibrational devices in order to (a) measure the capacitance change by electrostatic force and (b) obtain the frequency characteristics under external vibration.

5.2 Vibrational Device

Figure 4(a) shows the measurement setup used to move the movable plates by electrostatic force. A positive sinusoidal ac voltage with an offset bias was applied to one of the fixed plates. The displacement of the movable plates was observed with an optical microscope. By sweeping the frequency of the ac voltage, the resonant frequency where the displacement reaches a maximum value can be obtained. In addition, in order to quantify the movement, the capacitance between the movable plates and the other fixed plate was measured with an impedance analyzer.

In the setup in Fig. 4(b), the movable plates were driven by external vibration instead of electrostatic force. External vibration is applied to the devices in a direction parallel to the fingers of the comb-shaped electrodes with a vibration controller. Electric charges are induced at capacitance C between the fixed and movable plates with a dc voltage V . When the movable plate vibrates according to the external frequency f , the amount of electric charges Q changes, which causes an ac current I with a specific frequency. The current is expressed as,

$$I(t) = dQ/dt = d(CV)/dt = V \cdot dC/dt. \quad (2)$$

Capacitance C is a function of the displacement x of the movable plates. The displacement x is assumed to be a

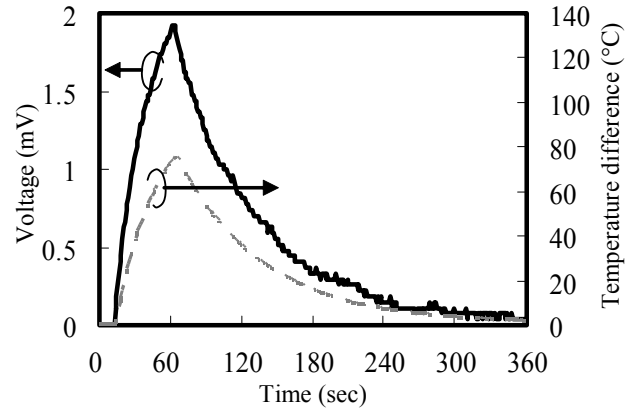


Fig. 5. Relationship between the output voltage of the thermoelectric device and the temperature difference when heated up and cooled down.

$\cos(2\pi ft)$, where a is an amplitude of the displacement and t is time. Thus, the current can be expressed as,

$$I(t) = V \cdot dC/dt = V \cdot (\partial C/\partial x)(\partial x/\partial t) \propto V \cdot f \cdot \sin(2\pi ft), \quad (3)$$

where $\partial C/\partial x$ can be approximated as a constant with a small amplitude for comb-shaped electrodes. A lock-in-amplifier can extract a small amplitude of the current $I(t)$ at the frequency f common to the stage-driving signal. This clarifies whether the devices are movable by external vibration as well as by electrostatic force. By sweeping the frequency of the driving signal, the relationships between the frequency and current can be obtained.

6 RESULTS

6.1 Characteristics of Thermoelectric Device

The measured thermoelectric device has a series of 127 thermocouples of Au and Si. The heater was switched on, and then off. Corresponding to the switching, the temperature difference and open voltage output increased and then decreased as shown in Fig. 5. The two curves had a good correlation, which means the measured

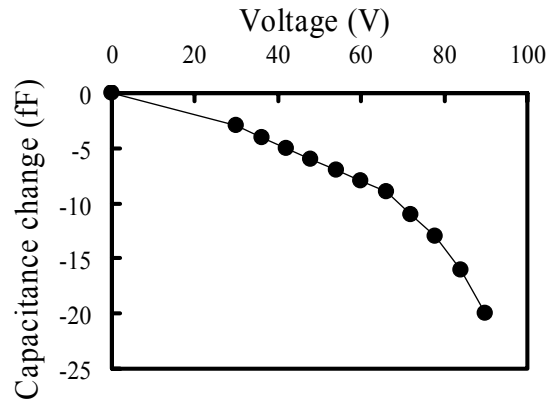


Fig. 6. Relationship between the capacitance change and the applied dc voltage of the vibrational devices.

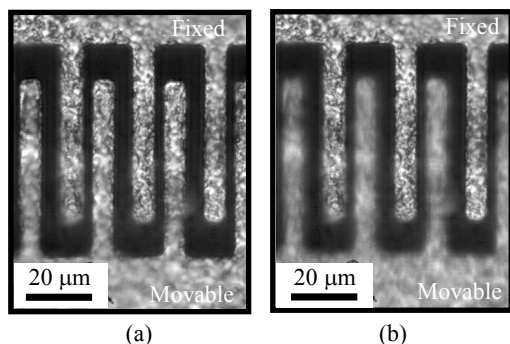


Fig. 7. Optical-microscope photographs of comb-shaped electrodes (a) without and (b) with an applied ac voltage (frequency = 2.2kHz, amplitude = 0 ~ 78V).

voltage originated from the intrinsic effect of thermoelectricity described in Equation (1). The maximum output voltage was about 2mV, and the Seebeck coefficient was calculated to be $0.2\mu\text{V/K}$. It is considered that the low value of the Seebeck coefficient compared to that in the literature [9] was caused by thermal loss in the thick substrate and over-estimation of the temperature difference due to the position of the commercial thermocouples. Optimization of the thermal structure of the substrate and measurement system can enhance the coefficient.

6.2 Characteristics of Vibrational Device

First, we applied a dc voltage to the vibrational devices. The plates were movable and the displacement increased as the applied voltage increased. The capacitance change due to the displacement was measured as shown in Fig. 6. The decrease of the capacitance shows that the device is movable, and therefore, has a variable capacitance.

Second, we applied an ac voltage with a sinusoidal wave to one of the fixed plates and observed its movement. Figures 7(a) and (b) show the images without and with the applied voltage, respectively. The ac voltage had a peak-to-peak amplitude of 0 to 78 V. The maximum displacement occurred at a frequency of 2.2kHz, which is seen as the blurry image of the movable plates in Fig. 7(b).

Third, a shaker was used to apply an external vibration with a sinusoidal wave to drive the devices. The acceleration was 80m/s^2 . When the bias voltage V was 9V, the output signal showed a peak about 2.3kHz. This is in good agreement of the measurement result in Fig. 7. Moreover, the output signal with a zero bias voltage is also shown in the graph. As explained above in Equation (3), the induced current is zero when V equals zero. The difference with and without the bias voltage V proved that the peak at 2.3kHz was not caused by parasitic capacitance or noise but originated from the vibration of the movable plates. It can be concluded that the vibrational device actually vibrates by due to external vibration and functions as a variable capacitor that generates an ac current.

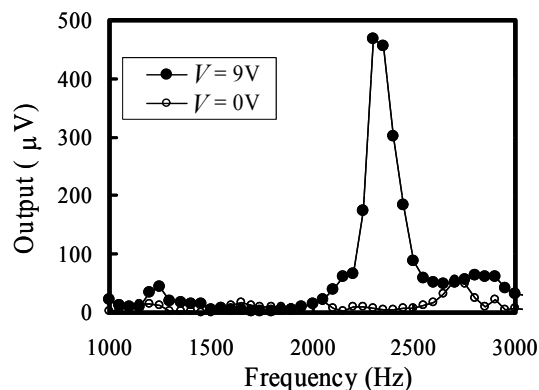


Fig. 8. Frequency characteristics of output signal with and without bias voltage V .

7. SUMMARY

We have proposed and fabricated a power generator with integrated thermoelectric and vibrational devices. Measurement systems for the thermoelectric and vibrational devices were devised. The obtained characteristics confirmed that the thermoelectric devices output voltage based on the thermoelectric effect. It was also clarified that the vibrational devices vibrate at low frequency and work as variable capacitors under the influence of external vibration. These devices convert thermal and vibrational energy into electrical energy.

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