Bimorph vibration energy harvester with flexible 3D mesh structure

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Abstract. In this paper, we propose a piezoelectric bimorph vibration energy harvester (VEH) with flexible 3D mesh elastic layer for the purpose of improving output power and lowering resonance frequency. Due to the high void ratio of the 3D mesh structure, it is possible to lower the bending stiffness of the cantilever. So, the deflection of the harvester and the strain in the piezoelectric layer increase. As a result of a vibration test, the resonance frequency is 26% lower and the output power is 1.5 times higher than the conventional solid flat plate VEH. Compared with the flat plate VEH, the proposed mesh VEH has 1.3 times larger tip deflection and the total output power is 20.4 μW that is possible to use as a power supply of low-power consumption sensor nodes for WSNs.

1. Introduction
Recently, self-powered sensor nodes for wireless sensor networks (WSNs) has been developed using VEH [1]. Vibration energy harvesting is classified as electromagnetic, electrostatic, triboelectric, and piezoelectric. Among the four types of harvesting methods, piezoelectric VEH has attracted much attention because of the higher energy density, the simplicity of configuration, and the compatibility with the MEMS technology [2,3]. In the piezoelectric VEH, a large variety of cantilever beams with an elastic layer and one or two piezoelectric layers have been presented [4-6].

A bimorph configuration has two piezoelectric layers, so it has a potential to achieve large electric power. However, the smaller the size of the cantilever-type VEH becomes, the more difficult it is to lower resonance frequency and to achieve large electric power that is enough for sensor node battery. Here, in this study, we propose a bimorph VEH with a flexible 3D mesh structure in order to control bending stiffness: to lower resonance frequency and to achieve large electric power simultaneously.

2. Design of bimorph VEH with 3D mesh structure

2.1. Configuration of VEH
The proposed vibration energy harvester is designed as bimorph configuration. Figure 1 shows a schematic of the proposed bimorph cantilever composed of an elastic layer having a flexible 3D mesh structure and piezoelectric layers on both sides. The dimensions of the proposed VEH are shown in table 1. In the bimorph configuration, the neutral axis is located at the center of the elastic layer. Since the strain of the piezoelectric layer is proportional to the distance from the neutral axis, increasing the distance causes large strain under identical cantilever deflection. On the other hand, when the thickness
of elastic layer increases, the deflection and the strain are reduced because the bending stiffness is increased. Moreover, the resonance frequency increases. Regarding these demerits, we aim to design and fabricate a flexible VEH to achieve large strain and low resonance frequency simultaneously. Therefore, in this study, we propose a method to reduce bending stiffness while increasing the film thickness of the elastic layer by applying a 3D mesh structure with voids as the elastic layer and evaluate the validity of the structure.

2.2. **FEM structural analysis of VEH**

Figure 2 represents the effect on the bending stiffness of the 3D mesh structure. The horizontal axis of the graph is the line spacing of the mesh structure in figure 1, and the vertical axis represents the ratio of the bending stiffness of mesh VEH to the flat plate VEH. The normalized bending stiffness is defined by dividing bending stiffness of a mesh harvester by that of a flat plate VEH. The FEM analytical model is made by using COMSOL Multiphysics 5.2a, and the result is calculated from the ratio of tip displacement when the static load is applied to the tip of a cantilever. The bending stiffness decreases with the increase of line spacing of mesh structure. From this result, it is found that the bending stiffness can be controlled and lowered without changing the device size, configuration, and basic fabrication process by adopting the mesh structure to the elastic layer of the bimorph VEH.

![Figure 1. Schematic of a proposed VEH with 3D mesh structure (10mm×21mm×280μm). The device consists of two PVDF piezoelectric layers bonded on both sides of a 3D mesh elastic layer and a proof mass at the tip. A sum of line spacing and line length is 100 μm.](image)

### Table 1. Dimensions of the proposed VEH

| Width | 10 mm |
|------|-------|
| length | 21 mm |
| Thickness: t_p | 40 μm |
| Thickness: t_e | 200 μm |
| Young’s modulus: Y_p | 0.95 GPa |
| Young’s modulus: Y_e | 3.25 GPa |
| Piezoelectric constant d_{31} | 22 pC/N |
| Piezoelectric constant d_{33} | 35 pC/N |
| Proof mass | 1.0 g |

![Figure 2. Normalized bending stiffness as a function of line spacing of mesh structure analyzed by FEM. The normalized bending stiffness is calculated by dividing bending stiffness of a harvester with the mesh elastic layer by that of a harvester with a solid flat plate elastic layer.](image)
3. Experiments

3.1. Fabrication of VEH with 3D mesh structure

The proposed VEH is fabricated by inclined photolithography [7] and bonding of piezoelectric PVDF sheet (KF piezo film: Kureha Corporation) and elastic SU-8 layer (Nihon Kayaku: SU-8 3005). Inclined photolithography is one of the fabrication technique to fabricate 3D microstructure by exposing UV light from the oblique direction for photoresist on a substrate. Here, the mesh structure is fabricated by inclined exposure twice from different oblique directions. The fabrication process of the 3D mesh structure is shown in figure 3. SEM images of the fabricated mesh structure using the inclined photolithography are shown in figure 4. In this paper, we fabricated the VEH prototype with a 3D mesh structure, which is designed as the line length and the line spacing of the mesh structure are both 50 μm.

3.2. Vibration Test

We evaluated the power generation performance by vibration test, and compared the proposed mesh type VEH with the device having a flat plate structure of the same size and thickness in the elastic layer. Experimental setup for vibration test is shown in figure 5. A load resistance of 10 MΩ is connected to the VEH, and the amount of output power is calculated from the measured output voltage and load resistance under oscillation. The acceleration monitored by an acceleration sensor becomes constant as 4.9 m/s².

4. Results and Discussion

The frequency response is shown in figure 6. In the mesh type VEH, the output power is 1.5 times higher than the flat plate one and resonance frequency is reduced by 26% at the same time. Since the bending stiffness decreases due to the mesh structure, the deflection of the bimorph cantilever increases and the amount of strain of the piezoelectric film also increases. Thus, the output power increases because of
the large strain in piezoelectric layer. In addition, figure 7 shows the output voltage waveform during the sinusoidal oscillation. In both the mesh and the flat types, we observed that sinusoidal output is synchronized with the oscillation frequency. As shown in Table 2, the output voltage of mesh type VEH is 1.3 times higher than that of the flat type one. Therefore, from the results of vibration test, mesh structure shows the validity for the elastic layer for bimorph VEH.

![Figure 6](image1.png)  
**Figure 6.** Frequency response of output power. In the proposed mesh VEH, the resonance frequency is lowered by 26% and the output power is increased by 1.5 times compared with the flat plate VEH.

![Figure 7](image2.png)  
**Figure 7.** Time response of output voltage of the proposed mesh and the flat plate VEHs under each resonant condition. Voltage amplitude generated by the mesh VEH is 1.3 times higher than one of the flat plate VEH.

| Resonant frequency [Hz] | Total electric power [µW] | Tip displacement [mm] |
|-------------------------|---------------------------|-----------------------|
| Mesh                    | 20.1                      | 20.4                  |
| Flat                    | 27.4                      | 13.3                  |

5. Conclusion
In this study, we confirmed the validity of the bimorph VEH with 3D mesh structure as an elastic layer. First, we showed that the bending stiffness of the mesh harvester can be controlled by changing mesh line spacing. Second, as a result of the vibration test, the resonance frequency of mesh harvester is 26% lowered and the tip deflection is 1.3 times larger compared with the flat plate VEH. Finally, the total output power is 20.4 µW that is possible to use as a power supply of low-power consumption sensor nodes for WSNs.

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