Influences of Fe-Ga Alloy Crystallinity for the Application to a Magnetostrictive Vibration Energy Harvester

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Abstract. An isotropic poly-crystalline Fe-Ga alloy was fabricated using a short-time process and its performance as a magnetostrictive vibration energy harvester was evaluated. Grain enlargement due to recrystallization was observed by annealing treatment exceeding 1100 °C, but no contribution to physical properties and power generation performance was observed. It was confirmed that the magnetostrictive vibration energy harvester using poly-crystal functioned and an output of 1.1 mW was obtained under the vibration condition of a resonance frequency of 106 Hz and acceleration of 0.8 G. This is an output of 28% compared with the case of using a single crystal. In a trial calculation, poly-crystalline Fe-Ga alloy can be fabricated at a cost of 1/6 of a single crystal, so potential for using poly-crystal is expected in applications not requiring high output.

1. Introduction

With the recent great development of IoT (Internet of things) technology, magnetostrictive vibration energy harvester that generates electricity from vibration using Fe-Ga alloy are attracting attention as an independent power source of wireless sensor nodes that monitors the condition of infrastructure and factory equipment [1]. The magnetostrictive vibration energy harvester has advantages, including a high power output, high efficiency and effective environmental endurance [2]. However, since Fe-Ga alloy is conventionally manufactured by a single crystal fabrication technique such as Bridgman method [3] or the Czochralski method [4], there is concern at the high cost of the single crystallization process and the material price.

This time, we fabricated a magnetostrictive vibration energy harvester using a poly-crystalline Fe-Ga alloy, omitting the costly single crystallization process and compared its performance with a device using a single crystal material.

2. Experimental procedure

Poly-crystalline Fe-Ga alloys were prepared by weighing Fe (99.99%) and Ga (99.9%) so as to be Fe-20 at. % Ga and melting it in an alumina crucible using a high-frequency induction heater furnace under a Ar+H₂ atmosphere. The mixture was heated to melting point or higher (about 1600 °C) in 10 minutes, maintained at that temperature for 10 minutes and cooled for 10 minutes, whereupon heating was stopped. The prepared material is shown in Figure 1. Although bubbles were observed on the surface, a poly-crystalline Fe-Ga alloy with a homogeneous metallic color could be obtained. The
obtained materials were then annealed 24 hours under an Ar atmosphere to consider the annealing effects on crystal quality. The annealing temperatures were 900, 1100 and 1300 °C.

The crystal grain and orientation were observed using electron backscatter diffraction (EBSD), while the saturation magnetostriction was evaluated using the strain-gauge method and search coils were wound over the samples to investigate the magnetization characteristics. After measuring the physical properties, the Fe-Ga alloys were cut to dimensions of 0.5x4x13 mm and incorporated into the mass production type magnetostrictive vibration energy harvester [5] to confirm their performance as energy harvesters. The appearance of the vibration energy harvester is shown in Figure 2.

3. Results and discussion

3.1. Physical property investigations

The synthesized Fe-Ga alloys were poly-crystal, with crystal grains of several hundred μm in size. Without any orientation in a specific direction, they became isotropic poly-crystals in macroscopic terms. Moreover, the annealed sample showed no change in crystal grain at 900 °C. However, at 1100 and 1300 °C, the size of the crystal grains grew to several mm due to recrystallization (Figure 3). As a result, only a few grains are contained in the material size used for the vibration energy harvester.
The measured magnetostriction constants ($\lambda_{3/2}$) are listed in Table 1. The all poly-crystalline Fe-Ga alloys shows magnetostriction constants of several tens of ppm. No improvement in magnetostriction due to annealing was observed. Although the crystal grain size was increased by annealing, they are still considered isotropic poly-crystals.

### Table 1. Magnetostriction constant for Fe-Ga poly-crystals.

| Sample                  | $\lambda_{3/2}$ (ppm) |
|-------------------------|----------------------|
| Non-annealed            | 75                   |
| Annealed at 900 °C      | 63                   |
| Annealed at 1100 °C     | 58                   |
| Annealed at 1300 °C     | 14                   |
| (Reference)             | 200-300              |
| Single crystal <100>    |                      |

![Figure 4. Magnetization characteristic curve of Fe-Ga alloys.](image)

The saturation magnetization is about 1.5 T, which is comparable to that of the single crystal and the difference between poly- and single crystals is the curved form in the near-zero magnetic field, as shown in Figure 4. No influence of the annealing temperature was seen in the magnetization characteristics.

#### 3.2. Vibration energy harvester performance evaluation

Figure 5 shows the time-resolved waveform of open-circuit voltage for the magnetostrictive vibration energy harvester made using the poly-crystalline Fe-Ga alloy; excited by a sinusoidal wave with a resonance frequency of 106 Hz and vibration acceleration of 0.8 G. It was shown for the first time that even an isotropic poly-crystalline Fe-Ga alloy functions as a vibration energy harvester. The peak voltage of devices using the poly-crystal was 1.5 V, but devices using non-annealed and annealed materials showed no significant differences.
Figure 6 is the time-resolved waveform connected to a load resistance of 510Ω. For comparison, the waveform of the energy harvester using a single crystal material is also shown. The generated power was calculated using peak voltage and load resistance, i.e. $V^2/R$, with generated power of 1.1 mW for a device using poly-crystal and 4.0 mW for a single crystal respectively. The generated power constituted about 28% of a single crystal, but output exceeding 1 mW could be achieved. This output was sufficient to transmit simple data such as a temperature sensor wirelessly, so for applications with low power consumption, there is expected to be scope to apply devices using poly-crystalline Fe-Ga alloy sufficiently as vibration energy harvesters.

3.3. Material cost estimation

Despite the raw material cost of Fe-Ga alloy, around $1/g, the Fe-Ga alloy single crystal currently costs more than $11/g, because the single crystallization process is expensive. Growth of a single crystal usually requires about one week to crystallize large material slowly. Conversely, the poly-crystalline preparation process for this work is only 30 minutes and a process of more than 20 times per week is possible, even including preparatory steps before and after. In other words, it is considered possible to reduce the process cost by 1/20. In this way, material costs including raw material costs can be reduced to 1/6 as seen in Figure 7. It should be noted that power generation performance of 28% (1/4 or more) was obtained at a material cost of 1/6 as compared with single crystals. For applications not requiring a large output, there is scope to use poly-crystalline Fe-Ga alloy.

![Figure 7. Price breakdown of magnetostrictive materials.](image)

4. Conclusion

In this work, an isotropic poly-crystalline Fe-Ga alloy was fabricated and evaluated as a magnetostrictive vibration energy harvester and during the annealing treatment, although crystal grain expansion due to recrystallization was observed at more than 1100 °C, no contribution to physical properties and power generation performance was observed. The magnetostrictive vibration energy harvester using poly-crystal could obtain an output of 1.1 mW although it was output of 28% of single crystal. Poly-crystalline Fe-Ga alloy is expected to have potential for use in applications not requiring high output.

References

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