MAGNETOCALORIC COOLING OF A THERMALLY-ISOLATED MICROSTRUCTURE

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Abstract: A solid-state micro magnetic refrigerator (SSMMR) has some advantages to cool micro devices because of its high efficiency and simple structure. In this study, we demonstrated the actual cooling of a thermally isolated microstructure, which is main component of the SSMMR, by magnetocaloric effect. The thermal isolation structure is composed of parylene high-aspect-ratio beams for both high thermal isolation and high stiffness. A magnetic field switch was designed and fabricated to control the magnetic flux density from 0 T to ca. 1 T. Under this magnetic flux density change, the maximum temperature change of 1.2 °C was confirmed.

Keywords: Magnetocaloric cooling, thermal isolation, magnetic field switch, magnetic refrigerator

INTRODUCTION

The temperature control of THz sensors, quantum devices etc. is important to reduce thermal noise. A solid-state micro magnetic refrigerator (SSMMR) is useful for microscale temperature control because of its simple structure and high efficiency. The cooling cycle is based on magnetocaloric effect, i.e. the thermal state change of a magnetic material such as La(Fe,Si1-x)Hx by external magnetic field [1]. This material has near room temperature Curie temperature (Tc), and thus the cooling cycle can work near room temperature. In this work, we demonstrated that the temperature of a thermally-isolated microstructure was raised and reduced by magnetocaloric effect.

THERMAL ISOLATION STRUCTURE

Figure 1 shows the principle of the SSMMR. The relation between entropy, S, and temperature, T, of the magnetic material is illustrated in Fig. 1(a). The phase change temperature, Tc, between ferromagnetic and paramagnetic phase can be controlled by an external magnetic field (B_OFF and B_ON). Figure 1(b) shows the cooling cycle, which consists of two isothermal processes and two adiabatic processes. The SSMMR is composed of thermally isolated magnetic material, magnetic field switch and thermal switches [2-5], as shown in Fig. 1(c). Each thermal switch changes thermal conductivity between the magnetic material and the cold or hot section. The adiabatic process is performed when all thermal switches are in OFF state (Fig. 1(c)), whereas isothermal process is performed when only one of the thermal switches is in ON state (Fig. 1(d)).

In this study, we demonstrated the magnetocalorical heating and cooling of the magnetic material, which was supported by a thermal isolation micro structure. Figure 2 shows the structure of a test device. For the SSMMR, the magnetic material must be supported by a thermal isolation structure, because the magnetic cooling cycle needs adiabatic process. In
addition, the structure should be stiff enough to resist magnetic force and contact force of the thermal switches. For these requirements, the magnetic material is glued on a silicon microstage, which is supported by the high aspect ratio parylene beams [2, 4]. The parylene beams are fabricated by a silicon lost mold process [2, 4, 6]. The fabricated test device is shown in Fig. 3.

**MAGNETIC FIELD SWITCHING**

Magnetic field is switched by rotating permanent magnets as shown in Fig. 4. In ON state, magnetic flux flows through the yoke, and a high magnetic field is applied to the measurement section. In OFF state, the magnetic flux flows across the yoke, and the magnetic field disappears at the measurement section.

Figure 5 shows the structure of the magnetic field switch. Two neodymium permanent magnets are actuated by electromagnetic actuators underneath them. The yoke is made of silicon steel. The magnetic field switch was designed using finite element method (FEM). 3D edge elements were used to create the calculation model [7]. Figure 6 shows the FEM results, where arrows show the magnetic flux density. The results show that the magnetic field switch successfully controls the magnetic field. The maximum and minimum magnetic flux density are 0.90 T and 0.00 T, respectively.

Magnetic flux density was measured using a hall element (HG302C, Asahi Kasei Microdevices). Figure 7 shows the relationship between the rotational angle of the permanent magnet and magnetic flux density. The rotational angle, $\theta$, is defined as $0^\circ$ when the switch is just in ON state. Magnetic flux density changes as a cosine function of $\theta$. The negative magnetic flux density means the flux in the opposite direction, but only the absolute magnitude of the magnetic flux density is important for the magnetocaloric effect. The measured maximum and minimum absolute magnetic flux density are ca. 0.97 T at $\theta = 0^\circ$ and 0 T at $\theta = 90^\circ$, respectively, which are consistent with FEM-predicted values.

**EXPERIMENTAL METHOD**

Figure 8 shows the experimental setup. The test device is placed on a device stage, and aligned as the magnetic material is subjected to the switched magnetic field. The temperature of the device stage is controlled, because the magnetic material has the optimum operation temperature [1]. Two Peltier
devices are used for the temperature control; one of them roughly cools the whole magnetic field switch, and the other precisely controls the temperature of the device. The magnetic field switch is placed in a vacuum chamber to reduce heat loss. The heat generated by the Peltier devices conducts to the chamber wall, and then the outer surface of the chamber is cooled by forced convection. The temperature of the magnetic material is measured by an infrared (IR) camera (TVS-8500, Nippon Avionics Co., Ltd.) through a CaF₂ window. Alumina-filled paste is placed on the silicon microstage to make the emissivity of IR region close to 1 for accurate temperature measurement.

EXPERIMENTAL RESULT

Figure 9 shows the temperature response of the microstage, where the magnetic field turned to ON and OFF at time $t = 5.5$ s and $t = 0$ s, respectively. When the operation temperature is higher than ca. 11 °C, the temperature is not changed by the magnetic field (Fig. 9(a)). On the other hand, the temperature is changed by the magnetic field when the temperature of the
The microstage is ca. 11 °C (Fig. 9(b)). This suggests that the \( T_C \) of the magnetic material is ca. 11 °C. The measured maximum temperature change is ca. 1.2 °C, which is roughly consistent with an estimated value [1]. These results demonstrate that the microstructure is actually heated and cooled by magnetocaloric effect. This cooling method can be applied to the SSMMR in combination with the thermal switches which we previously reported [2].

The \( T_C \) of the material can be changed by modifying the hydrogen content of the \( \text{La(Fe}_{1-x}\text{Si}_{1-x})_3 \) compounds [1]. Therefore, we can select appropriate operation temperature depending on applications. In addition, the series connection of multiple SSMMRs with different operation temperature will offer larger temperature change.

**CONCLUSION**

We designed and fabricated thermally isolated micro structure with magnetic material and magnetic field switch applicable for SSMMR. The microstructure was successfully heated and cooled by magnetocaloric effect. The obtained temperature change was ca. 1.2 °C under the magnetic flux density change as high as 1 T. This technique is essential to realize SSMMR.

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**REFERENCES**


