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論文内容要旨

A small size and high efficiency refrigerator is important for microdevices such as infrared detectors and quantum devices. These devices need low temperature to reduce thermal noise. There are a lot of types of micro refrigeration devices such as a Joule-Thomson refrigerator, a Stirling refrigerator, a Peltier refrigerator and so on. Both high efficiency and simple structure are preferred for a micro device application. From these points of view, fluid devices such as the Joule-Thomson refrigerator has difficulty for miniaturization because of their complex structure. On the other hand, the efficiency of the Peltier refrigerator is not so high. We focused on a solid state magnetic refrigerator, which has both high efficiency and simple structure. The magnetic refrigerator is based on a magnetocaloric effect, which controls the thermal state of the magnetic material by applied magnetic field. We choose $La(Fe_xSi_{1-x})_{13}H_y$ as a working material, which has large magnetocaloric effect due to 1st order magnetic phase change. We use a magnetic Carnot cycle as a refrigeration cycle, which consists of two adiabatic processes and two isothermal processes. This cycle can be realized by the solid state magnetic refrigerator, which consists of the magnetic material, thermal switches and a magnetic field switch. Two thermal switches connect the thermally isolated magnetic material with a hot and a cold heat reservoir. The isothermal process can be done with one of the thermal switches in ON state and the other in OFF state. The adiabatic process can be done with all thermal switches in OFF state. In this study, we developed the components of the micro magnetic refrigerator and the refrigeration system.

In chapter 2, we discuss about the thermal switch. A solid contact type thermal switch is suitable for the micro magnetic refrigerator, because of its simple structure and high performance. To thermally isolate a thermal contactor from the other components such as an actuator, the thermal contactor is supported by a thermal isolation structure, which should be stiff enough to generate contact force in ON state. We designed the thermal isolation structure using high aspect ratio parylene beams with stiffening silicon sub-structures. The performance of the thermal switch was confirmed by a numerical simulation using finite element method (FEM). From the numerical simulation, the stiffness increased by a factor of 2.4 with the stiffening sub-structures. On the other hand, the thermal loss increased by only ca. 6%.

In ON state, a thermal contact resistance (TCR) limits the performance. We measured the TCR under a small contact pressure region at which the MEMS structures can survive. The measured TCRs between two mirror polished silicon surfaces were in the range from 400 to 1000 mm^2K/W under the contact pressure region between 8 and 54 kPa. We also investigated the effect of carbon nanotubes as a TCR reduction material. With a CNT carpet which was generated on the silicon surface, the TCR reduced to be ca. 1/3 of which without CNTs. When the contact surface was bent, the TCR between two mirror polished silicon surfaces was quite high (ca. 8000 mm^2K/W) regardless of the contact pressure. This suggests that the contact area was quite limited and then the contactors were almost separated. But even when the surface was bent, CNTs could reduce the TCR.

The thermal switch was made using MEMS fabrication technology. The parylene high aspect ratio structure was made by silicon lost mold process. The OFF state thermal isolation property was determined by a thermal response of the thermal contactor. The thermal contactor was heated by a Pt thin film heater fabricated on it. The

temperature of the contactor was determined by an electrical resistance of the heater. The measured temperature response was compared with a thermal model, which consists of heat capacities and thermal resistances. Fitting the measured values with the theoretical response of the thermal model, the thermal resistance between the contactor and the external body was determined as ca. 2.7×10^4 K/W, which was as high as FEM predicted value.

Then, the stiffness of the thermal isolation structure was measured. The thermal contactor was loaded by a piezoelectric actuator with a micro indenter. The applied load and displacement were measured by an electrical scale and a photonic sensor, respectively. The measured stiffness with and without stiffening sub-structures were 1.7×10^3 and 2.8×10^3 N/m, respectively. From these values, the stiffening factor was 1.6, which was smaller than the FEM predicted value (2.4). Using another FEM model, it was confirmed that the degradation of stiffness was caused by seams within the parylene structures.

In chapter 3, we discuss about the heating and cooling of a microstructure by the magnetocaloric effect. The magnetic material ($La(Fe_xSi_{1-x})_{13}H_y$) was glued on a silicon microstage which was supported by the parylene thermal isolation structure. The magnetic field was modulated by a magnetic field switch. High magnetic field could be obtained by concentrating the magnetic flux using a tapered shape yoke. Permanent magnets were used as a magnetic flux source. By rotating the magnets, the magnetic flux flows through (ON state) or across (OFF state) the yoke, which results in changing the magnetic flux density of the measurement section (gap of the yoke). The yoke structure was designed using a 2D FEM numerical simulation. The measured maximum magnetic flux density was ca. 0.17 T, which was roughly 1/10 of the FEM predicted value. The experimental result showed that the out-of-plane flux leakage was dominant, which cannot be considered by 2D simulation. Then we developed the designing tool using 3D edge-element FEM. Validity of the tool was confirmed by comparing the predicted values with the measured results. The calculated magnetic flux density was well consistent with the measurement. The structure of the yoke was then modified using this designing tool. The measured maximum magnetic flux density was ca. 0.95 T, which was as high as the result of the designing tool (0.9 T). In addition, the magnetic field could be modified by rotating the permanent magnets.

A fabricated thermally isolated magnetic material was placed on the magnetic field switch. This equipment was placed in a vacuum chamber to reduce unnecessary heat loss. Because the magnetic material has optimum operation temperature, two Peltier devices were used to control the ambient temperature of the test device. The temperature of the magnetic material was measured by an infrared thermal imager. The magnetic field induced temperature fluctuation of ca. 1 ℃ was observed, when the ambient temperature was set to be ca. 11 ℃. On the other hand, when the ambient temperature was higher or lower than this temperature, the measured temperature change was quite small. These results mean that the material was successfully heated and cooled by the magnetocaloric effect.

In chapter 4, we discuss about the solid state micro magnetic refrigerator. The magnetic refrigeration device was constructed by combining the thermally isolated magnetic material with two thermal switches. The thermal switches were actuated by solenoids. The magnetic field switch was designed for the refrigerator. The maximum magnetic flux density was measured as high as 1.3 T. The magnetic refrigeration cycle was then operated. The cycle period was ca. 5 s. A cold plate (the contactor of the cold side thermal switch) could be cooled as high as ca. 0.6 ℃.

In chapter 5, we discuss about the improvement method for the micro magnetic refrigerator. We developed a numerical simulation tool of the refrigerator. The tool deals with a thermal model which consists of heat capacitors, magnetic materials, thermal resistances and thermal switches. First, a thermal model of the micro refrigerator, which we used in chap. 4, was examined. The calculated temperature change was ca. 0.9 ℃, which was a bit higher than the measured value. Then, the effect of each parameter was examined. The heat capacity of the cold plate was too small, then the temperature fluctuation as high as ca. 1 ℃ was induced by a small heat input which flows through the insulation structures. The temperature fluctuation could be suppressed as the heat capacity of the cold plate increased. Then, the periods of each operation phases were examined. The periods of the adiabatic processes should be as small as possible. But the periods were limited by a response time of the magnetic material and a switching time of the magnetic field switch. The response time of the magnetic material was reported within 1 s, but there is no faithful investigation on the response time of the material. The measurement of the response time of the magnetic material is helpful for optimization of the operation periods. The period of isothermal processes had optimum values. The period shorter than the optimum value prevents the heat transfer between the magnetic material and the thermal contactor. On the other hand, longer period increases unnecessary heat input which flows through the thermal isolation structures. A small thermal resistance of ON state thermal switch showed higher performance, which can be done by reducing the TCRs using CNTs discussed in chap 2. Larger thermal resistance of OFF state thermal switch also increased the performance. From these results, the parameters of the refrigeration device was optimized.

The adiabatic temperature change of the magnetic material is limited as high as 6 °C under 2 T magnetic flux density modulation. It means that a practical magnetic refrigerator should have a multistage configuration. A thermal model of the multistage magnetic refrigerator was created. There were a lot of design parameters of the multi stage refrigerator, these parameters were optimized by a conjugate gradient method. After optimization, the n-stage micro magnetic refrigerator could cool the cold plate n times larger than that of the single stage refrigerator.

The magnetic refrigerator has an optimum operation temperature. The numerical simulation showed that the performance degrades when the ambient condition changed. The combination with other refrigeration device such as the Peltier device, which is not affected by the ambient condition, is one of the possible solution for wide operation range.

We also discussed about a new structure of the micro magnetic refrigerator. Instead of the thermal switches, thermal diodes, which change the thermal resistance with respect to the heat flow direction, were examined. We confirmed that the magnetic refrigeration could be done with thermal diodes by numerical simulation. This type of magnetic refrigerator does not need actuators for thermal switches, it can be more preferable for the micro magnetic refrigerator.

In this study, we designed the novel solid state micro magnetic refrigerator. First, the components of the refrigerator were developed. The thermal switch was fabricated and the performance was measured. From the experimental results, the TCR could be reduced by high contact pressure. In addition, the TCR could be reduced by using CNTs. Then, we developed the thermally isolated micro magnetic material and the magnetic field switch. We also developed the tool for designing the magnetic field switch. Using these components, we confirm that the magnetocalorical temperature change of the micro structure with the magnetic material was as high as 1 °C. Then, we demonstrated the cooling cycle. The maximum cooling temperature was as high as 0.6 °C. Finally, we discussed about improvement methods.

論文審査結果の要旨

微小信号を扱うマイクロセンサや量子デバイスでは，熱雑音が問題となるため，小形冷凍器で局所的に冷却することが求められる。従来の冷凍器としては，流体の相変化を用いた熱サイクルによるもの，およびペルチェ効果を用いたものが代表的である。しかし，前者は流体制御のための種々の要素が必要であるため小形化に向いておらず，また，後者は効率が低いため大量のジュール熱を発生する。これらに対して磁気冷凍器はシステム構成を単純にでき，しかも理論的に高い効率を達成できると考えられる。しかし，これまでに磁気冷凍器をMEMS（Micro Electro Mechanical Systems）技術等を駆使して超小形化する試みは報告されておらず，冷凍サイクルの成立性，期待される性能，技術的課題などは明らかにされていなかった。

本論文は，磁気冷凍器を超小形化するために，システム構成の提案，システムの構成要素の開発，冷凍サイクルの実証，熱モデルを用いた理論検討などを行った成果をまとめたものであり，全6章からなる。

第1章は序論であり，研究の背景が論じられた後，磁気冷凍技術が説明され，超小形化に適した構成として熱スイッチを用いた全固体型のマイクロ磁気冷凍デバイスが提案されている。

第2章では，マイクロ熱スイッチの開発について述べている。マイクロ熱スイッチでは，OFF時の断熱性を上げるための断熱構造，およびON時の熱抵抗を下げるための接触子が重要である。前者のためには，低熱伝導率材料からなる細い梁等で接触子を支える必要があるが，同時に接触熱抵抗を下げるためには，十分な接触力を発生させるために支持部の剛性も必要である。これらの相反する要求機能を満たすために，アスペクト比の高いパリレンのマイクロビームによって接触子を支持し，さらにシリコンの補助梁で熱損失を増やさず剛性を上げる構造を提案し，有限要素法を用いて設計を行った。また，設計したマイクロ熱スイッチを MEMS 技術を用いて作製した。さらに，接触熱抵抗を低減するために，化学的気相堆積法によって接触子にカーボンナノチューブを高密度に成長させ，カーボンナノチューブの変形によって真接触面を増やす方法を検討し，これによって接触熱抵抗を約3分の1に低減できること実証した。これらの成果はマイクロ磁気冷凍器の実証に必須である上，他のマイクロデバイスにも利用可能であり，有用かつ重要な知見である。

第3章では，磁気熱量効果によって微小な磁性体の加熱・冷却が可能であることが示されている。磁性体として適度なキュリー温度を有し，かつ潜熱を伴う相転移，つまり大きな磁気熱量効果を有する材料が有利であり，$La(Fe_xSi_{1-x})13H_y$ を選択した。これを前述したパリレンの断熱構造で支えた。また，磁性体に印可する磁界をON/OFFするために磁気スイッチを有限要素法を用いて設計し，製作した。これらを用いて微小な磁性体の加熱・冷却が可能であることを示したことは，マイクロ磁気冷凍器の実証に向けての大きなマイルストーンであり，重要な成果である。

第4章では，磁気冷凍サイクル試験について述べている。ここまでに開発したマイクロ熱スイッチと磁気スイッチを用いてマイクロ磁気冷凍デバイスを構築し，一段の冷凍サイクルで約0.6 ℃の冷却を実現した。これによって全固体型のマイクロ磁気冷凍デバイスの成立が初めて示され，有用かつ重要な成果が得られている。

第5章は考察であり，熱モデルを用いて冷凍サイクルの性能見積もり，設計パラメータの最適化，多段サイクルの検討などを行っている。その結果，4章で述べた結果の妥当性を確認するとともに，性能向上のための指針が明らかにされており，これは有用な成果である。

第6章は結論である。

以上，本論文は，熱スイッチを用いた全固体型マイクロ冷凍器を提案し，その構成要素を開発し，実際にシステムを構築して冷凍サイクルの成立を実験的に実証したものであり，ナノメカニクスとマイクロマシン工学に寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として合格と認める。