LOW CONTACT RESISTANCE MICRO THERMAL SWITCH WITH CARBON-NANOTUBE-ENHANCED CONTACTOR

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ABSTRACT

We demonstrated considerable reduction of thermal contact resistance (TCR) in microscale using carbon nanotubes (CNTs), and applied this technology to a micro thermal switch for magnetic refrigeration. A micro thermal contactor with a PECVD-grown 10 μm long "CNT carpet" shows a TCR of ca. 600 mm^{2}K/W at a contact pressure of 20 kPa. The reliability of this data was confirmed by the extrapolation of published data in macroscale based on an empirical equation. The Off/On thermal resistance ratio of the thermal switch was ca. 7.3.

KEYWORDS

Thermal switch, Carbon nanotube (CNT), Thermal contact resistance

INTRODUCTION

Micro thermal devices such as micro heat engines, micro refrigerators and micro reactors are important for energy harvesting, energy conversion, temperature controlling etc [1]. These devices often need to dynamically control a heat flow, which is possible by a thermal switch. We are developing a micro magnetic refrigerator using a MEMS-based thermal switch. Our theoretical consideration suggests that the Off/On thermal resistance ratio must be at least 14 to establish the refrigerating cycle. However, it is difficult to obtain sufficiently low TCR in microscale. TCR is predominantly caused by a nanoscale surface roughness, and thus the surface roughness must be absorbed by elastic deformation by sufficient contact pressure to reduce the TCR. However, the contact pressure available by microactuators is too weak to deform the solid contact surface.

Another method to reduce TCR is to use a soft and high-thermal-conductance material for a contactor. Mercury was used as a contact material [1], but to directly actuate mercury droplets in vacuum is difficult [2]. In this study, therefore, we used a "CNT carpet" as a contact material, because CNT is an excellent elastic material and has a high thermal conductance. This idea was demonstrated in macroscale, i.e. at high contact pressure by Xu *et al* [3]. Cho *et. al* evaluated CNT contacts for a MEMS-based thermal switch, and demonstrated the effect of TCR reduction by CNT in low contact pressure region [4]. As mentioned, the application of our thermal switch is the micro magnetic refrigerator, and thus excellent heat isolation and minimal heat capacity are required for the contactor. In this study, we designed, fabricated and evaluated the thermal switch with such a CNT-enhanced contactor.

MEASUREMENT OF CNT ENHANCED TCR

Objective

Contact pressure applicable for MEMS structures is quite small, and thus the TCR of CNT-enhanced contactors in a low contact pressure region must be measured for the design of the thermal switch. Because the characteristics of CNT depend on the growth apparatus and conditions, the comparison of our measured data with the published ones [3, 4] is also valuable.

Structure of test contactors

The structure of test contactors for measuring TCR is illustrated in Fig. 1. The test contactors with and without the "CNT carpet" are compared to confirm the effect of CNTs. Figure 1 (a) shows the test contactor with CNTs. The contact area is designed as 5 mm square. The CNTs were grown by PECVD (plasma enhanced chemical vapor deposition) using C_2H_2 and H_2 on sputter-deposited Fe

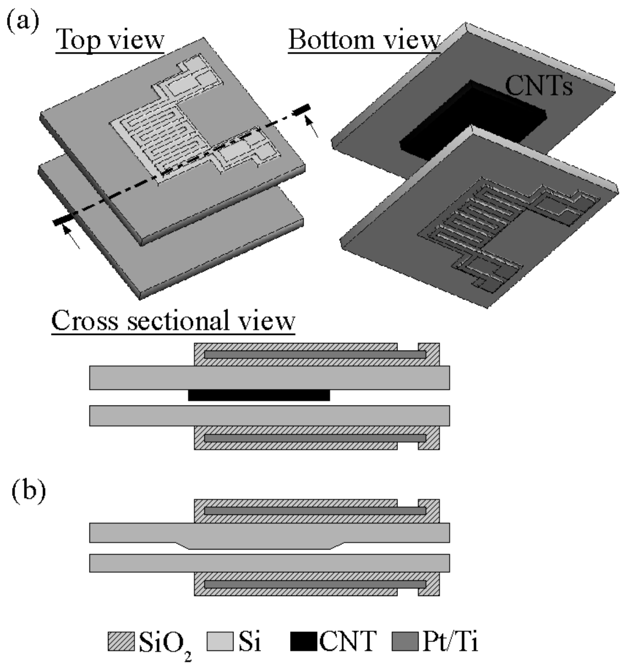

Figure 1. Structure of the thermal contactors. (a) CNT-enhanced thermal contactor. A "CNT carpet" is formed on the contact surface. (b) Cross sectional view of the reference thermal contactor without CNTs. Each contactor has a Pt thin film temperature sensor.

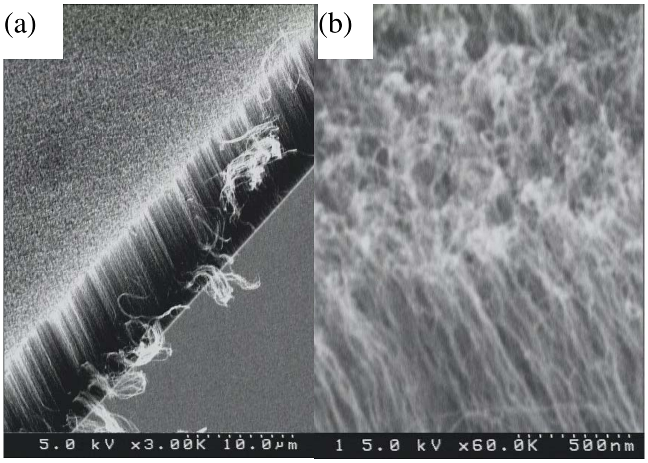

Figure 2. SEM image of the "CNT carpet." (a) CNTs are vertically aligned. (b) Magnified image of the CNTs.

catalyst [5]. As found in Fig. 2, ca. 10 µm long CNTs are grown vertically like a carpet. The Pt thin film heater and temperature sensor are formed on the opposite surface. The test contactor without CNT has a mirror polished silicon plane with the same area as the "CNT carpet", as shown in Fig. 1 (b).

Experimental setup

TCR is defined as

$$R_{th} = \frac{\Delta T}{\dot{q}}\,[\mathrm{m^2K/W}], \qquad (1)$$

where ΔT is temperature difference between two contacting surface and $\dot{q}$ is heat flux which flows through the contact area. Figure 3 shows an experimental setup to evaluate the TCR of the contactor. The heat flux which flows through the contact interface is obtained by measuring temperature distribution in the metal rod underneath the test contactor. The temperature difference is obtained from the temperature of each Si plate. Because the TCR is quite larger than the thermal resistance in the Si plate and CNTs, it can be assumed that the temperature of the contact surface is identical to that of the Si plate.

Unnecessary heat flow, which causes measurement error, is eliminated by the thermal insulator. The temperature of the thermal insulator is controlled by the heater as it is identical to that of the sample, as shown in Fig. 4. This temperature balance method makes heat dissipation from the measurement section nearly zero. The setup is in a vacuum chamber at 0.4~1.0 Pa. The contact pressure is controlled by a weight, and the weight stage contacts with the test contactor at a sharp edge for uniform loading.

Result and discussion

Figure 5 shows the relationship between contact pressure, P, and TCR, R_{th}. The measured TCR of the CNT-enhanced thermal contactor is 600 mm^2K/W at a contact pressure of 20 kPa. The results for the CNT-enhanced thermal contactor follow Tachibana's equation [6] as

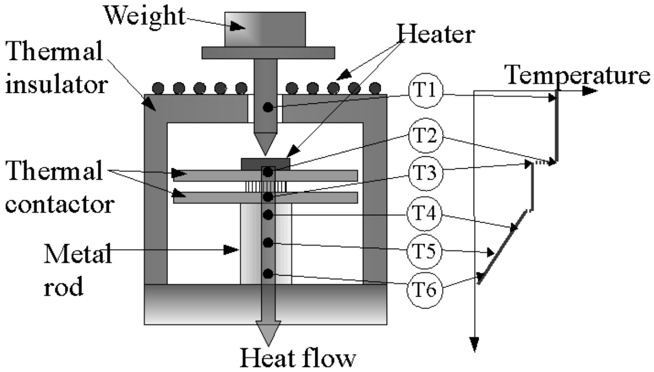

Figure 3. TCR measurement setup. Temperature drop at the interface is measured using thermocouples T2 and T3. The heat flux is measured by T4~T6. Contact pressure is controlled by the weight.

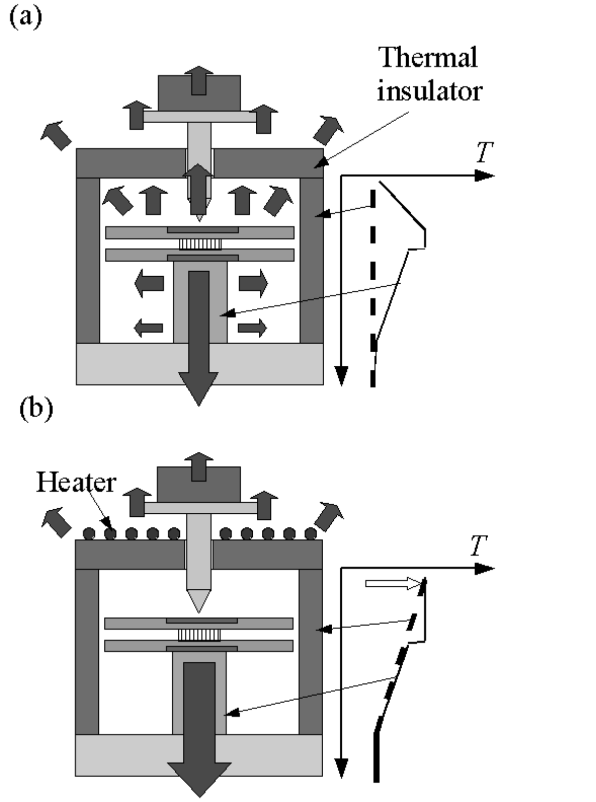

Figure 4. Principle of the active thermal insulation. The solid line shows the temperature of the sample and the metal rod. The dashed line shows the temperature of the thermal insulator. (a) Without active thermal insulation, the heat loss from the metal rod to the thermal insulator causes measurement error. (b) With active thermal insulation, the temperature of the thermal insulator is controlled as it is identical to that of the sample.

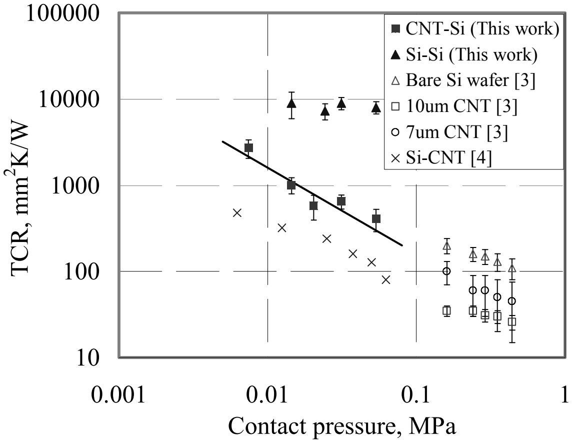

Figure 5. Relationship between TCR and contact pressure for CNT-enhanced contactors. The solid line shows the fitted result using Tachibana's equation. The hardness of the "CNT carpet" is assumed to be 10. Data from Refs. [3, 4] are also shown.

$$R_{th} = \frac{16}{P}, \tag{2}$$

representing that TCR is inversely proportional to contact pressure. The Brinell hardness of the "CNT carpet" assumed in the equation is 10.

The hardness of the "CNT carpet" was measured using a triangular pyramid indenter. The hardness is calculated as

$$H = \frac{F}{S}, \tag{3}$$

where F is the contact force and S is the contact area. The measured hardness of the "CNT carpet" was 13 ± 7. The hardness calculated here is not completely equal to Brinell hardness, but might be similar judging from its definition. Therefore, Eq. (2) is reasonable for the "CNT carpet". In addition, our data well connects to the previous data in a high contact pressure region [3].

On the other hand, the TCR of the reference thermal contactor without CNTs (i.e. Si to Si contact) has a TCR of ca. 8000 mm^2K/W regardless of the contact pressure as shown in Fig. 5. This value is approximately identical to the thermal resistance of the radiation heat transfer, suggesting that the real contact area is very limited due to weak contact pressure.

THERMAL SWITCH

Structure

The structure of the thermal switch is shown in Fig. 6. To apply the thermal switch to micro heat cycles, minimizing the heat capacity generally results in high performance. Additionally, higher contact pressure leads to lower TCR. Therefore, a structure with high stiffness and low thermal conductivity is required for the support of the contactor. In this work, the CNT-enhanced thermal contactor is supported by parylene beams, because parylene has low thermal conductivity and is easy to be fabricated into high aspect ratio structures [7]. The parylene beam is designed to increase geometric moment of inertia without increasing thermal conductivity, i.e. the height of the beam is approximately 20 times larger than the width.

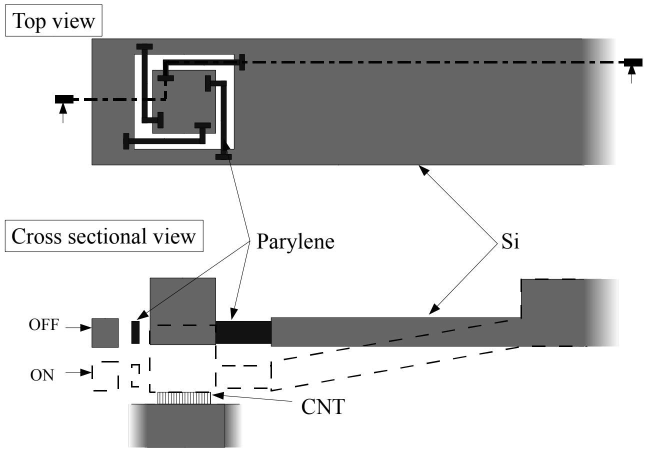

Figure 6. Structure of the micro thermal switch. The thermal contactor is supported by the high stiffness parylene beam for thermal insulation.

The contactor is placed at the leading end of the silicon cantilever. The cantilever is actuated by an external actuator. It does not increase heat capacity, because the thermal contactor is thermally isolated from the cantilever.

Fabrication process

Figure 7 shows the fabrication process of the thermal switch. First, a SiO_2 thin film is thermally grown on a Si substrate. Then, the backside of the Si substrate is etched by DRIE (deep reactive ion etching) technique using SiO_2 as an etching mask. After that, deep trenches, which will be used as the parylene beam mold, are formed by DRIE from the front side. Parylene is deposited to fill the trenches completely. Parylene deposited outside of the trench is removed by O_2 ashing. Finally, Si is etched away to form the parylene beam and Si cantilever.

CNTs are deposited on another Si substrate. The fabricated thermal switch is placed and mechanically fixed on the Si substrate with CNTs. Figure 8 shows the photograph of the fabricated thermal switch.

Experimental setup

To measure the performance of the thermal switch, a micro heater and a thermocouple are fixed on the thermal contactor. Figure 9 shows the experimental setup. The Si cantilever is actuated by a 3 axis manipulator with a sharp needle. The experiment was done in a vacuum chamber at ca. 1.0 Pa.

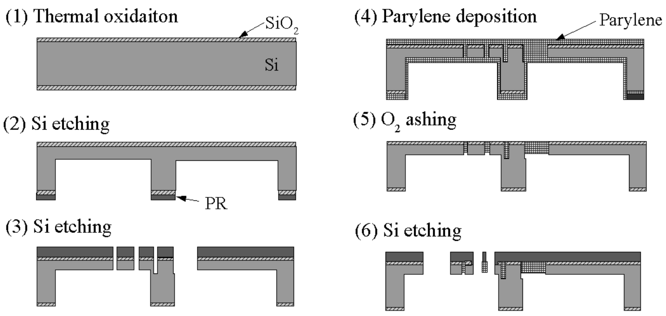

Figure 7. Fabrication process of the micro thermal switch.

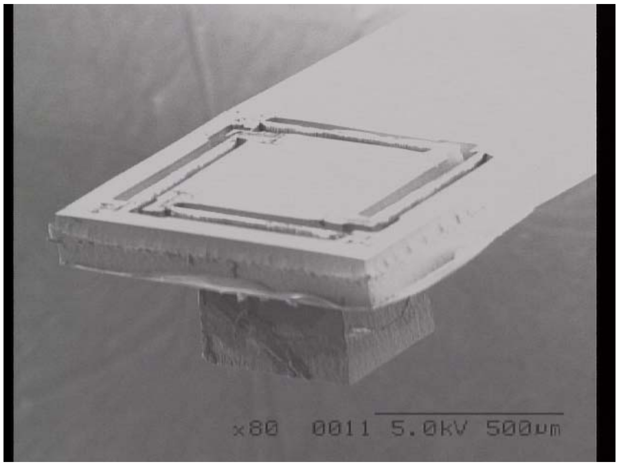

Figure 8. SEM image of the micro thermal switch

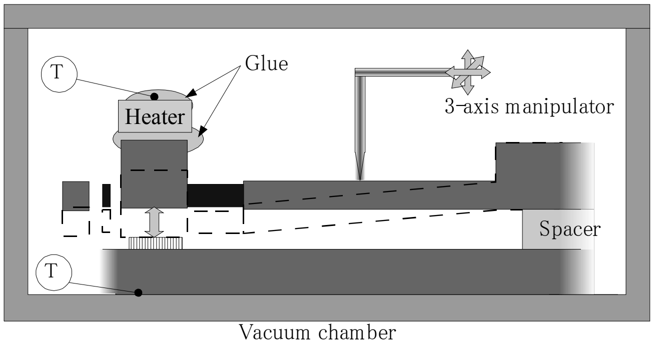

Figure 9. Experimental setup for the evaluation of the micro thermal switch.

Result and discussion

Measured On and Off state thermal resistances were 1.5×10^3 K/W and 1.1×10^4 K/W, respectively. Off/On ratio of the thermal resistance was ca. 7.3, which is not enough to establish the micro magnetic cooler. The thermal resistance in On state is roughly acceptable, but that in Off state is impractically low in comparison with a theoretically estimated value of 4.9×10^5 K/W. This might be because the glue which is used to fix the micro heater and thermocouple partially filled the trench. In addition, the thermal resistance between the heater and the contactor might not be negligible. These problems will be solved using a thin film heater and temperature sensor fabricated together with the contactor.

CONCLUSION

TCR reduction using a "CNT carpet" was demonstrated in a contact pressure region of 7.4−54 kPa. The TCR was 600 mm^2K/W at a contact pressure of 20 kPa. The relationship between TCR and contact pressure follows an empirical equation. From the fitted empirical equation, the hardness of the "CNT carpet" is estimated at ca. 10, which is almost consistent with the measured hardness, suggesting the measurement is reasonable.

The thermal switch with the "CNT carpet" as a contactor and a parylene thermal isolation structure was designed, fabricated and tested. The Off/On ratio of thermal resistance was ca. 7.3. The performance is probably underestimated by undesired thermal loss due to the misassembly of the measurement setup.

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