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Microinsulation for a Thermionic Microbattery

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Abstract

A microinsulation concept has been designed for use in MEMS devices. The design is carried out in the context of a thermionic microbattery, which converts the decay heat from radioactive isotopes directly to electricity using a vacuum thermionic diode. The role of the microinsulation is to maintain the isotope source temperature high in order to maintain good conversion efficiency. This paper provides a conceptual design and a thermal model of the micro insulation and examines the parameters that affect the thermal conductance of the microinsulation, which can have apparent thermal conductivity on the order of 10^{-4} W/mK and can be used for a variety of MEMS thermal management applications. Our models indicate that this microinsulation will provide the high performance necessary for a nuclear thermionic MEMS power source.

Keywords: Microinsulation, Thermionic, microbattery, MEMS

1 INTRODUCTION

Numerous studies have been carried out regarding on technologies for providing electrical power to MEMS devices. The electrical power can be converted from various energy sources, such as chemical, solar and radioisotopes using a variety of conversion processes. One example is a radioisotope powered thermionic microbattery [1]. The microbattery converts the radioisotope decay heat directly to electricity using a vacuum thermionic diode. It requires a micro scale thermal insulation to maintain high radioisotope source temperature and thus achieve high conversion efficiency. There are currently no available insulation concepts suitable for MEMS-scale applications, but there are some similar concepts used for other applications. One commercially available example is the MULTI-FOIL™ insulation developed by Thermo Electron Corporation. This, and other multifoil concepts, work well, but do not appear capable to being adapted to the MEMS-scale, so there exists a need to develop a novel thermal insulation for MEMS devices. For the thermionic microbattery, this insulation should maintain temperature gradients of more than 1000 K at very short distances (less than 100 microns). This insulation should be designed and fabricated by semiconductor and MEMS fabrication techniques so as to be integrated easily with the other parts of the microbattery.

2 MICROINSULATION

Figure 1 shows a schematic of an example of our microinsulation concept design. An array of thin-walled, half-circular microtubes separates the top and bottom layers, creating a gap, which is evacuated to reduce gas conduction. The microtubes have thin wall thickness and are fabricated from a low thermal conductivity material such as SiO_2 to minimize the solid conduction. The top layer is made or coated by low emissivity material, such as gold or silver, to reduce radiation heat transfer between the top and bottom layers. Individual microinsulations can also be stacked on top of another and bonded together to make a multileveled assembly.

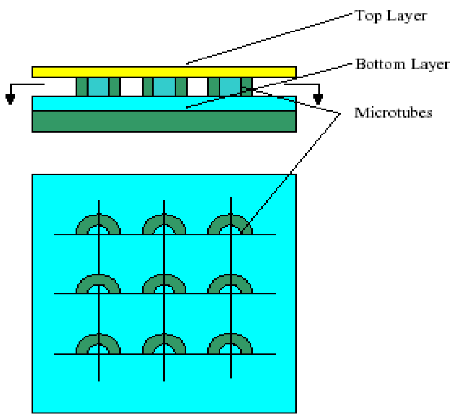
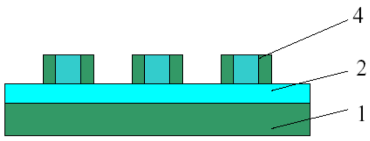


Figure 1 An example of a microinsulation design (not in scale)

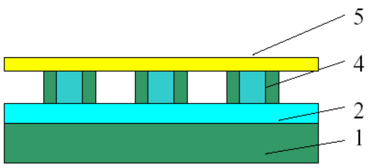
Figures 2 (a) to (d) illustrate the cross section views of the fabrication process of a single microinsulation.

(a) An etch stop layer (2) has been deposited on top of a substrate (1). The stop layer (2) can be Si.

(b) A second layer (3) has been deposited on top of stop layer (2). The second layer (3) should have low thermal conductivity such as SiO_2.



(c) The second layer (3) has been patterned and etched to make freestanding, thin-walled half-circular microtubes (4).



(d) A top layer (5) has been bonded on top of the microtubes (4). The top layer (5) should be coated with low emissivity material such as gold.

3 PHYSICAL MODELLING

To investigate the feasibility of this concept, a computational model has been built. The schematic of the heat transfer model is shown in Figure 3. This steady state, one-dimensional model includes several heat transfer modes, including solid conduction through the walls of the microtubes and gas conduction and radiation through the gap between the top and bottom layers. Free convection is not considered because the two layers are too close to allow development of convection cells and because the gas pressure should be sufficiently low for convection to be of no consequence. In the model, Q is the total heat generated by the radioisotope, Q_s, Q_g, Q_r are heat flows through the mircotubes, gas, and radiation respectively, T_2 and T_∞ are the cold side and environment temperatures and are assumed constant and identical respectively; T_1 and T_0 are hot side and radioisotope source temperatures respectively and assumed identical; ε_1 and ε_2 are emissivities of the top and bottom layer surfaces respectively, and H is the height of microtubes. The model also assumes that there are no heat losses laterally, which means all heat fluxes are parallel to the axial direction of the microtubes and that all surfaces are gray surfaces so that their emissivities are independent of the wavelength of the radiation.

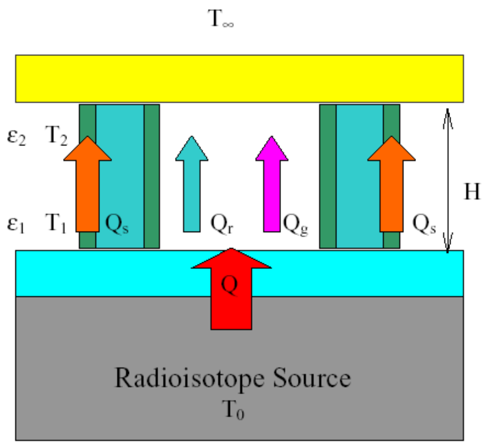


Figure 3 Heat transfer modeling through a microinsulation

For the problems involving combined radiation and conduction, a simple model approach is to assume that both heat transfer modes are uncoupled and the desired temperatures and heat fluxes can be found by adding separate solutions. Unfortunately, uncoupled problems are not as common as coupled problems, especially when the total energy flux is specified, so the entire problem typically must be treated simultaneously because of the nonlinear coupling of the unknown temperatures. [2] In some situations it may be possible to assume that each heat transfer process acts independently because only weak coupling occurs.

The energy balance equation is

$$Q = Q_S + Q_r + Q_g = Q \cdot (h_S + h_r + h_g) \qquad (1)$$

where h_S, h_r, and h_g represent the fractions of total heat flows by solid conduction, radiation and gas conduction respectively, and Q is the total heat flow.

The heat flow by conduction through the microtubes is given by

$$Q_s = Q \cdot h_S = \frac{(T_1 - T_2)}{\frac{H}{kA_S}} \quad (2)$$

where k is the thermal conductivity of the microtube material and A_S is the total cross section area of the microtubes.

The heat flow by radiation from the bottom layer to the top layer is given by

$$Q_r = Q \cdot h_r = \frac{s \cdot A_r \cdot (T_1^4 - T_2^4)}{\left(\frac{1}{e_1} + \frac{1}{e_2} - 1\right)} \quad (3)$$

where σ is the Stefan-Boltzman constant, ε_1 and ε_2 are emissivities of top and bottom layer surfaces, and A_r is the total radiation cross-section area.

The two layers are so close that the gas conduction between them is under free-molecule regime. Thus the heat flow by conduction through the gas is

$$Q_g = Q \cdot h_g = k_{gas} \cdot A_g \cdot (T_1 - T_2) \quad (4)$$

where A_g is the gas conduction cross-section area assumed to be identical to A_r, and k_{gas} is the gas thermal conductivity given as [3]

$$k_{gas} = \frac{1}{2}(g + 1) C_V \frac{P}{\sqrt{2pRT}} H \quad (5)$$

where γ is the ratio of the heat capacity at constant pressure to that at constant volume, C_V the heat capacity at constant volume, T is the mean temperature of T_1 and T_2, R is the gas constant, and P is the vacuum at temperature T.

By solving equations (1) through (5), The thermal conductance of the microinsulation can be obtained as

$$C = \frac{Q}{(T_1 - T_2)A} \quad (6)$$

where A is the cross-section area of the top and bottom layers.

The apparent thermal conductivity of the microinsulation, which is convenient for comparison to conduction through suitable solid materials, is defined as:

$$k_{app} = C \cdot H \quad (7)$$

The conceptual design parameters used in this model are given in Table 1.

Table 1 Design parameters of a typical microinsulation

Parameters	Values
Top and Bottom layers cross-section area, A	1cm * 1cm
Gap width between the two layers, H	10 microns
Vacuum between the two layers, P	0.1 Torr
Diameter of microtubes	200 microns
Wall thickness of microtubes	4 microns
Cold side temperature, T_2	300 K
Total heat applied on the microinsulation, Q	1.0 W
Top and Bottom layers surface emissivity, ε_1 ε_2	0.05, 0.5
Thermal conductivity of SiO_2, k	1.4 W/mK

4 RESULTS OF THEORETICAL ANALYSIS

Figures 4-6 show typical results for this proposed design. In Figures 4 and 5, decreasing the number of microtubes and the microtube wall thickness reduces the heat conduction cross-sectional area between the top and bottom layers. Thus a lower thermal conductance and a higher hot side temperature can be obtained. The apparent thermal conductivity for a microinsulation with nine microtubes is about $2.5*10^{-4}$ W/mK, which is two orders of magnitude below a typical silica aerogel and on the same order of MULTI-FOIL insulation. On the other hand, very thin wall thicknesses and inadequate numbers of microtubes can result in a mechanical instability of the microinsulation structure.

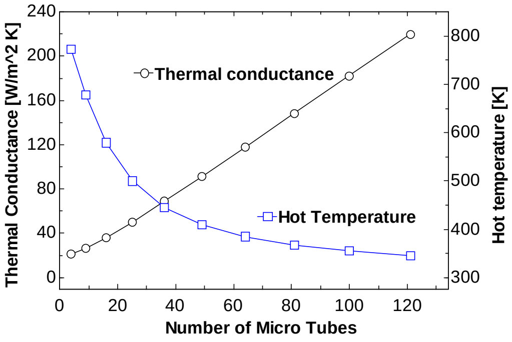


Figure 4 The hot side temperature and thermal conductance as functions of number of microtubes

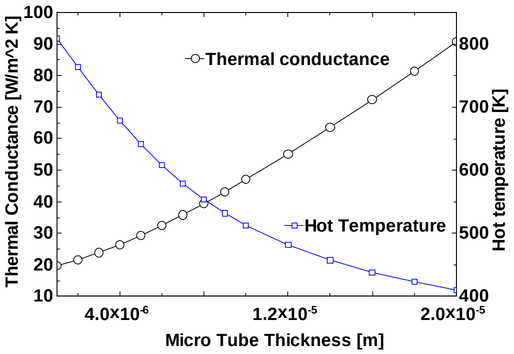


Figure 5 The hot side temperature and thermal conductance as functions of microtube wall thickness

Figure 6 shows that solid conduction through the microtubes wall is the primary heat transfer path in the microinsulation when the number of microtubes is more than about ten. The gas conduction is negligible under vacuum.

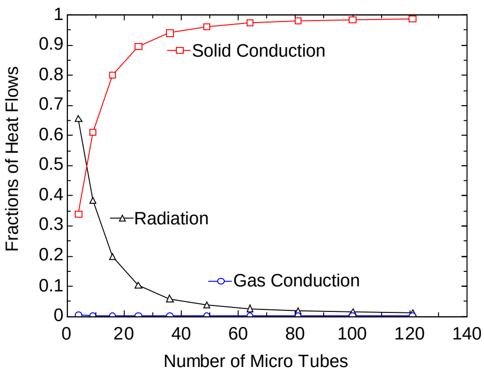


Figure 6 The fractions of three heat transfer modes as functions of the number of the microtubes

In Figure 7, when the heights of microtubes become large, the hot and cold temperature difference becomes large, therefore the microinsulation has low thermal conductance. But the high microtubes would require much more time in the fabrication process and make the microtubes vulnerable to collapse.

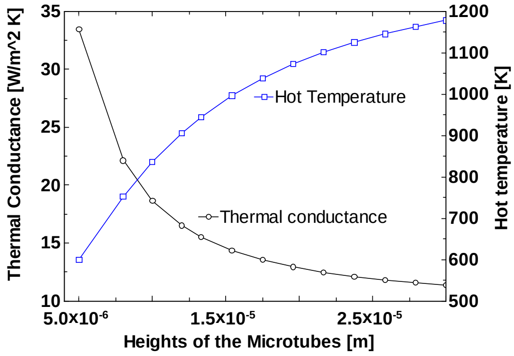


Figure 7 The hot side temperature and thermal conductance as functions of microtube heights

5 CONCLUSIONS

The analysis above indicates that the microinsulation concept design can achieve very low apparent thermal conductivity and can allow high operating temperatures for a thermionic microbattery. The apparent thermal conductivity is on the order of 10^{-4} W/mK. Furthermore, the microinsulation is fabricated by semiconductor and MEMS techniques so they could be integrated into the microbattery and other MEMS devices easily.

REFERENCES

[1] Donald B. King et al. “Microminiature thermionic converters” US Patent 6,294,858 Sept. 25, 2001

[2] Robert Siegel, John R. Howell, Thermal radiation heat transfer, Hemisphere Pub. Corp., 1992

[3] F.M. Devienne, “Low Density Heat Transfer”, Advances in Heat Transfer, Volume 2, Academic Press, 1965