THERMAL SWITCH FOR SATELLITE TEMPERATURE CONTROL

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ABSTRACT

An Active Radiator Tile (ART) thermal valve has been fabricated using silicon micromachining. Intended for orbital satellite heat control applications, the operational principle of the ART is to control heat flow between two thermally isolated surfaces by bringing the surfaces into intimate mechanical contact using electrostatic actuation. Prototype devices have been tested in vacuum and demonstrate thermal actuation voltages as low as 40 volts, very good thermal insulation in the OFF state, and a large increase in radiative heat flow in the ON state. Thin anodised aluminum was developed as a coating for high infrared emissivity and high solar reflectance.

INTRODUCTION

There are applications for devices which can control the radiative transfer of heat into or out of an object; the application of interest for this study is orbital satellites. A novel approach for controlling the radiative heat flow between the satellite and the environment has been recently proposed [1]. Active Radiator Tiles (ARTs) rely on a variable mechanical contact to control the heat flow between two surfaces, creating a thermal switch or valve. Desired properties of the thermal switch device are a high thermal resistance at rest, a high thermal conductance when activated, and low power operation. In this paper we report the construction of ART prototypes and the experimental verification of the principle of operation. A generalised side view of the proposed device is shown in Figure 1. The operating principle is to control the flow of heat between a hot side (Base) and a cold side (Radiator) of the device by direct mechanical contact between the two sides, with electrostatics supplying the driving force.

In the OFF state (no actuation), the two plates are separated by thermal insulators (polyimide) from 10 to 20 µm tall, which minimises the conductive heat transfer Q_{ins}. The interior cavity surfaces of the complete ART device (upper surface of the Base plate and lower surface of the Radiator plate)

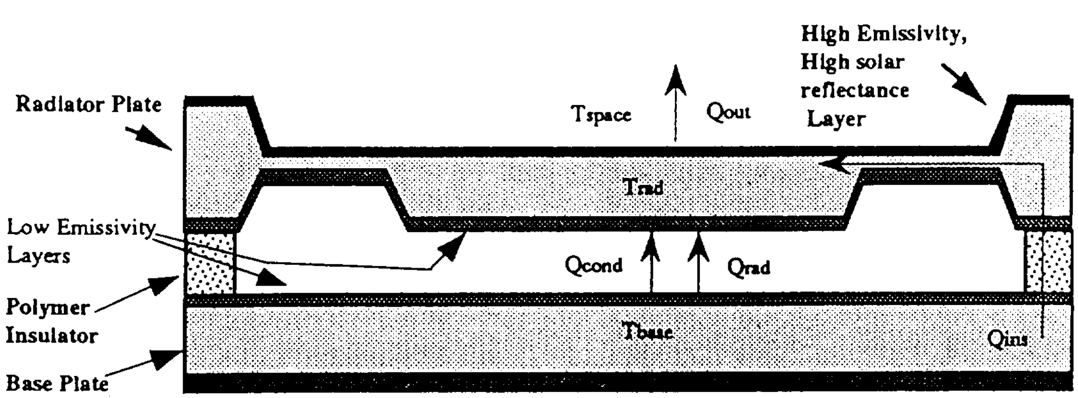

Figure 1. Schematic side view of Active Radiator Tile.

are coated with low-emissivity layers (aluminum and PECVD nitride) to minimise radiative heat transfer Q_{rad} between the plates. In this state the heat flow from the Base to the Radiator is very low and the device presents a large thermal resistance from the Base to the environment.

The silicon Radiator plate is etched anisotropically to form a large membrane with a large central contacting boss. Application of a suitable voltage across the two plates will cause a deflection of the Radiator plate into intimate contact with the Base plate, allowing heat transfer by conduction Q_{cond} from the Base to the Radiator, where the heat can then be radiated to the environment as Q_{out} (the ON state). The exterior surface of the Radiator plate, which will directly face the operating environment, is coated with a high-emissivity layer of paint for maximum radiative heat flow to the environment in the ON state. The combination of dual facing low-emissivity layers and a high-emissivity exterior surface allows for high thermal resistance when the device is at rest, and a high thermal conductance to the environment when the device is actuated. Thus the ART device acts as a thermal valve or switch, actively controlling the flow of heat to the environment in response to an input voltage.

THERMAL/OPTICAL CONSIDERATIONS

The basic desired properties of the ART device are a good radiative heat flow in the ON state and a minimum heat flow in the OFF state. To achieve a good radiative heat flow in the ON state, we require a high-emissivity exterior surface. To minimise the heat flow in the OFF state, the interior cavity surfaces should have as low an emissivity as possible. Since the ART will operate in high-vacuum there is no convective heat transfer, and if the support posts have a negligibly high thermal resistance all of the heat flow between the plates is radiative. A simple theoretical model of the OFF state thermal characteristics can be developed if the conductive heat flow Q_{ins} through the support posts can be ignored. Also assumed is the total reflection of solar energy by the radiator outer coating. Referring to Figure 2, the radiative heat transfer from the Base to the Radiator plate can be written in the form

$$Q_{r,cav} = A \cdot \sigma \cdot E_{br}\left(T_{base}^4 - T_{rad}^4\right) \tag{1}$$

where A is the area of the plates, σ is the Stephan-Boltzman constant, and

$$E_{br} = \left(\frac{1}{\varepsilon_{bc}} + \frac{1}{\varepsilon_{rc}}\right)^{-1} \tag{2}$$

with ε_{bc} and ε_{rc} the emissivities of the Base and Radiator surfaces of the cavity [1]. The interchange factor E_{br} accounts for reflection and absorption within the optical cavity. A similar equation describes the heat flow from the Radiator to the environment, thus

$$Q_{r,out} = A \cdot \sigma \cdot \varepsilon_{re}\left(T_{rad}^4 - T_{space}^4\right) \tag{3}$$

where ε_{re} is the emissivity of the Radiator exterior. In equilibrium, $Q_{r,cav} = Q_{r,out}$. Combining eq. 1 and eq. 3, we can derive the following two equations:

$$Q_{r,out} = A \cdot \sigma \cdot \frac{E_{br}\varepsilon_{re}}{E_{br} + \varepsilon_{re}}\left(T_{base}^4 - T_{space}^4\right), \tag{4}$$

$$T_{rad} = \sqrt[4]{\frac{E_{br}T_{base}^4 + \varepsilon_{re}T_{space}^4}{E_{br} + \varepsilon_{re}}}. \tag{5}$$

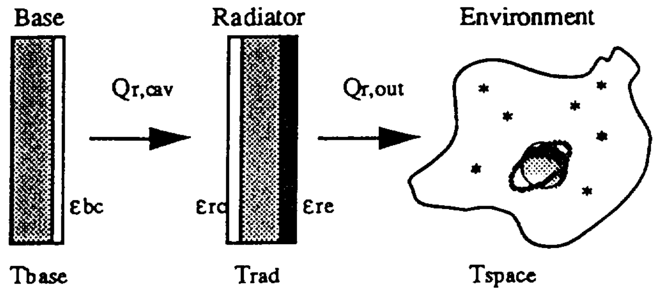

Figure 2. Optical cavity of ART. The net heat flow is from the Base to the Environment.

Since we require a high external emissivity, $\varepsilon_{re} \approx 1$, for small E_{br} the quantity $[(E_{br}\varepsilon_{re})/(E_{br}+\varepsilon_{re})]$ in eq. 4 reduces to simply E_{br}. Considering eq. 2 in conjunction with eq. 4 illustrates the potential for very high thermal isolation in the OFF state. For instance, if we set $\varepsilon_{bc} = \varepsilon_{rc} = \varepsilon$, with $\varepsilon \ll 1$, $E_{br} \approx \varepsilon/2$. The effective emissivity to the environment in the OFF state can be about half the emissivity of the cavity layers, which translates to a factor of two increase in effective thermal resistance between the heat source and the environment; while still retaining a high emissivity in the ON state.

CONSTRUCTION AND TESTING

The ART prototypes are constructed using typical silicon micromachining techniques with 5 inch 625 μm thick silicon wafers. For Base plates, the bare silicon wafers are coated with aluminum and a PECVD nitride insulating layer, then photoimageable polyimide is used to create support posts from 10 microns up to 50 microns in height. The heat radiation when actuated depends on good thermal contact between the two plates of the device when in contact, and the level of thermal contact depends on applied pressure [2], so it is necessary to have a very high quality insulating layer on the interior surfaces to allow high applied voltages (for high applied electrostatic pressures) without breakdown. This is essentially related to the mechanical stiffness of the membrane supporting the radiator plates: the Radiator plates are constructed using timed double-sided anisotropic etching to create a membrane 5 to 10 μm thick with a large central contacting area approximately 300 μm thick. The size of the prototypes in this study is approximately 1 inch square. The voltage required for good thermal contacting would have been much less with a corrugated [3] membrane supporting the radiator.

The prototypes were tested in a small turbopumped vacuum chamber at pressures between 10^{-6} mbar and 10^{-5} mbar. Higher background pressures (> 10^{-4} mbar) would noticeably degrade the thermal isolation between the two plates. The Base of each device was attached with silver epoxy to an aluminum heater block assembly; the heater assembly was then mounted via thermal insulators in the vacuum chamber. A scanning infrared camera thermometer was used to monitor the temperatures of both the Radiator and the Base (where the temperature of the Base is equal to the temperature of the heater block) through an infrared window. The temperature of the heater block was also monitored with a thermocouple. Calibration of the infrared camera to correct for the infrared window absorption was accomplished by viewing the infrared signal from both the Radiator and the heater block as the block was ramped to various temperatures in both air and vacuum. The Base temperature range used for testing was approximately 40°C to 165°C.

Two different styles of prototypes were tested; assemblies which were only suitable for determining the OFF state thermal isolation, and assemblies which could be actuated and demonstrate both ON and OFF states.

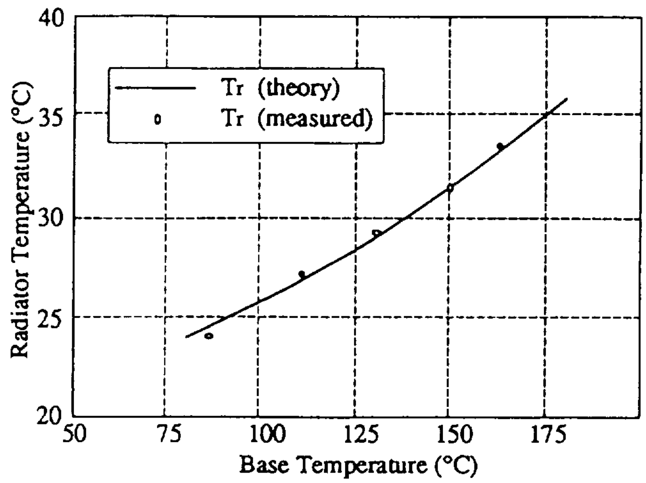

Figure 3. Temperature of the Radiator exterior versus the Base temperature. Values for the theoretical curve are: $\varepsilon_{bc}=0.14$, $\varepsilon_{rc}=0.07$, $\varepsilon_{re}=0.94$, *and* $T_{space} = 20°C$.

For testing the OFF state, ART devices were built which resembled as closely as possible the idealized device, including a high-emissivity layer of black paint on the exterior. Stress in the black paint applied to the exterior of the Radiator plates would curve the Radiators to the point that they could not be used for actuation.

The testing of the ON state required ART devices with a non-ideal exterior surface of bare aluminum, which had a serious impact on the heat flow which could be obtained to the environment. Since the amount of heat radiated to the environment is proportional to the emissivity of the Radiator exterior, in the actuatable devices the heat differential between the Radiator and the Base in the OFF state was much less than for the idealized Radiators.

The ART prototypes were actuated using capacitance-voltage (CV) measurement equipment which could apply up to 40 volts DC. This made it possible to monitor the motion of the ART device once a voltage was applied, via the change in capacitance. The maximum voltage which could be applied was limited by defects in the insulating PECVD layer; however the voltage range was sufficient to clearly demonstrate a variable thermal conductivity as a function of applied voltage.

In parallel, a process was investigated that allows for integration of a high emissivity coating with thin micromachined devices. Anodised aluminum was selected since it combines high emissivity ε_{IR} in the infrared with high solar reflectance R_S, e.g. low solar absorptance $\alpha_s=1-R_S$ [4, 5, 6].

RESULTS

OFF state. The ART prototypes achieved an OFF state thermal isolation very close to that predicted from the simple thermal model, demonstrating a thermal behaviour dominated by radiative heat transfer from the Base to the Radiator plate. Figure 3 shows a graph of the Radiator temperature as a function of the Base temperature calculated using eq. 5, and the measured values. The emissivity values used to derive the theoretical curve were measured on the actual device layers. The agreement between the simple model and the measured values is excellent. Note that the Radiator plate, which is spaced only 10 µm from the Base, can remain at a temperature only 15°C above room temperature while the Base is heated to over 160°C.

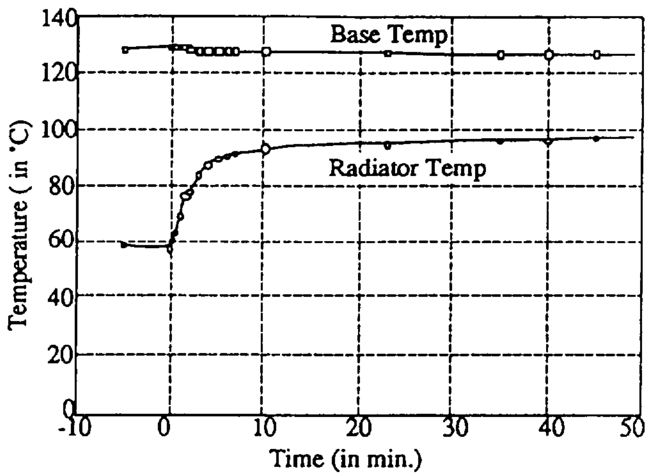

Figure 4. Temperature of Radiator after actuation.

ON state. The ability to control the heat flow to the environment was demonstrated. The ART Radiator temperature as a function of time after device actuation can be seen in Figure 4. As expected, the temperature of the Radiator increases once the device is actuated. In this case, there is a rather large temperature difference between the Radiator and the Base due to the low actuation voltage. Note that the temperature of the Base, which is heated with a constant power, drops slightly due to the heat flow into the Radiator and from there to the environment.

Actuating the device at a higher applied voltage would result in a smaller temperature difference between the Radiator and the Base and a faster response time during the actuation. This can be seen in Figure 5, which shows the temperature response of the device as a function of the applied voltage. Note that appreciable turn-on voltages are much higher than the voltages required for simple physical contact; this is expected as the thermal contact resistance decreases with increasing applied pressure[2]. Figure 5 also indicates that the current study gathered data at the very minimum voltage required for appreciable thermal switching.

Mechanical. Representative results of CV testing are also shown in Figure 5. The relative capacitance (arbitrary units) at low voltages shows a parabolic increase in capacitance attributed to

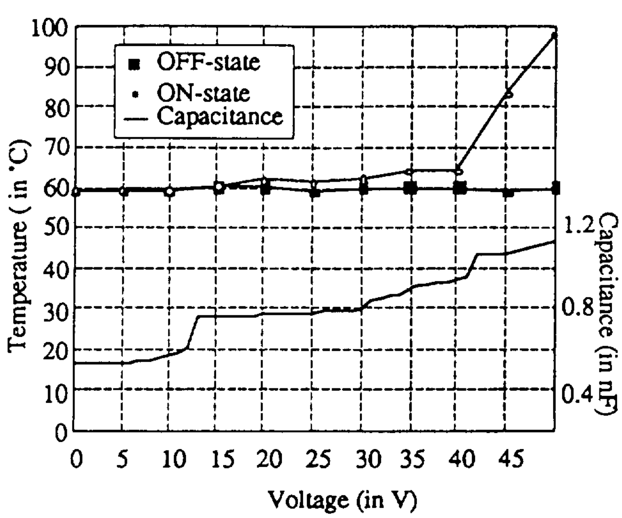

Figure 5. Temperature of Radiator after 5 min. actuation at indicated voltage, and relative capacitance.

the movement of the Radiator plate in response to the applied potential; then a sudden increase in capacitance as the Radiator plate comes into contact with the Base plate. The initial plateau at 12 volts was verified as the point of initial contact at the center of the contacting boss by observing the motion of the Radiator under an optical microscope. Several smaller disparities can be seen in the capacitance as the voltage is increased; this could be due to the different corners of the square membrane boss coming into contact. Note that thermal switching does not occur until the applied voltage is much higher than the voltage needed for simple contact.

The DC current into a device actuated at 50 volts was measured at 10 nA. The steady-state power required is therefore 500nW for the prototype, which compares with a transmitted heat flow of about 20 milliwatts; so the temperature rise during actuation is not due to joule heating. This power consumption is less than 1 milliwatt per square meter.

High emissivity coating. The high IR emissivity (ε_{IR}) coating was developed based on a standard process for the anodisation of aluminum in a sulphuric acid solution [7]. This process results in the formation of alumina with a reported value of $\alpha_s/\varepsilon_{IR}$ that can be as low as 0.19 [4, 5, 6]. Parameters for our study were the thickness of the as evaporated aluminum and the anodization time, which determines the thickness of grown alumina. Spectral reflectance in the 0.3 to 2 µm range, where most of the solar energy is concentrated, was measured using an integrating sphere set-up for diffuse reflectance measurements. Infrared spectral emissivity ε_{IR} was measured separately between 2.5 µm and 25 µm using a specular reflectance set-up (the spectral emissivity is calculated as $\varepsilon_{IR}=1-R_{IR}$). It can be seen from figure 6, where data for wavelenghts that are typical of the spectra of concern in satellite cooling are plotted, that the IR emissivity saturates about 0.9 when the alumina thickness reaches a few microns.

However, the solar reflectance drops very quickly for increasing alumina thickness, so that we could not reach the 0.19 value published for $\alpha_s/\varepsilon_{IR}$. This undesirable trend appears to be related to the thickness of as evaporated aluminum. Our efforts to increase Rs in further developments should should be concentrated on the aluminum itself from which alumina is grown.

CONCLUSION

The ART prototypes have proven the principles of operation of a thermal switch for satellite temperature control. The prototypes demonstrate a high degree of thermal isolation in the OFF state, a low actuation voltage and a corresponding low operating power, and when actuated drastically decrease their thermal resistance and radiated heat to the environment.

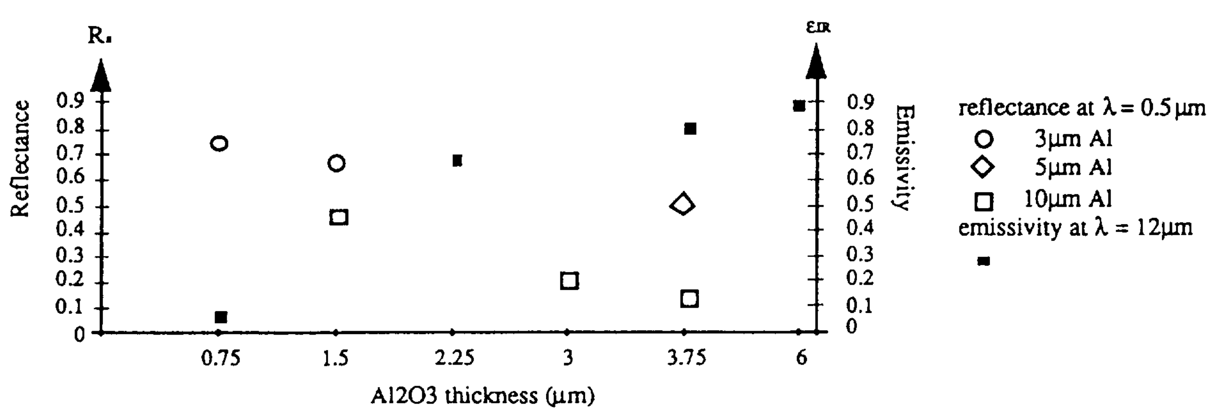

Figure 6. Measured solar reflectance and infrared emissivity as a function of the thickness of grown alumina for various thicknesses of the as deposited aluminum

A new design of thermal switches with lower actuation voltage, fully processed in a micromachining technology and that could resist to launch conditions is presently under development.

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REFERENCES

[1] Slater et al; "ART: A Novel Thermal Valve for Temperature Control Applications". *J. Micromechanics and Microengineering*, vol.5, no.2 (1995) pp.186-188

[2] Yüncü et al, "Thermal Contact Conductance - Theory and Applications". *Proc. NATO Adv. Study Inst. on Cooling of Electronic Systems*, 1993, pp. 29-54

[3] J. H. Jerman. "The fabrication and use of micro machined silicon diaphragms". *Sensors and actuators*, vol. **A21-A23** (1990)

[4] D. Weber, "Spectral emissivity of solids in the infrared at low temperature". *J. Opt. Soc. Am.*, **49-815** (1959)

[5] G. Haas, "temperature stabilization of highly reflecting spherical satellites". *J. Opt. Soc. Am.*, **49-918**(1959)

[6] L. Johnson, "Spacecrafts radiators". Space/Aeronautics, 37,76 (January 1962)

[7] F. A. Lowenheim "Deposition of inorganic films from solution", Thin film processes, Academic Press (1978), p251