380838.

4

MEMS LOUVERS FOR THERMAL CONTROL

J. L. Champion, R. Osiander, M. A Garrison Darrin, T. D. Swanson*

The Johns Hopkins University – Applied Physics Laboratory, Laurel, MD 20723

*NASA Goddard Space Flight Center, Code 545, Greenbelt, MD 20771

Abstract

Mechanical louvers have frequently been used for spacecraft and instrument thermal control purposes. These devices typically consist of parallel or radial vanes, which can be opened or closed to vary the effective emissivity of the underling surface. This project demonstrates the feasibility of using Micro-Electromechanical Systems (MEMS) technology to miniaturize louvers for such purposes. This concept offers the possibility of substituting the smaller, lighter weight, more rugged, and less costly MEMS devices for such mechanical louvers. In effect, a *smart* skin that self adjusts in response to environmental influences could be developed composed of arrays of thousands of miniaturized louvers. Several orders of magnitude size, weight, and volume decreases are potentially achieved using micro-electromechanical techniques. The use of this technology offers substantial benefits in spacecraft/instrument design, integration and testing, and flight operations. It will be particularly beneficial for the emerging smaller spacecraft and instruments of the future. In addition, this MEMS thermal louver technology can form the basis for related spacecraft/instrument applications.

The specific goal of this effort was to develop a preliminary MEMS device capable of modulating the effective emissivity of radiators on spacecraft. The concept pursued uses hinged panels, or louvers, in a manner such that heat emitted from the radiators is a function of louver angle. An electrostatic comb drive or other such actuator can control the louver position. The initial design calls for the louvers to be gold coated while the underlying surface is of high emissivity. Since the base MEMS material, silicon, is transparent in the IR spectrum the device has a minimum emissivity when closed and a maximum emissivity when open. An initial set of polysilicon louver devices was designed at the Johns Hopkins University Applied Physics Laboratory in conjunction with the Thermal Engineering Branch at NASA's Goddard Space Flight Center

1. Introduction

All spacecraft and the instruments they support require an effective thermal control mechanism in order to operate as designed and achieve their expected lifetimes. In an increasing number of satellites, optical alignment and calibration require a strict temperature control. Traditionally the thermal design is part of the spacecraft design determined by all the subsystems and instruments. Heat load levels and their location on the spacecraft, equipment temperature tolerances, available power for heaters, view to space, and other such factors are critical to the design process. Smaller spacecraft with much shorter design cycles and fewer resources such as heater power, volume, and surface, require a new, more active approach.

A number of active methods which vary the heat rejection rate in a controlled fashion are commonly used to maintain a reasonable thermal equilibrium. One such method is to cold bias the spacecraft and use simple electrical resistance make-up heaters to control the temperature. However, this can require considerable electrical power, which the spacecraft may not have available at all times. Another approach is to employ a radiator connected with variable conductive heat pipes , capillary pumped loops, or loop heat pipes. This approach is effective but adds weight , cost and complexity. In addition there are ground testing issues with heat pipes. Another approach is to use mechanical louvers that can open to expose a radiative surface and close to hide it. While functional, traditional mechanical louvers are bulky, expensive, subject to damage, and require significant thermal analysis to evaluate the effect of different sun angles.

In order to meet current and future space science goals, miniaturized spacecraft with greatly reduced size and mass, short design and build cycles and restricted resources (power, command, control, etc.) are required. Spacecraft in this very small size range, 10 to 20 kg, will require smaller thermal control subsystems. Their low thermal capacitance will subject them to large temperature swings when either the heat generation rate or the

IN-18
064308

thermal sink temperature changes. The ST5 Constellation, for example, has a requirement to maintain thermal control through extended earth shadows, possibly over 2 hours long.

2. Variable Emittance Thermal Control Surfaces

All spacecraft rely on radiative surfaces to dissipate waste heat. These radiators have special coatings, typically with low absorptivity and a high infrared emissivity, that are intended to optimize performance under the expected heat load and thermal sink environment. Given the dynamics of the heat loads and thermal environment it is often necessary to have some means of regulating the heat rejection rate of the radiators in order to achieve proper thermal balance. The concept of using a specialized thermal control coating or surface which can passively or actively adjust its emissivity in response to such load/environmental sink variations is a very attractive solution to these design concerns. Such a system would allow intelligent control of the rate of heat loss from a radiator. Variable emissivity coatings offer an exciting alternative that is uniquely suitable for micro and nano spacecraft applications.

Variable emittance thermal control coatings have been under development at NASA-Goddard Space Flight Center (GSFC) since the mid-1990's. These coatings change the effective infrared-red emissivity of a thermal control surface to allow the radiative heat transfer rate to be modulated upon command. Three technologies have been under consideration, electrochromic and electrophoretic devices, and most recently micro-electromechanical devices.

For electrochromic devices, the emittance modulation is achieved using crystalline electrochromic materials whose reflectance can be tuned over a broad wavelength (2 to 40 microns) in the infrared. The electrochromic process is a reversible, solid-state reduction-oxidation (redox) reaction. These materials become more reflective as the concentration of an inserted alkali metal (typically lithium) increases. This change is due to an increase in the electron free density, which causes the material to undergo a controlled transition between an IR transparent wide gap semiconductor and an IR reflective material. The electrochromic material is typically sandwiched between ITO electrical grids and is also in contact with an ion-conducting layer that contains the alkali metal. When a small bias voltage (typically +/- 1 VDC) is applied, the alkali ions shuttle to one side or the other, thus changing the effective emissivity of the surface.

Electrophoretic devices involve the movement of suspended particles (i.e., very small flakes) through a fluid under the application of a small electrical field. The particles carry electric charges that are acted upon by this field thus causing their movement through the fluid medium. This medium is highly absorptive. The particles are made of, or coated with, a material that has a high reflectivity. When an electric field is applied the flakes are attracted to the electrode and align themselves with their faces parallel to the surface, thus displacing the absorptive fluid medium. They overlap and form an essentially flat surface that is both a high reflector and spectrally reflective. When the electric field is reversed the flakes are drawn to the electrode on the other side of the highly absorbing fluid medium. The exposed surface thus becomes highly absorptive. This process has been demonstrated to be reversible and should be repeatable for thousands of cycles.

3. Miniature Louvers

Another way to change the emissivity of a surface is the use of mechanical louvers, where, similar to the macroscopic, traditional thermal louvers, a mechanical vane or window is opened and closed to allow an alterable radiative view to space. Micro-machining techniques allow the designer to generate arrays of such structures with feature sizes on the order of micrometers. This approach

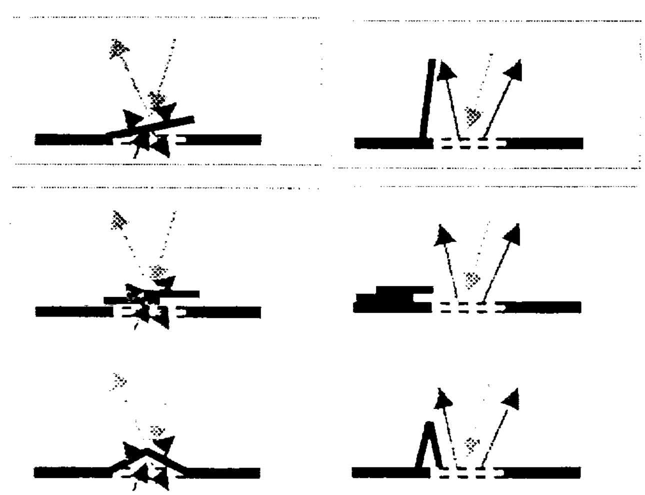

Fig. 1: DIFFERENT CONCEPTS FOR A THERMAL CONTROL LOUVER

to variable emissivity control offers distinct advantages over traditional mechanical louvers with regard to size, weight, mechanical complexity, redundancy, and cost. In addition, the analysis effort is simpler since the dependence on sun angle can be eliminated by having micro louvers face all directions. This micro louver approach may offer distinct advantages over the electrochromic and electrophoretic approaches discussed above.

Figure 1 shows three different concepts of the micro louver approach. Micro-electro-mechanical (MEMS) louvers are similar to miniature venetian blinds that can be opened or closed to expose an underlying thermal control coating. The base material for the current device is silicon while the louvers are coated with a metal, in this case gold. Gold coated surfaces have a very low emissivity, with values of 0.02 to 0.03 commonly quoted. The MEMS louver is typically 500 μm on a side and cover an underlying, high emissivity surface. The "effective emissivity" of the surface can be modulated in a controlled fashion by varying either the open area of the micro-louvers or the total number of micro-louvers that are opened.

The emittance variability is given by the difference in area-coverage of the open and closed louver. This may be on the order of 90 %, which allows emissivity-variations somewhere between 0.1 and 0.9. The louvers can be actuated actively by remote control or passively using smart feedback such as bi-morph devices. The small feature sizes make these louver concepts compatible with miniature spacecraft.

4. Prototype MEMS Louver

The development of the louver concept can be divided into three different tasks: The louver design, the louver fabrication, and the actuation. Our early efforts focused on the design of the louvers for fabrication using the MCNC Multi-user MEMS process (MUMPs). Two generations of prototype MEMS louvers have been developed. Both sets of the polysilicon devices were designed at APL, fabricated at the MCNC Technology Applications Center under the MUMPs program, and subsequently released and tested at APL. . This first iteration of MEMs louvers was fabricated at the MEMS Technology Applications Center , Research Triangle Park, NC under the he Multi-User MEMS Processes, or MUMPs, and subsequently released and tested at APL. The second generation louver designs include improvements to the hinge designs, corrugated louver structures, and gold coating on the louvers. For the design of the hinges, a rapid prototyping stereo lithography technique was used, where the design was "printed" as a plastic mold. This

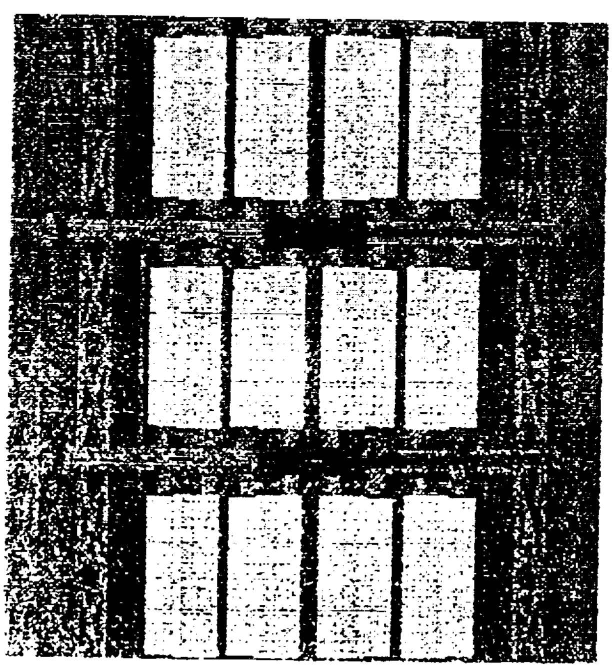

Fig.2: ARRAY OF MEMS LOUVERS WITH MANUAL ACTUATION FOR SETS OF TWO EACH

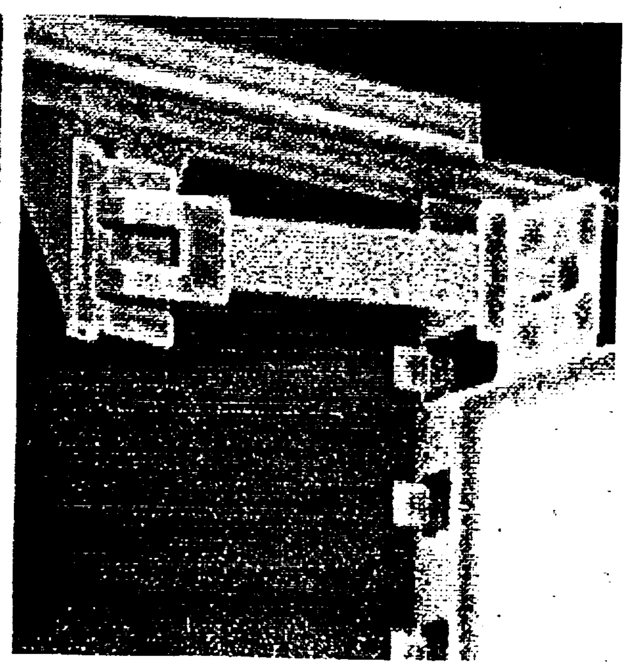

Fig. 3: HINGE DESIGN FOR THE MEMS LOUVERS IN *Fig.2*

allowed flaws in the hinge design to be detected at a early stage before running the relatively long MUMPs processing trail. Several sets of louvers have been grouped together to allow for measurements of emissivity variation using an infrared imager with a close focus attachment. All louvers were designed for manual actuation. A scanning electron microscope (SEM) image of a group of louvers is shown in *figure 2*. This image shows an array of six dual-sets of louvers together with the structure to allow manual actuation. The corrugated structures in the louvers are visible as well as the gold coating and the etch holes. In order to prevent bending from residual stress after the gold coating, the louvers were coated in small, non-overlapping 20x20 μm areas. After the release only a small amount of bending was observed on the louvers which was reduced even further by thinning the gold coating to 100 nm. *Figure 4* shows SEM images of the louvers in the semi-open and open condition.. The other concepts depicted in *Figure 1* were also developed and prototypes for these devices are shown in *Figures 5 and 6*. The F*igure 5* shows

three "sliders" next to each other, each about 0.5 x 1.5 mm in size. The actuation was intended to be manual. The sliders also are gold coated and have corrugated structures for support. *Figure 6* shows a "folding louver" in the closed position. All SEM pictures were taken after the louvers were released, and any residual polysilicon was removed from the back surface. Although transparent at the IR wavelengths of interest, the silicon substrate itself is not suitable as a radiative surface due to its low emissivity and high reflectivity. Hence, after removal of the silicon substrate by etchant during post processing these louvers will be placed on a surface suitable for radiative heat loss.

5. Infrared Emissivity Measurements

Although the louvers are not mounted on a radiator, infrared images taken at room temperature in the 8-12 μm wavelength range allow a reasonable demonstration of their performance. Infrared images were taken using a Mikron Scanner, which scans the image with two mirrors onto a HgCdTe detector with a spatial resolution of 320x240 pixels. Using a close-focus attachment, the image resolution was in the order of 2 μm per pixel, way below the resolution limit given by the wavelength. Calibration was performed on an emissivity standard, and the room temperature background was subtracted. An emissivity image of the materials on the dies is shown in *Figure 7*. The structures are the gold-coated "sliders" on the left, the silicon structures (for the manual actuation) in the middle, and the SiN subsrtate coating on the left. The emissivity varies from 0.3 for the SiN to 0 (0.02 is the literature value[1] for gold). The same measurements were performed for the louver arrays in the closed and open position. The emissivity images are shown in *Figures 8 (array closed) and 9* (array partially open). The average

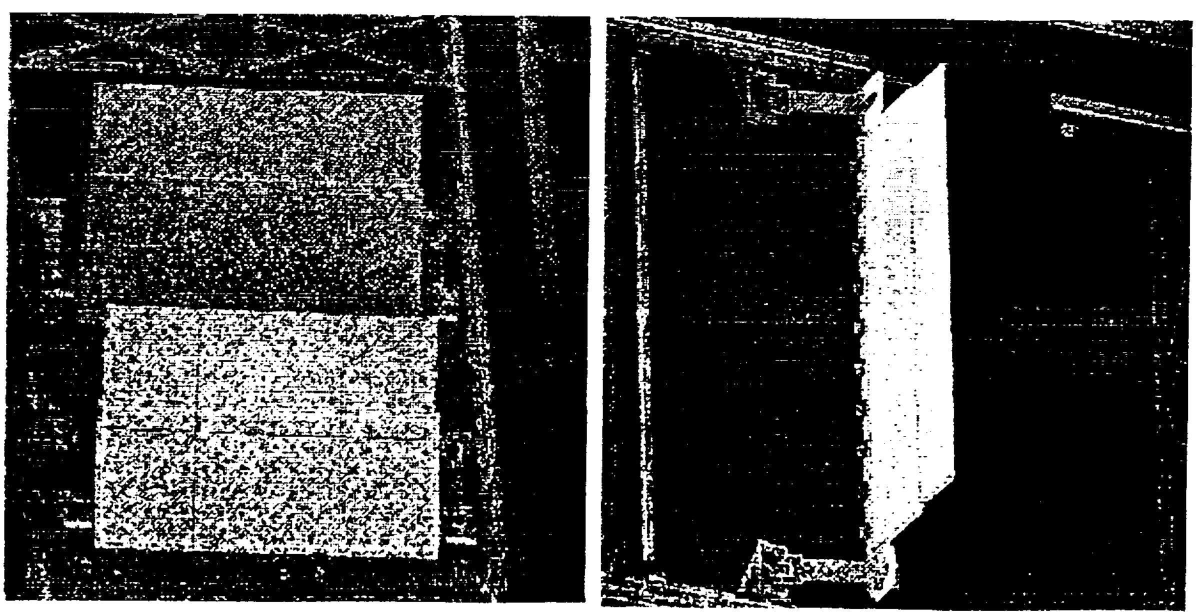

Fig. 4: SEM IMAGE OF LOUVERS IN THE SEMI-OPEN AND OPEN POSITION. THE WIDTH OF EACH LOUVER IS 500 μM

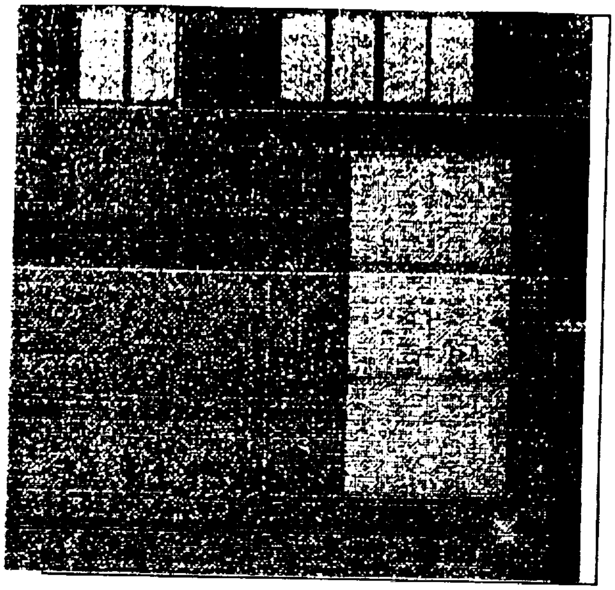

Fig. 5: SEM IMAGE OF A "SLIDER", ARRAY, EACH 0.5 X 0.75 MM

(TO BE SUPPLIED)

Fig. 6: SEM IMAGE OF A "FOLDING LOUVER"

emissivity □ for the louver area changes from 0.1 in *Figure 8* to 0.2 in *Figure 9*, according to $\square = 0.3 * A_0 + (n-n_c) * A_n$, where A_0 is the uncovered area, n is the number of louvers with area A_n, and n_c is the number of closed louvers. 0.3 is the emissivity for the SiN background. Experimental setup improvements will allow measurements to be taken at increased temperatures with reduced background radiation. (the discussion immediately above is confusing to me)

Hence, a change in the effective emittance of a surface has been successfully demonstrated. Significant improvements to the data quoted above appear possible once certain design improvements, such as a better radiative substrate and denser packaging, can be instituted.

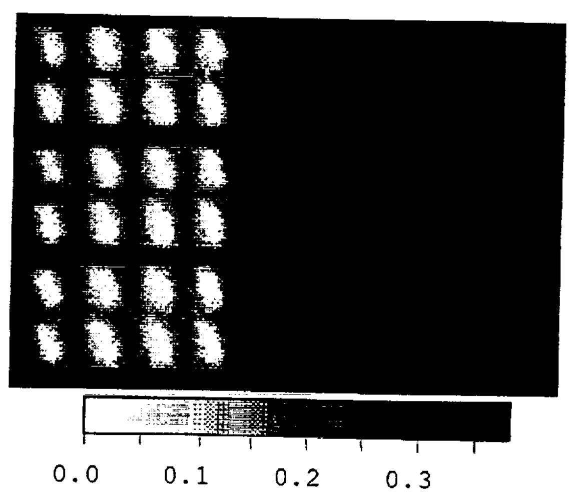

Figure 7. EMISSIVITY IMAGE (2 X 3 MM)OF CLOSED, GOLD COATED "SLIDERS" (LEFT), SI STRUCTURES, AND BARE SIN.

6. Louver actuation for thermal control

For a successful application of the louver concept for spacecraft thermal control, an actuation mechanism has to be identified which allows the highest individual louver control possible with a minimum of space necessary. Note, that all the space covered by the actuation is not active and presents an emissivity bias. Highly individual louver control provides the best accuracy in setting the emissivity and further allows increased control of the spatial emissivity variations. Further, low power consumption and zero power in a static condition are required for small spacecraft applications. Several actuation mechanisms have been considered and in part, implemented. One implementation was the use for an electrostatic comb drive. While this is a low power, reliable and straight-forward designed MEMS actuation mechanism[2], disadvantages arise due to the large area requirement and from a space-craft perspective, relatively high driving voltages. In addition, static charging of the surface from space radiation could be an issue. Another mechanism used in some prototype louvers is a "heatuator"[3], which does not have the high voltage requirement but still takes up a lot of area on the louver chip. Both actuation mechanisms are solutions where the actuation devices could be placed outside of the active area above the radiator, but in this case individual control of the louvers will be difficult.

A different actuation mechanism is under consideration for the next generation. It involve coating of the actuation structures with a metal different than gold to create a bi-morph, which can is heated electrically to generate actuation in connection with the change due to different thermal expansion. Such an actuation mechanism could be used in a *smart* way, where the surface temperature directly controls the louver actuation. Similar in function could be the use of shape memory alloy coatings such as Titanol for the actuators[4].

7. Reliability Aspects

There are many reliability issues surrounding the extended use of MEMS devices for spacecraft applications.[5] The louvers must survive through the launch and operate in the harsh environment of space. In addition, the effects of pre-launch storage must also be taken into consideration. A non-exhaustive list of the of MEMS reliability concerns includes: stiction, ground contamination, fatigue including radiation, wear, and vibrational loading induced. An extended evaluation of these issues is currently under study and only a brief overview is given here.

8. Conclusions

To date, two generations of prototype MEMS louvers have been developed clearly demonstrating the feasibility of using arrays of devices for miniaturized satellite thermal control. Successful actuation of the initial devices and the results of preliminary emissivity testing indicated the validity of the hinged louver concept for thermal control applications. After verification of space qualification of the louvers, the next step will be to fly one or more very small prototypes in a standard calorimeter as experiments on upcoming spacecraft.

Numerous future NASA missions such as the ST5 Constellation, will undergo significant changes in its thermal environment and will require means of modulation in the spacecraft's' heat rejection rate. Specifically, the ST5 Constellation spacecraft will undergo an approximately 2-hour or longer eclipse during which time the instruments must survive and possibly operate. Given their small capacity for power storage by batteries and low thermal capacitance, the best strategy will be to "close off" their radiator area and radically reduce their heat loss rate. One recent Aerospace study[6] predicted heater power savings of 50 to 90% and a nearly 4:1 reduction in component temperature variations. In addition to the obvious weight and power savings, the technology of MEMS louvers for thermal control would greatly simplify spacecraft design and qualification testing and also allow adaptive response to changing power levels or unexpected thermal environments once on-orbit.

Acknowledgements

The program was funded by NASA under contract XXXX . Thanks go to R.L. Edwards and J. Layton and XXX for their help on processing of the MUMPs dies.

References

[1] IR Handbook
[2] Comb-drive reference
[3] Heatuator reference
[4] Shape Memory Alloy Reference
[5] JPL 99-1
[6] Aerospace Study