HEAT PIPE INTEGRATED MICROSYSTEMS*†

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Abstract

The trend in commercial electronics packaging to deliver ever smaller component packaging has enabled the development of new highly integrated modules meeting the demands of the next generation nano satellites. At under ten kilograms, these nano satellites will require both a greater density electronics and a melding of satellite structure and function. Better techniques must be developed to remove the subsequent heat generated by the active components required to meet future computing requirements. Integration of commercially available electronics must be achieved without the increased costs normally associated with current generation multi chip modules. In this paper we present a method of component integration that uses silicon heat pipe technology and advanced flexible laminate circuit board technology to achieve thermal control and satellite structure. The electronics/heat pipe stack then becomes an integral component of the spacecraft structure.

The Stacked Nanosat

Thermal management on satellites has always been a problem. The shrinking size of electronics and voltage requirements and the accompanying reduction in power dissipation has helped the situation somewhat. Nevertheless, the demands for increased onboard processing power have resulted in an ever increasing power density within the satellite body. With the introduction of nano satellites, small satellites under ten kilograms and under 1000 cubic inches, the area available on which to place hot components for proper heat dissipation has dwindled dramatically. The resulting satellite has become nearly a solid mass of electronics with nowhere to dissipate heat to space.

Greater on-orbit mission requirements will mean higher power components and a greater number of them. Components will need to be placed on circuit boards stacked within the interior of the satellite. State-of-the-art ASICs (Application Specific Integrated Circuits) and PLDs (Programmable Logic Devices) can be expected to operate over 125 MHz, dissipating as much as 3-5 Watts each, even though the supply voltage will drop to 1.8 V. Nanosats using laser communications will need high power lasers cooled to maintain their reliability. In either case, the spreading of heat away from these devices is crucial. Therefore, a method of removing heat from the interior of the satellite is required.

One possible solution to this problem is the use of silicon heat pipes interposed between electronic boards to carry heat efficiently to the edges of the nanosat. A heat pipe is 200 to 300 times better at carrying of heat than solid copper [1]. Figure 1 shows an example of such a nano satellite.

The silicon heat pipe is attached to an aluminum frame using a thermally conductive epoxy or solder preform. The frame serves three purposes. First, the aluminum frame provides a heat conduction path from the edge of the heat pipe to radiators on the surface of the satellite. Secondly, it serves as an attachment point for extended structures attached to the satellite such as solar panels, radiators, antenna and telescopes (for communications or sensors). Finally, the

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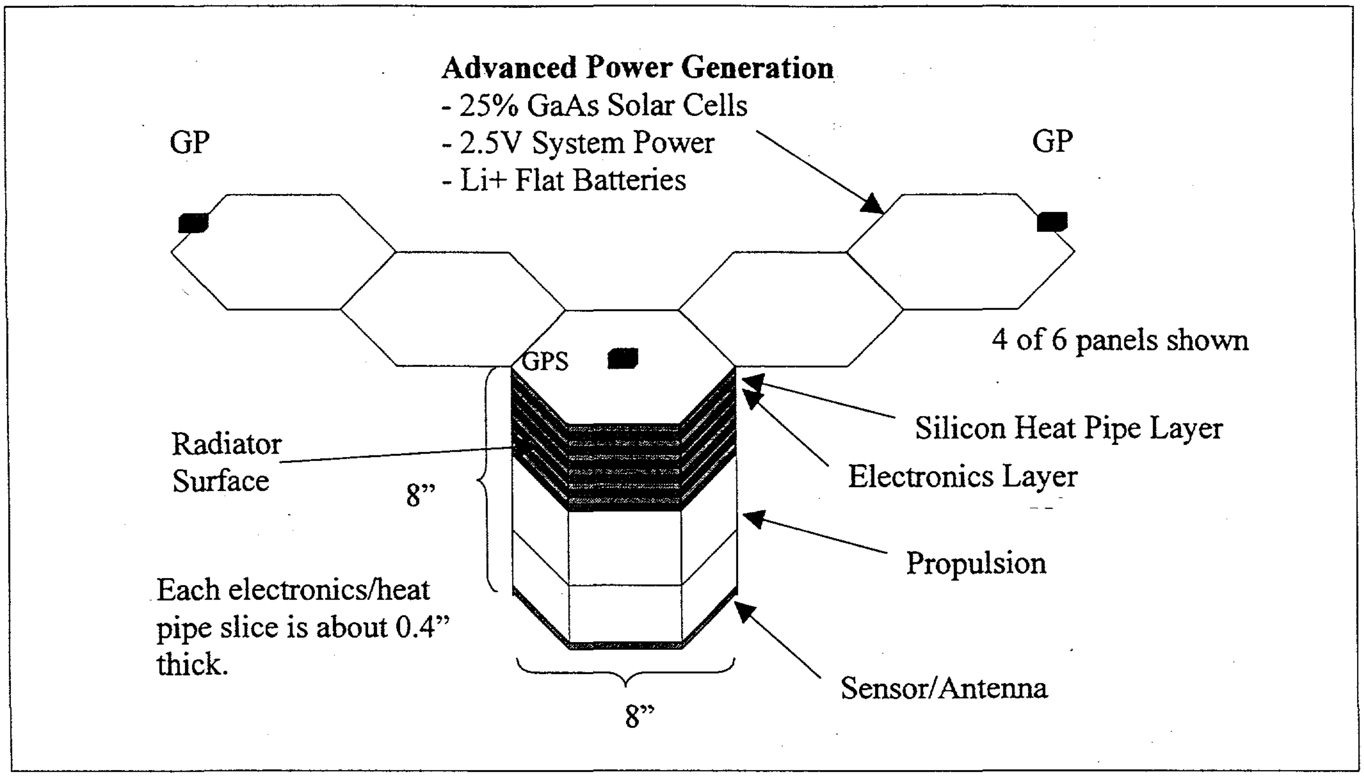

Figure 1. Example of a nanosat constructed of heat pipe and electronic slices.

aluminum serves as an effective radiation shield to protect the enclosed components. By having a measure of radiation shielding, more commercial grade components can be used and the cost of the nanosat can be kept to a minimum. Radiators, located at the edge of the heat pipe slices, can be as simple as anodized aluminum or they can be more sophisticated, having sun louvers. The radiators themselves could contain heat pipes and extend away from the satellite body to provide enhanced cooling capacity.

An 8 inch diameter hexagonal satellite, 8 inches tall, has at best 234 square inches of external surface from which to radiate heat into space. Assuming the radiators are on the sides and the bottom and are painted with white epoxy (which can dissipate 391 W/m2, this nanosat can dissipate from 40 W in full sun to 60 W in shadow[2]. It is apparent that even a nanosat can be expected to generate significant amounts of heat in the high density interconnect (HDI) circuits inside that must be dealt with properly[3].

The electronic components are surface mounted to a thin, lightweight, multi-layer copper on flexible film as shown in Figure 2. The

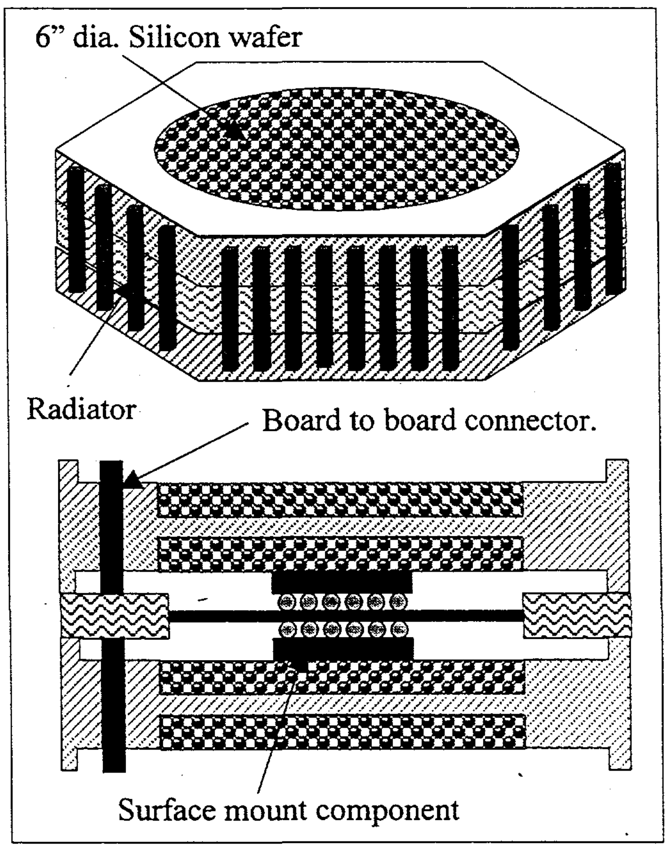

Figure 2. Integrated silicon heat pipe and electronics stack.

packages make thermal contact to the surface of the silicon heat pipe through soft thermal pads. Electronic components can be placed on both sides of the flexible circuit interconnect.

Silicon Heat Pipes

A heat pipe is a sealed chamber with a cooling liquid introduced under partial vacuum [4][5]. Heating of the liquid by hot components placed on the surface of the heat pipe evaporates the liquid forming vapor. The heat of vaporization carries heat away from the active component. The vapor condenses at the cool edge delivering heat to the environment. A wick structure, consisting of very small gaps etched into the silicon, draws the condensed liquid back to the hot area by capillary action. Continuous flow of liquid and gas is assured since this is a closed system. The cross section of a typical heat pipe is shown in Figure 3.

The silicon heat pipes are constructed of a silicon wafer that has been etched with a fine wick pattern. An example of one such cross pattern is shown in Figure 4. One advantage in using silicon heat pipes for heat removal is the reduction in the heating of one component by a neighboring component. As illustrated in Figure 3, the use of a silicon heat pipe dramatically reduces the maximum temperature of the active component and nearby silicon as compared to a solid metal heat sink. This graph illustrates only relative temperature. This means that components can be placed closer to each other resulting in a higher density packing of the components.

Flexible Circuit Board Design

Sandia is currently developing a circuit board that in essence becomes part of the structure of the satellite. In an effort to keep the weight as low as possible, we are using the card edge to serve as the outer wall of the satellite. The circuit board has an FR4 board around the edge which is approximately .075" thick.

The edge serves as a ridge connection surface for surface mounted board-to-board connectors. These connectors make-up the electrical signal bus and also serve to distribute power throughout the satellite. A flexible user definable bus consisting of 500 lines is located at the periphery

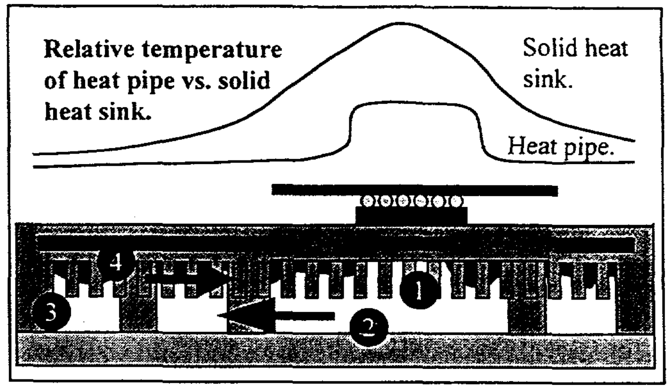

Figure 3. Silicon heat pipe cross section with relative thermal profile compared to solid metal heat sink.

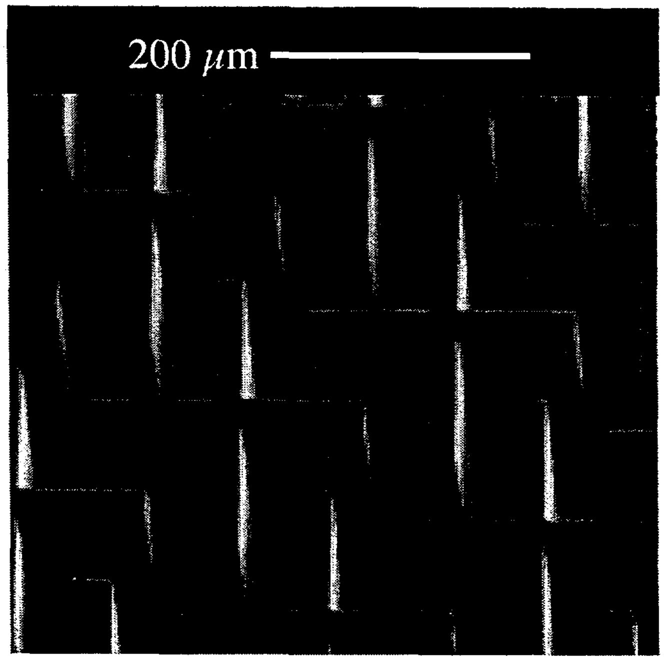

Figure 4. Silicon heat pipe wick structures etched 325 um into a silicon wafer.

of the circuit-card. Six 100-pin connectors are distributed around the periphery of the satellite. One of the connectors is allocated as a PCI bus. The connectors are connected in a stacked fashion through holes in the aluminum frame holding the silicon heat pipe. The routing resources within this flexible interconnect scheme can be allocate as needed by the designer.

The card edge has a hexagonal shape that matches the shape of the interposing heat pipe carrier. The inside of the board is a circular "drum head" multi layer copper on laminate flex circuit. The components are attached to the circuit board in this area using reflow solder techniques. This is similar to wafer level chip scaled packaging in that very high circuit densities are achievable with the ability to rework/repair components as needed [6].

Integrated Silicon Heat Pipe and Electronics

Silicon heat pipes have a number of advantages over heat pipe constructed from other materials. Silicon heat pipes offer the ability to put the heat pipe structure beneath the active components of a processed silicon wafer. This would be one way of efficiently cooling the heat generated by wafer scale integrated systems. Using this technique, all the functions of a satellite could be reduced to a few silicon wafers. The integration of the heat pipe and the electronics would further reduce the size and weight of the satellite.

The "silicon satellite", while possible to build in the near term, might not be the most desirable form for building a nanosat. The costs might be out of reach of most missions and only feasible for the high volume applications where the cost of the silicon electronic/heat pipe wafers that make up each subsystem can be amortized over thousands of satellites. Still the cost may be too high since nearly all commercially available electronics are packaged for use on tin/lead solder interconnect systems i.e., printed circuit boards. Repackaging components for other applications could be costly. Not all silicon processes are easily compatible. The variety of devices needed to realize a fully operational system might preclude complete integration. There are also Intellectual Property (IP) issues. How do you get access to every design of every integrated circuit needed in your system? Issues such as these may never completely be resolved.

High power components can be directly attached to the silicon heat pipe because the coefficient of expansion more closely matches that of the die. The removal of the expansion matching interposer means that greater heat transfer can be sustained and lower die temperatures can be maintained.

Summary

In the future, the size of satellites will decrease dramatically while the functional requirements will push up the power dissipation of the electronics. The result is more heat being generated in a smaller volume. The development of the nanosat is will require better ways of removing the heat to the satellite radiators. The silicon heat pipe can be used to move heat efficiently from the center of the satellite to the edges where it can be radiated into space. The silicon heat pipe can be stacked with electronic slices creating a high density 3D electronics package that can also serve as the structure of the nanosat.

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[1] Eds Wiley J. Larson and James R. Wertz, "Space Mission Analysis and Design," Microcosm, Inc. and Kluwer Academic Publishers, 2nd Ed., 1992, p. 413.

[2] Calculated using Ref [1] Eq. 11-16 and Table 11-42, pp. 420-422.

[3] Jerry Rusell, "The Evolution of Thermal Management in HDI," HDI: The Magazine of High-Density Interconnect, Sept. 1998.

[4] David Benson, et al, "Ultrahigh-capacity Micromachined Heat Spreaders," Microscale Thermophysical Engineering, vol. 2(#1), Jan-Mar 1998, pp. 21-30.

[5] In the News, "Heat Sinks Alleviate Thermal Spreading Resistance," Advanced Packaging, March 1999, p. 18.

[6] Joseph Fjelstad, "Wafer-Level CSPs Using Flexible Film Interposers," HDI: The Magazine of High-Density Interconnect, Mar. 1999.