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SAND97–0100 • UC–704
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Micro-Machined Heat Pipes in Silicon MCM Substrates

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

SF2900Q(8-81)

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Abstract

Multichip modules (MCMs) containing power components need a substrate with excellent heat spreading capability to both avoid hot spots and to move dissipation heat toward the system heat sinks. Polycrystalline diamond is an excellent MCM heat spreading substrate but remains several orders of magnitude too expensive and somewhat more difficult to process than conventional mother-board materials. Today's power MCMs concentrate on moderately priced silicon wafers and aluminum nitride ceramic with their improved thermal conductivity and good thermal expansion match to power semiconductor components in comparison to traditional alumina and printed wiring board materials. However, even silicon and AlN substrates are thermally challenged by designers' needs. We report on the integral fabrication of micro-heat pipes embedded in silicon MCM substrates (5 x 5 cm) by the use of micromachined capillary wick structures and hermetic micro-cavities. This passive microstructure results in more than a 5 times improvement in heat spreading capability of the silicon MCM substrate over a large range of power densities and operating temperatures. Thus diamond-like cooling is possible at silicon prices.

Contents

Introduction

This report is submitted as a completion requirement for a Sandia LDRD project "The Ultimate Heatpipe" which was performed in fiscal years 1995 and 1996. David Shen was the principal investigator during much of this period, but has subsequently left Sandia to further his formal education.

The total project knowledge can not yet be reported since intellectual property is at stake. A technical disclosure was submitted on some of the inventions of this LDRD effort. The patent application was submitted and returned with only one minor revision requested. At this point the revised application is back in the patent office. We expect this patent to be awarded shortly. In addition, another technical disclosure is being prepared which contains some technology generated during this LDRD as well as during related activities. Sandia is in preliminary negotiations with several companies interested in obtaining intellectual property rights in this area. For these reasons this report is sticking to exactly what has been publicly disseminated in the past.

Technical Problem: Functional density continues to increase in microelectronics systems. With this concentration comes higher waste heat density. For example, top end microprocessors can dissipate 5-40 Watts over a footprint of 4 square centimeters. With this trend to cope with, thermal management techniques have proliferated. In all cases, an improved thermal conductivity in the substrate material results in higher density and cooler operation of the system. To this end industry has developed substrate materials that are more conductive than traditional alumina ceramic and glass / epoxy laminates. (See Table I).

Of course some metals like copper have fairly high thermal conductivity. However, the high thermal coefficient of expansion (TCE) of copper compared to silicon ICs produces a reliability problem on assembled substrates undergoing temperature or power on/off cycles. Thus one key to thermal management would be to have a material that has high thermal conductivity and also matches the TCE of silicon or GaAs. To this end much research has taken place looking at AlN, polycrystalline diamond, and SiC materials.

Thermal management is not just solid material properties but also fluid flow dynamics. The fan is ubiquitous as a way of getting airflow to cool a chassis. Some early work by Fabian Pease at Stanford showed that pumped liquids through microchannel substrates could achieve 2000 W/cm^2 levels of cooling. However, for space and weapon use only passive systems can achieve high reliability under all conditions. Normally, passive systems implied solid substrate bulk heat conductivity. However, heat pipe technology offers a passive system with effective heat conductivity much above bulk materials.

A third consideration is cost. Polycrystalline diamond has many great substrate properties, but cost is not one of them. At the time of this study, diamond substrates 1 x 1 x .2" cost $1000 with little indication of becoming cheaper in time.

The invention of the silicon substrate with embedded micro-heatpipes was initiated by this list of needs:

1. A substrate of high thermal conductivity but a match of TCE with components.

2. A passive system driven only by the waste heat.

3. A potentially manufacturable but low cost substrate.

The next chapter is a slightly revised version of the paper given at the IEEE Multichip Module Conference in Santa Cruz in February 1996 (MCMC'96). This paper reveals all Sandia wants to publicly release before intellectual property rights are completely addressed.

MATERIALS	Therm Conduct W/cm-K	TCE 10-6 / K	Cost substrate $ / square inch	scaling with area cost trend
Alumina	**0.25**	**11.3**	**$0.09**	**6" limit**
FR-4	depends on copper	13.0	$0.07	constant to 36"
AlN	1.00 - 2.00	4.1	$0.35	6" limit
Silicon	1.48	4.7	$1.00	6"-10" limit
heat pipe in silicon	**8.00 - >20.00 (?)**	**4.7**	**$3.00**	**6"-10" limit**
Al	2.37	41.8	$0.0009	scales as area
Cu	3.98	28.7	$0.0015	scales as area
Diamond	10.00 - 20.00	1.0-1.5	$1000.00	scales as area sqd
Kovar	0.13	5.0	$0.027	scales as area
heat pipe in Kovar	**>8.00 (?)**	**5.0**	**$0.10**	**scales as area**
molybdenum	2.50		$1.25	scales as area
AlSiC	2.00 (at 70%)	7.1(70%)	$1.00 (?)	casting size limited

TABLE I

Micro-Machined Heat Pipes in Silicon MCM Substrates

Abstract

Multichip modules (MCMs) containing power components need a substrate with excellent heat spreading capability to both avoid hot spots and to move dissipation heat toward the system heat sinks. Polycrystalline diamond is an excellent MCM heat spreading substrate but remains several orders of magnitude too expensive and somewhat more difficult to process than conventional mother-board materials. Today's power MCMs concentrate on moderately priced silicon wafers and aluminum nitride ceramic with their improved thermal conductivity and good thermal expansion match to power semiconductor components in comparison to traditional alumina and printed wiring board materials. However, even silicon and AlN substrates are thermally challenged by designers' needs. We report on the integral fabrication of micro-heat pipes embedded in silicon MCM substrates (5 x 5 cm) by the use of micromachined capillary wick structures and hermetic micro-cavities. This passive microstructure results in more than a 5 times improvement in heat spreading capability of the silicon MCM substrate over a large range of power densities and operating temperatures. Thus diamond-like cooling is possible at silicon prices.

Motivation

Substrates with higher thermal conductivity are continually under development to meet the demand of increasing power density on modules. For example, considerable effort in polycrystalline diamond [1] and AlN ceramic are underway today. In addition, several companies market metal cold plates which transfer heat from a substrate through heat pipes to a remote condenser unit, all within a desktop computer.

After much development, the cost of a one inch square diamond substrate is still in the \$300-\$1000 range. In addition, cost scales much faster than substrate area. Heat pipes intended for electronics cooling are scaled down versions of larger designs of the past but still are relatively large compared to the working substrate to be cooled. To overcome the cost and size difficulties, Sandia Labs pursued a concept of embedding micromachined heat pipe structures within an otherwise standard silicon substrate (See Figure 1). This results in a passive fluid cooling system internal to the thin substrate. The resulting substrate is a large silicon area only twice the standard wafer thickness so that an MCM or power supply module could be built using this silicon (in wafer or rectangular format) as the foundation. With an effective heat conductivity comparable to diamond, the micromachined silicon spreads the heat from a local heat source (eliminates hot spots) and effectively transfers thermal energy to any heat sink in contact. In addition, such a structure still has the coefficient of thermal expansion of silicon; thus, power and temperature cycling poise little threat. Alternatively, the concept could be implemented with a metal sheet chosen with CTE near that of silicon (such as Kovar). The microformed embedded heat pipes would enhance the thermal conductivity just as in the silicon development units despite Kovar's conductivity of only 22% of the silicon conductivity. Since the working fluid conducts most of the thermal energy, the heat pipe efficiency could be high in spite of the lower Kovar conductivity.

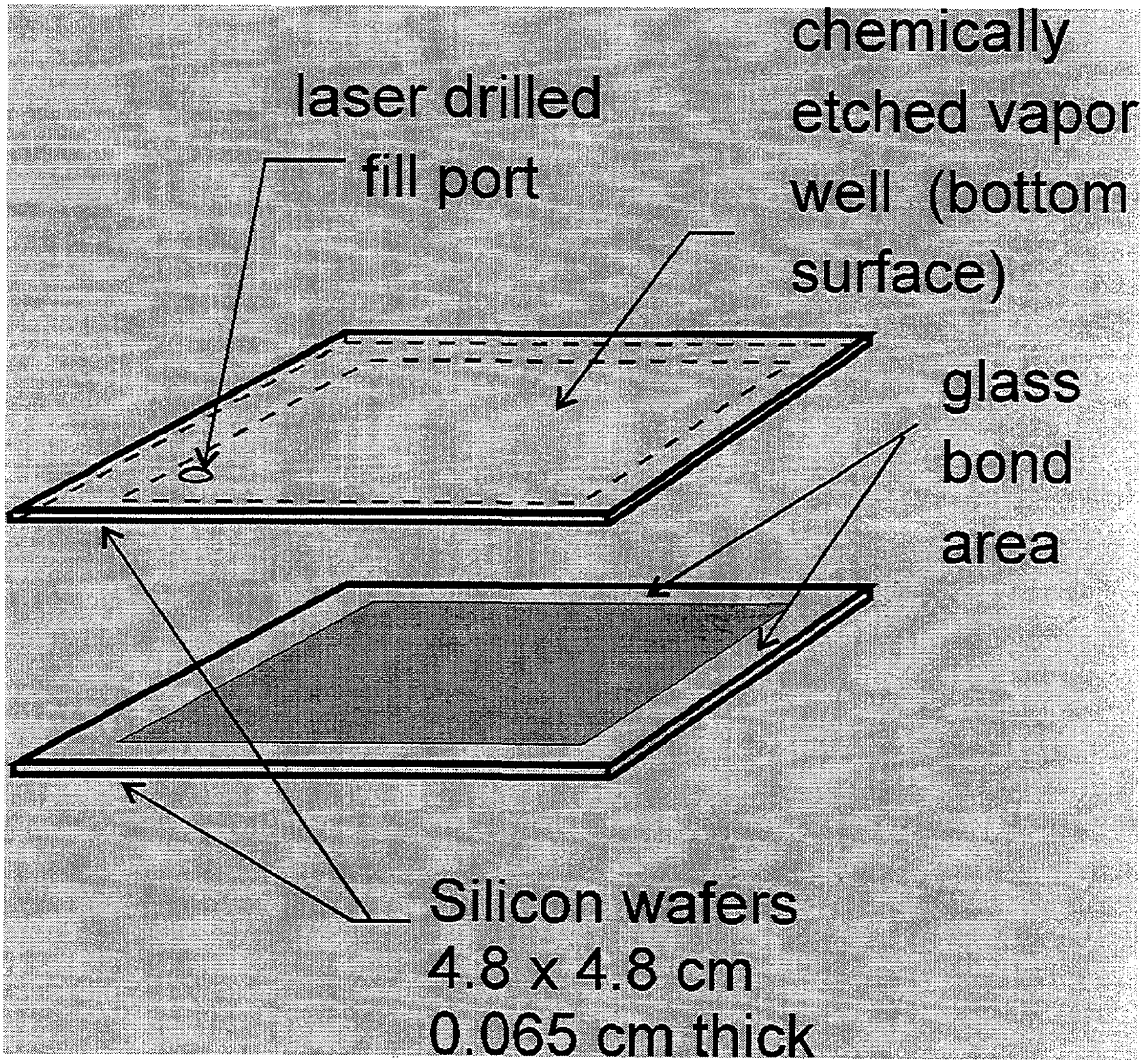

Figure 1. Two silicon wafers are bonded to form a hermetically sealed heat pipe.

Related work performed at Texas A&M [2] uses micro-channels etched in the back of the active silicon itself to transfer fluid and enhance heat spreading. Again their system is passive, requiring no active fluid pumping, with the device heat providing the fluid pressure drop. Their micro-channels are v-groves etched within the silicon and sealed with a metal deposition process.

Fabrication History

Sandia's development started with modeling based on macro-heat pipe formulas and experience. Such modeling suggested that for alcohol working fluid a wick structure with channels of 50-75 micron dimensions would be optimal. The first units were prepared by sawing 75 micron deep grooves into a wafer's surface using an IC wafer saw. The grooves were center spaced at 150 microns. Some of the surfaces were grooved in perpendicular directions (See figure 2). Over the last year, as deep etch techniques for silicon micro-machining have become standard, masked etching of more complex wick patterns has become the standard approach (See figure 3).

Wicking experiments comparing the cooling efficiency of long strips of silicon both with and without wicking patterns were reported in last year's proceedings [3]. These wick evaluation experiments performed with evaporation into air determined the maximum available liquid flow rate that can be driven by surface tension forces.

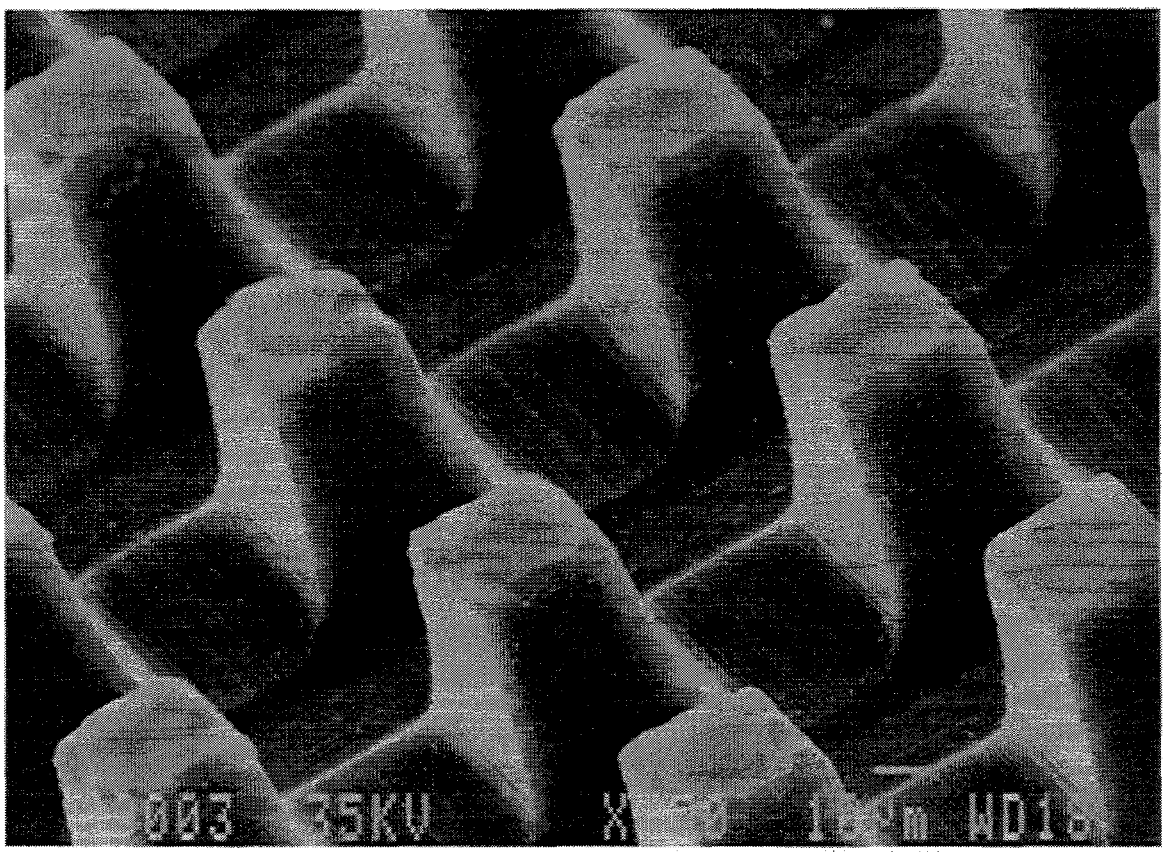

Figure 2. Wick pattern prepared with bidirectional saw cuts on a silicon wafer surface

Models of the wick performance and their relation to cooling in heat pipes were developed. Since then the experiments have been repeated in a chamber first evacuated and then equilibrated to the vapor pressure of the working fluid. The results correlated directly to the experiments in air.

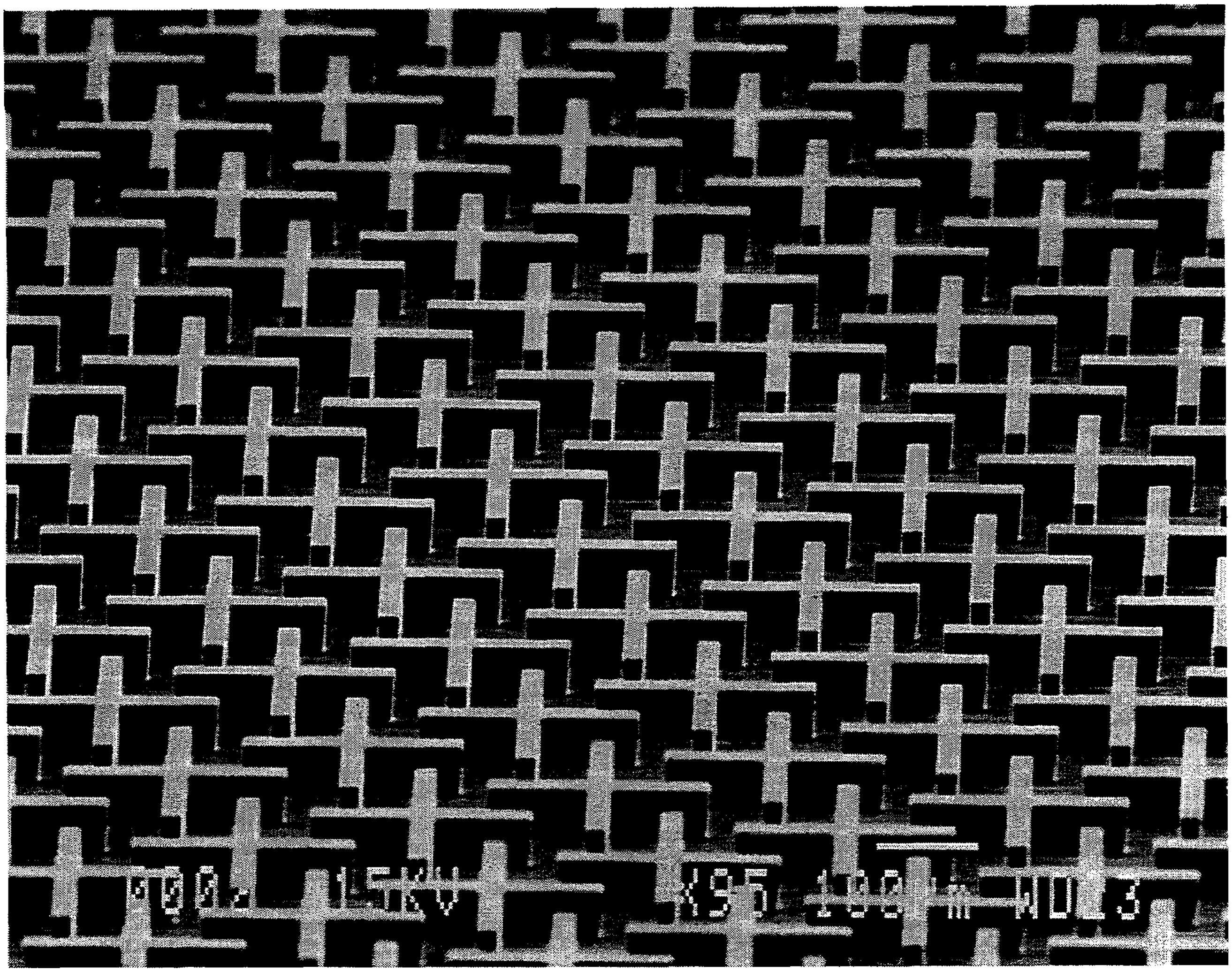

Figure 3. Wick pattern on silicon prepared by a photomask and deep plasma etch techniques.

To make enclosed micro-heat pipes the back of an approximately 4.8 cm square silicon substrate is patterned with a wick structure using deep anisotropic plasma etch. The boundary of the substrate is left unpatterned to act as the hermetic seal ring for the substrate assembly. The other silicon piece in the assembly is etched using KOH to produce a shallow well corresponding to the wick area in the substrate. A layer of borophosphate silica glass is deposited on this piece. The two pieces can now be wafer bonded together along the seal ring with temperatures of about 800 C for 10s of minutes [4]. This seal tests hermetic with standard helium leak checking performed at the most sensitive level.

After the appropriate MCM patterning, or thermal test chip bonding to the substrate, the heat pipe is filled through a small port laser drilled in the substrate. This filling includes evacuation of the embedded heat pipe, filling with a controlled quantity of alcohol or other coolant, and sealing of the assembly.

Testing

The finished units, one using a working fluid and one running empty as a control, are mounded in the edge clamping heat sink as shown in figure 4. The temperature profiles of the surface of the MCM substrate are measured with a high resolution infrared imaging camera. The Sandia test chip (ATC04) is applied to the center of the substrate and powered up to 10s of watts per square cm. The temperature gradients are recorded and compared to determine an effective heat conductivity of the silicon with the working embedded heat pipes. Results of a typical run are shown in Figure 5. The thermal gradients measured for the filled and unfilled assemblies show more than a factor of 5 higher conduction due to the passive fluid heat handling system.

Discussion

The effective conductivity shown in these tests are all in the range of 8 W/cm/C, or about twice that of copper and silver, and approaching the conduction of polycrystalline diamond substrates of the same dimensions. Additional development is needed to optimize wick and vapor return cavity designs, ease the evacuation and fluid charging procedures, and increase the units capacity to resist dryout at even higher power levels. Analysis and variations in designs tested to date indicate that considerable performance gains may be achievable.

References

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[3] Shen, D. S., et al., "Micro Heat Spreader Enhanced Heat Transfer in MCMs", Proceedings of the 1995 IEEE Multi-Chip Module Conference MCMC'95, Santa Cruz, pp 189-194.

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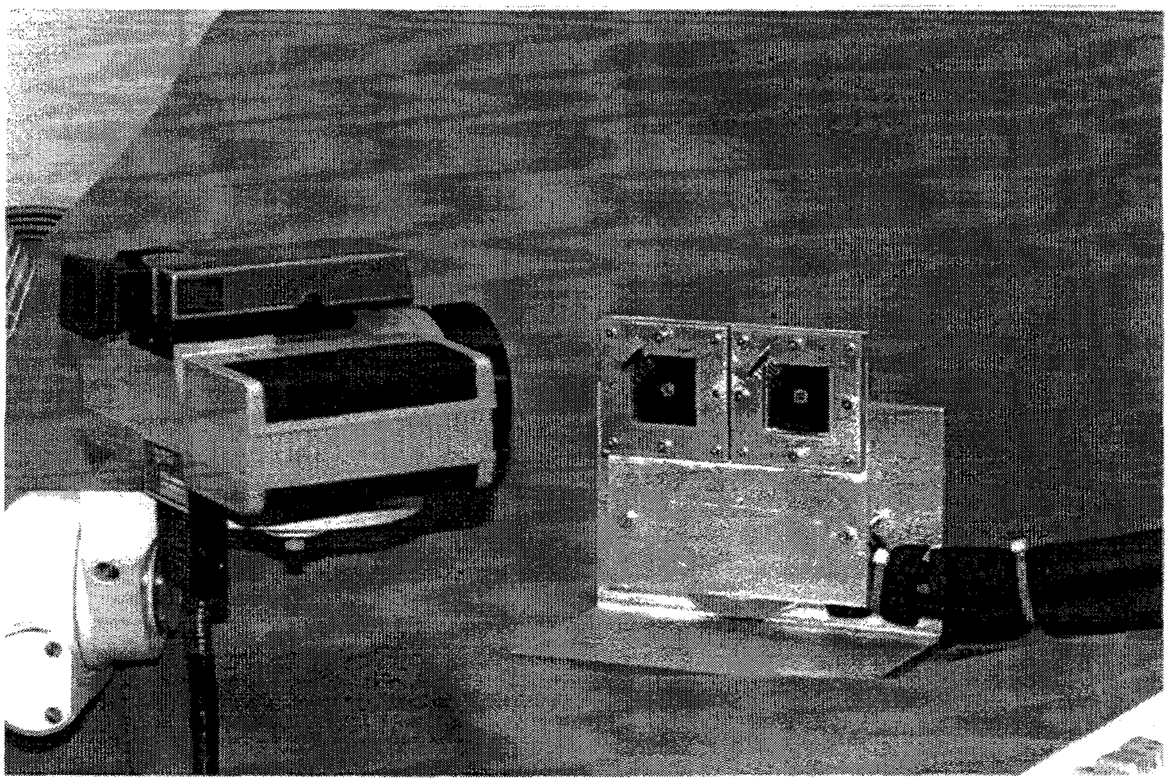

Figure 4. Testing with two heat pipe assemblies in a test fixture on a thermally controlled mounting frame. The infrared cameral allows detailed comparison of temperatures on the two assemblies.

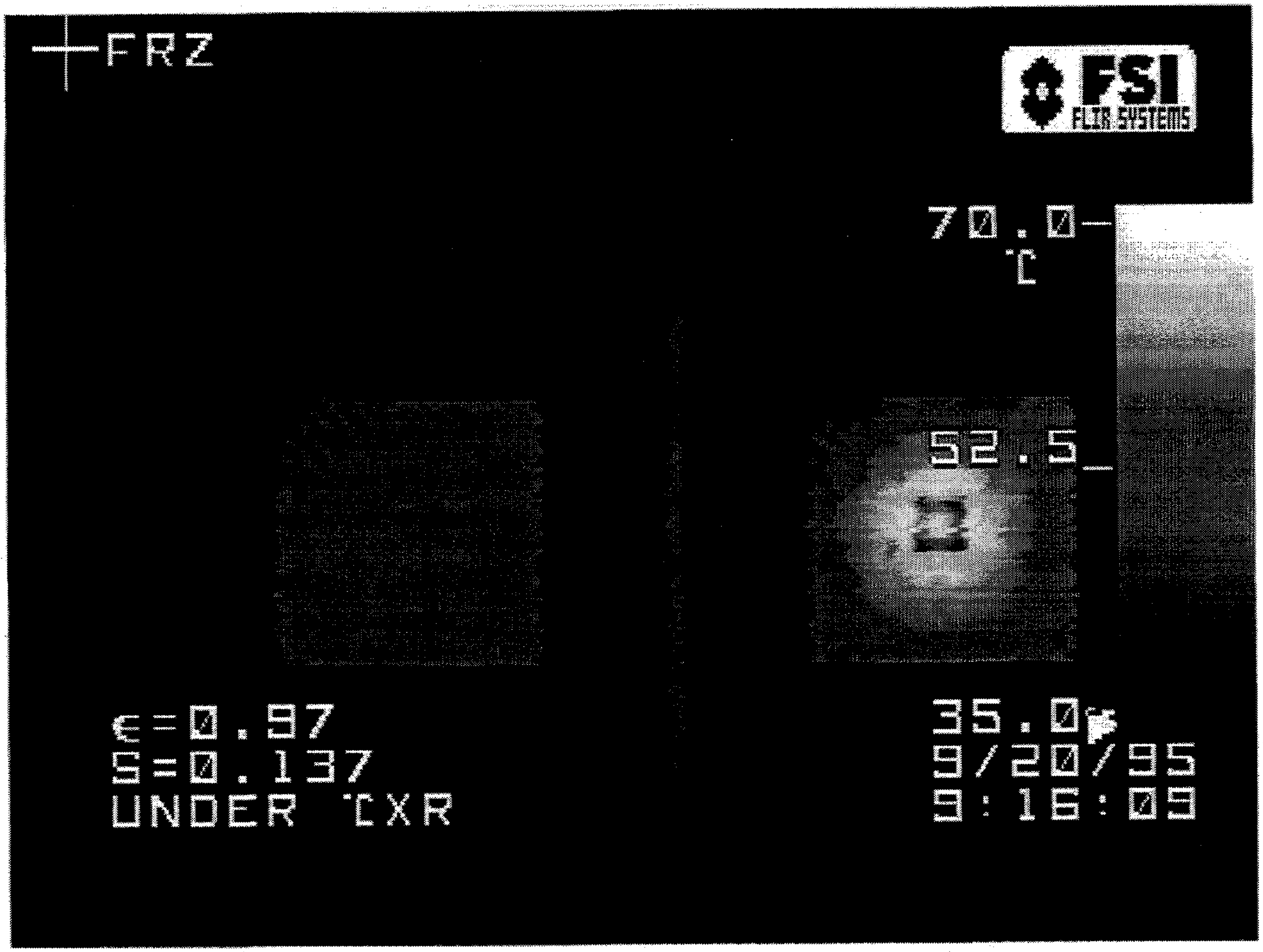

Figure 5. Temperature distribution on a methanol filled heat pipe (left) and an unfilled assembly (right). Temperatures on the left assembly are nearly isothermal with a factor of five smaller gradient than the unfilled assembly.

Conclusion

The silicon substrate with integral micro-machined heat pipes was a technical success. Heat conductivity higher than bulk metals and comparable to polycrystalline diamond were achieved. Further developments to optimize performance and lower manufacturing cost are necessary before the marketplace will embrace this advance.

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