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ON THE CHARGING AND THERMAL CHARACTERIZATION OF A MICRO/NANO STRUCTURED THERMAL GROUND PLANE

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ABSTRACT

As power densities in electronic devices have increased dramatically over the last decade, advanced thermal management solutions are required. A significant part of the thermal resistance budget is commonly taken up by the heat spreader, which serves to reduce the input heat flux and connect to an increased area for heat removal. Thermal ground planes are devices that address this issue by utilizing two-phase heat transfer achieving higher effective thermal conductivities than conventional solid heat spreaders. This study describes the need for and design of a charging station to accurately dispense the working fluid and a thermal characterization experiment to characterize performance. The design study includes detailed analysis of accuracy and validation of the setup.

NOMENCLATURE

A	Cross section area	[m^2]
$C_{shapefactor}$	Shape factor	[-]
k_{TGP}	Effective TGP thermal conductivity	[W/m-K]
L	Length	[m]
Q	Heat load	[W]
dT	Temperature gradient	[K]
TGP	Thermal Ground Plane	

INTRODUCTION

Due to advances in miniaturization and demand for high performance electronics, power densities in components have increased significantly over the last decade [1]. Heat fluxes approaching or exceeding 100 W/cm^2 [2] are becoming more common in high performance electronics applications posing significant challenges to the thermal management system. As electronic components operating temperatures are limited, it is normally desirable to remove the heat with a minimum temperature difference between the microelectronics and the ultimate heat sink. This translates into a desire for cooling solutions to have minimal thermal resistance.

Common components of the thermal resistance budget include thermal interface resistance, heat spreading and convection to the coolant medium. Heat pipes are often employed to efficiently spread heat to the convective surface area.

Heat pipes are systems consisting of a hollow chamber lined with a wicking structure as illustrated in Figure 1. This wicking structure is filled with a working fluid under saturation conditions. Heat conducts through the substrate and wicking structure to the wick-liquid interface. When heat is added, fluid evaporates from the wick structure. Gradients in vapor pressure drive vapor to cooler areas of the device where it recondenses and rejects its heat. Capillary forces in the wick return the liquid to the evaporator and the cycle is repeated. Due to the efficiency of the two-phase heat transfer processes, heat pipes are able to have effective thermal conductivities that are significantly greater than common solid conductors such as copper or aluminum.

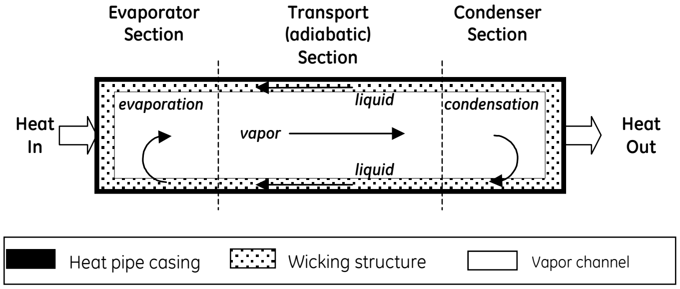

Figure 1. Heat pipe operation

The Defense Advanced Research Projects Agency (DARPA) has recognized the need for advanced thermal solutions to enable next generation high performance electronics systems and multi-chip modules under a program to develop a novel thermal ground plane (TGP). A thermal ground plane is a planar heat-spreading device at near uniform temperature that can function as thermal “ground”. Program targets for the final device include an effective thermal conductivity 100X greater than current copper alloy substrates (target: 20.000 W/m-K effective thermal conductivity).

An intermediate objective is to produce a device of dimensions 30mm x 30mm x 3mm (Figure 2, Figure 3). Development challenges, including fabrication, charging, and thermal performance characterization are amplified by the limited dimensions of this intermediate prototype.

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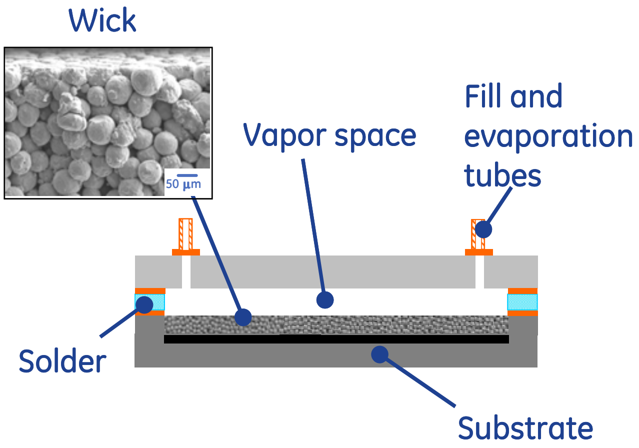

Figure 2. TGP components

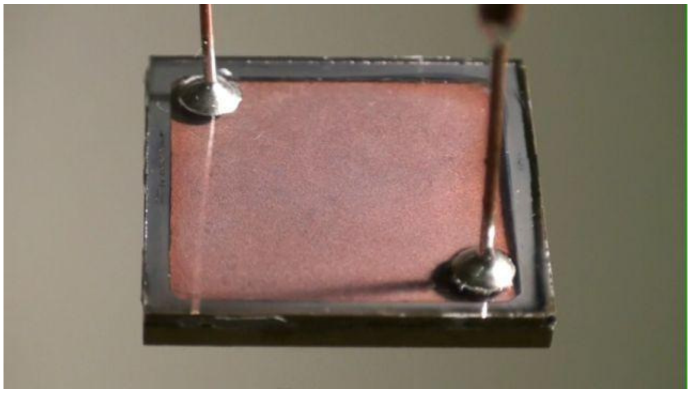

Figure 3. TGP prototype
(sample with transparent top for visual charging inspection)

Charging becomes increasingly challenging with decreasing size prototypes as the amount of of working fluid that needs to be dispensed accurately reduces. This poses significant challenges and requires the development of an accurate charging system described in this study.

Measurement of the effective thermal conductivity of such prototypes is challenging, as effective temperature gradients across the device are minimal. This study describes the evalution and selection of different thermal measurement techniques depending on prototype performance and the validation results of such system.

IMPORTANCE OF CHARGING ACCURACY

An important process in the development of such thermal ground plane is the charging or filling of the device with liquid under saturation conditions. To this purpose, a filling station is required to successfully fill the system with both liquid and saturated vapor. The removal of non-condensables from the system is important as these can block part of the condenser, which would negatively impact system performance or cause chemical degradation. This requires a process of evacuation before filling can commence. Previous studies (e.g., [3, 4]) have shown a link between k_{TGP} and the amount of liquid used to charge heat pipes. Overfilling the device can flood the condenser portion of the device, reducing the efficiency of the local two-phase heat transfer mechanism. Underfilling makes the device susceptible to dryout resulting in a significant drop in heat transfer rate. Both filling extremes ultimately compromise k_{TGP} by increasing the effective temperature difference required to transport a given heat load between the evaporator and condenser. Most practical heat pipes operate at fill levels that are higher than optimal to minimize the potentially undesirable consequences of evaporator dryout.

CHARGING STATION

A charging station for thermal ground planes accomplishes two critical tasks i.e. evacuation of the device and filling with the working fluid. The evacuation step is vital to remove non-condensables prior to the introduction of the working fluid. In case of miniature device designs, as employed in this study, the evacuation step can be very time consuming because of the greatly reduced pumping speeds given the constricted evacuation ports. This consideration often imposes practical limits to the level of vacuum that can be attained in the devices prior to filling. The second aspect of charging is the ability to dispense the desired fill volume accurately. The accurate dispensing of the working fluid becomes even more critical in the case of miniaturized devices such as described thermal ground plane where optimum fill volume is as low as O (10µl) – O (100µl).

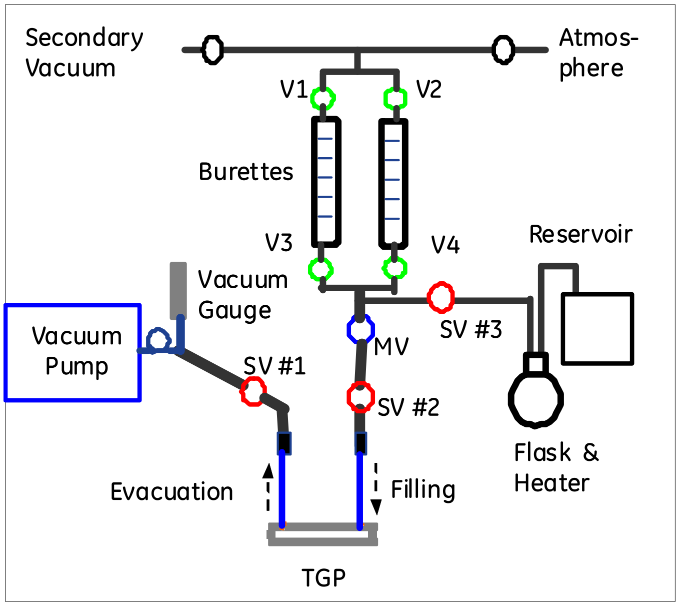

Figure 4. Schematic illustration of the thermal ground plane charging station

Various methods have been proposed in the literature [5,6,7] to fill thermosyphons and heat pipes. This study utilizes an evacuation and back-fill technique, a common filling technique for low to moderate temperature working fluids. In this method, the device is first evacuated to the desired vacuum level.

Following evacuation, the working fluid is distilled and de-gassed in a multi-step process and finally introduced into the evacuated device. As the working fluid is introduced in the device, it instantly flashes provided the vacuum level is below the vapor saturation pressure at the filling temperature. With continued filling, the internal pressure inside the device increases until the vapor saturation pressure of the working fluid is attained. Following this point, both vapor phase and liquid phase can coexist in the device and the volume fraction of the liquid phase increases with further filling as it saturates the wick structure. The devices can also be filled at different filling temperatures to control the volume fraction of the vapor and liquid phase for a given fill level.

Figure 4 shows a schematic illustration of the charging station developed in this study. The device to be filled (TGP) is attached to the charging station through pre-fabricated fill tubes on the device itself. One of the fill tubes is connected to the vacuum pump and is used for evacuating the device while the other fill tube is connected to the filling circuit and it is used to fill the device. The set-up consists of an upper manifold that is connected to a roughing vacuum pump (~10^{-3} Torr) on one end and open to atmosphere at the other end. This manifold is initially isolated from the atmosphere and the coarse vacuum is used to fill the burettes using water from the reservoir following purification using a flask and a heater.

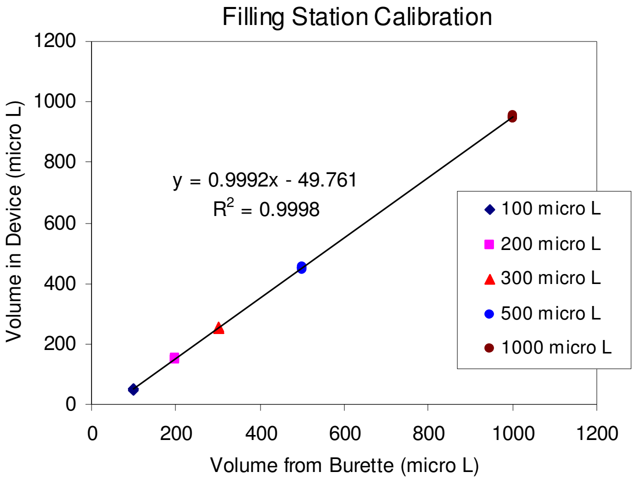

Figure 5. Typical calibration results for a 3ml burette for 100µL to 1ml dispensed volume.

The filling station can be designed with multiple burettes (with varying resolution and capacities) so as to allow the filling of devices with vastly different capacities and sizes. The burettes can be selectively filled using valves V1 – V4 (Figure 4). Once the burettes are filled, the upper manifold is opened to atmosphere. In parallel, opening shut-off valve SV #1 and keeping SV #2 closed can evacuate the device (upto ~10^{-6} Torr). Following evacuation, the evacuation tube is crimped close to the TGP and closing the shut-off valve V #1 isolates the vacuum pump. The vacuum in the device is used to perform filling by opening shut-off valve V#2 and adjusting the metering valve M for the desired flow rate from the appropriate burette (valve V3 or V4). The operator dispenses the desired volume of water from the burette by carefully reading the burette graduations. Once the desired volume has been dispensed, the device's fill tube is crimped and sealed and the filled device can be disengaged from the filling station.

The charging station used in this study was designed with 2 burettes of 3ml and 100ml volume with numerous graduations. The charging station is thus capable of dispensing fill volumes as small as ~O (10µl) upto ~O (10ml). However, initial calibration of the charging station was performed only for the 3ml burette. Initial characterization revealed three distinct factors that contribute to the filling error i.e. operator error in reading the burettes with repeatability, the error associated with the burette graduations and the dead volume of the filling circuit. Taking measures that aid in accurate and repeatable reading of the burette graduations can reduce the operator error. The error associated with the burettes, an outcome of variance in burette diameter over the span of the burette or error in the printed burette graduations, can be accounted for through systematic calibrations of the burette. Burette calibration can be especially critical for cases where the filling volume is of the same order as the finer burette graduations. The third source of filling error i.e. dead volume in the fill circuit is more difficult to reduce except through careful design and selection of the valves and manifolds of the fill station. Generally, smaller valves and manifolds are preferred.

Figure 5 shows typical results from the calibration of the 3ml burette. During calibration, a specific volume of water was dispensed by the operator from the burettes (100µl – 1ml in Figure 5). Following filling of the devices, the difference between the filled and unfilled weight of the devices was used to estimate the actual volume of fluid in the device. Each fill volume level was repeated 5 times.

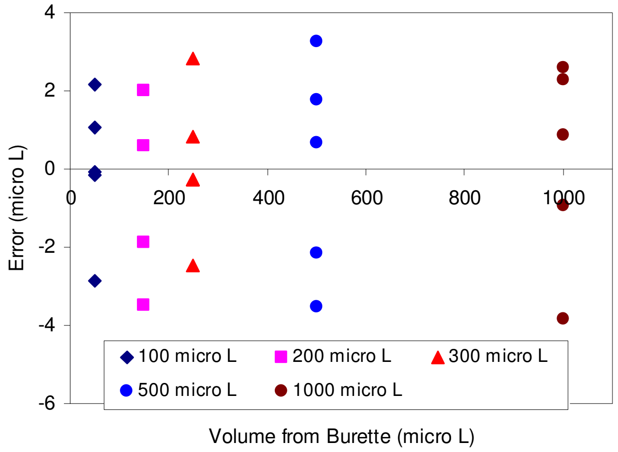

Figure 6. Filling error as a function of dispensed volume (from the burettes)

The difference between the volume dispensed from the burette and the actual volume in the device is associated with the dead volume of the fill circuit. In order to reduce fill uncertainty and improve repeatability, the dead volume should ideally be small and repeatable. The charging station yielded a dead volume of ~49.8µl (±1.6µl) irrespective of the fill volume. Figure 6 shows the filling error as a function of the volume dispensed from the burette. Based on this data, the filling uncertainty was thus found to be ±2µl, deemed sufficient for thermal ground plane prototype development.

To validate filling volume, intial thermal ground plane prototypes have been developed with one transparent side. This allows for visual access to evaluate overfill volume (Figure 3).

THERMAL CHARACTERIZATION EXPERIMENT DESIGN

Characterization of thermal performance consists of evaluation of heat transport capability and efficiency of heat transport. As relevant fluid properties are temperature dependant, performance of a thermal ground plane, should be evaluated over a range of device conditions. As effective conductivity increases, it inherently becomes more challenging to measure effective temperature differences of near isothermal devices. The accuracy objective for the thermal characterization setup is defined as 10% accuracy on thermal conductivity measurement of a 30mm x 30mm x 3mm prototype device.

A calorimetry experiment is used to estimate the temperature rise across a sample as a function of heat input. The experiment imposes near uniform heat flux input through a 30mm x 10mm area and it is assumed that heat flux exits the sample in near uniform fashion through a similar area as shown in Figure 7.

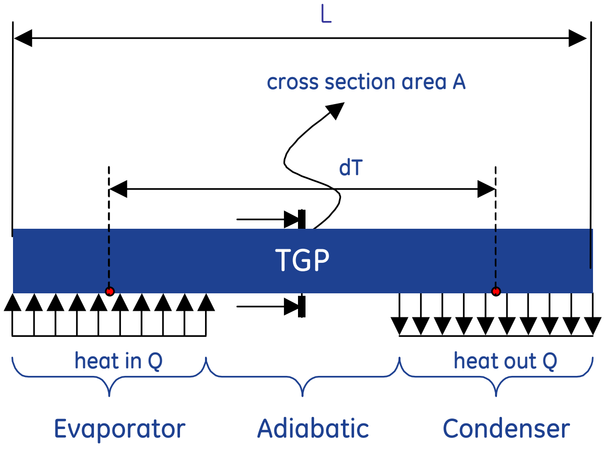

Figure 7. Experiment parameter definitions

The effective conductivity can be derived from the one-dimensional Fourier equation corrected by a shape factor as defined by Eq. 1.

$$k_{TGP} = \frac{Q}{dT}\frac{L}{A}\cdot C_{shapefactor}$$ Eq. 1

The shape factor, introduced to correct for the two-dimensional heat flux path in the one-dimensional equation, is a function of device thickness. The shape factor correlation was numerically evaluated to be around 0.6 for geometries relevant to this program. The relative accuracy can be defined as:

$$\frac{\Delta k}{k} = \frac{1}{k}\left(\frac{\partial k}{\partial Q}\Delta Q + \frac{\partial k}{\partial dT}\Delta dT + \frac{\partial k}{\partial L}\Delta L + \frac{\partial k}{\partial A}\Delta A\right)$$ Eq. 2

It was found that the temperature difference measurement error dominates the uncertainty, especially for high performance devices. Figure 8 illustrates this effect.

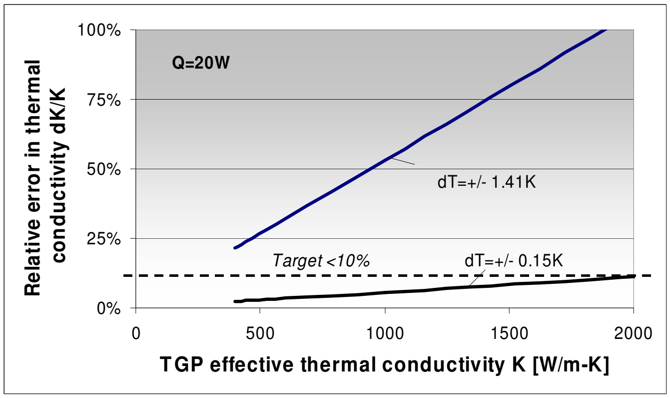

Figure 8. Effect of temperature measurement uncertainty on thermal conductivity measurement error

Due to desire of minimal interference in the heat flux path, thermocouples are the solution of choice due to their small bead size compared to RTDs. Thermocouples utilize the principle of development of a voltage potential at the junction of two dissimilar metals. The thermocouple potential corresponds to the temperature difference between the measurement bead and the temperature reference in the data acquisition system. Although thermocouples can be calibrated within 0.1 degrees Kelvin accuracy using an RTD, the accuracy of the DAQ internal reference can often only be guaranteed within 0.5 degrees Kelvin. Alternatives to enhance the temperature measurement accuracy include the utilization of an external temperature reference or a differential tempeture measurement using a thermopile.

THERMAL CHARACTERIZATION EXPERIMENT

A sketch of the thermal characterization setup can be observed in Figure 9. The purpose of the setup is to provide a heat path between heat source and sink through the test sample, with minimal heat loss to ambient.

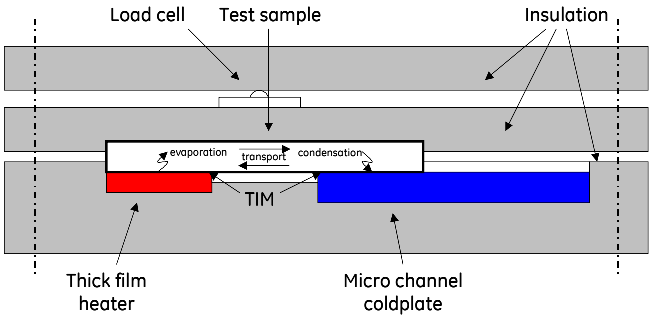

Figure 9. Thermal characterization components

An Agilent E3634A power supply is used as constant current source to a thick film heater. The heater substrate is made of a high thermal conductivity material to provide uniform heat flux to the sample. Thermal interface material is used to minimize thermal interface resistance between sample, heater and cold plate. A high performance micro-channel cold plate is used as heat sink. Cold plate flow and temperature are controlled by a Cole-Palmer EW-12108 chiller. Insulation is provided around the components of the setup to minimize heat loss to ambient. As thermal interface material performance varies greatly with contact pressure, the applied compressive load is measured using a load cell. Care was taken to supply sufficient compressive load to reduce contact pressure sensitivity. Additional insulation was packed around the setup to minimize heat loss through the gaps between the shells. Data acquisition of thermocouples and load cell is performed using an Agilent 34970A DAQ.

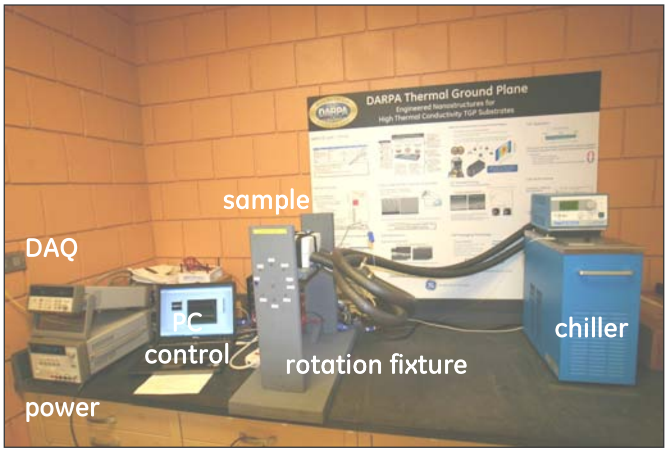

Figure 10. Thermal characterization setup

Power supply, temperature bath and DAQ are controlled using LabVIEW software (Figure 10). The test setup is placed on a rotation fixture in order to evaluate orientation dependant performance of the thermal ground plane devices.

Insulation performance was characterized using a heat loss test. In this test, the cold plate was drained while a small amount of heat was added by the heater. Effectively this characterizes the thermal resistance of the heat path from heater to ambient through the insulation package. Heat losses were found to be on the order of 7% and dependant on the mean temperature rise of the system over ambient. All heat loads presented in this study describe the amount of heat going through the sample, with the electrical input power corrected by the heat loss to ambient.

THERMAL CHARACTERIZATION EXPERIMENT VALIDATION

Solid conductors of known conductivity and similar geometry were used to validate system performance. Validation was performed using Alloy 110 copper (thermal conductivity of 388 W/m-K at 20 C). A finite element model was prepared in ICEPAK with matching test conditions. The sample was instrumented in thermopile configuration. Two constantan leads were attached to the center of the heat input and output sections (see Figure 7). The electrical and thermal connection was confirmed using a resistance measurement. The copper sample itself was used as copper lead between the two measurement points, effectively creating two T-type thermocouples with inversed potential. The effective voltage difference measurement was transformed into a temperature gradient using the Seebeck coefficient from NIST T-type thermocouple tables. Using this method temperature gradient measurement accuracy of ±0.15 degrees K was achieved. Results comparing total temperature rise across the system from heater to cold plate are presented in Figure 11.

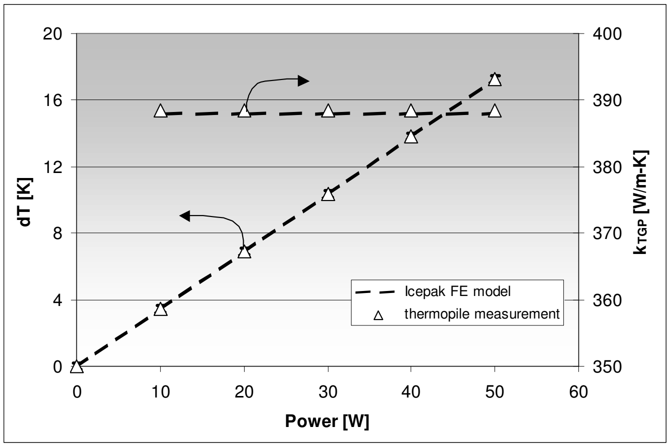

Figure 11. Comparison between ICEPAK model and Experimental temperature rise and derived effective TGP thermal conductivity

Figure 11 confirms a match between experimental results and numerical data within measurement error range (<1%), thus giving confidence in the developed measurement system and it's potential in measuring minitature thermal ground plane prototype devices.

CONCLUSION

Thermal ground planes employ two-phase heat transfer mechanisms to transfer heat efficiently making them attractive heat spreaders. The effective thermal conductivity of a thermal ground plane varies with both fill volume, operating temperature and imposed thermal load. Due to the miniaturized dimensions of the protoype to be developed, accuracy of the charging and thermal characterization systems is critical to achieving desired performance.

A TGP charging station was developed based on the evacuation and backfill technique. Practical limits on acceptable evacuation times were found to be limiting the vacuum levels that could be reached for evacuation. Fill accuracy related challenges in filling miniature devices were found to be operator error in reading the burettes with repeatability, error associated with the burette graduations and filling circuit dead volume. Charging station validation showed ability to charge micro system with accuracy of ±2µl.

Thermal characterization of thermal ground planes includes evaluation of thermal transport capability and thermal transport efficiency. As effective thermal conductivity increases, it inherently becomes more challenging to measure effective temperature differences of near isothermal devices. Thermopile measurement techniques were found to be the most accurate. Excellent agreement (<1%) was found between numerical and experimental results during validation using a copper sample.

Sensitivity analysis and validation of minimal error are determined to be critical components going forward in the development and validation of thermal ground plane prototypes.

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