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Experimental evaluation of metallic phase change materials for thermal transient mitigation

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ABSTRACT

The military has various high rate transient pulse applications which create unique thermal management challenges due to their high heat flux and short pulse duration. Phase change materials (PCMs) have been studied due to their ability to absorb thermal energy with minimal temperature increase. This work investigates the performance of metallic PCMs (Fields' metal (32.5Bi/51In/16.5Sn wt%) and 49Bi/18Pb/12Sn/21In wt%) acting as an integrated thermal buffer for high power 19 ms pulses. Two commercially available organic PCMs (PureTemp 29® and PureTemp 58®) and a dielectric gel (Sylgard 527®) were used for comparison. The studied materials were deposited directly in contact with the heat-dissipating surface of a custom micro-fabricated heater chip with an embedded resistance temperature detector (RTD) for in-situ temperature measurement. PCMs were subjected to 19 ms pulses and a maximum heat flux of 338 W/cm^2 (relative to heat source area). The Bi/Pb/Sn/In PCM was able to reduce temperature rise during the pulse by 60 °C (63%) for 120 W and 81 °C (68%) for 160 W using the dielectric gel as baseline. In comparison the best performing organic PCM, PureTemp58, only reduced temperature rise by 16 °C (17%) and 17 °C (14%) for 120 W and 160 W, respectively. This supports previous assertions in the literature that metallic PCMs can be an enabling thermal protection technology for high rate transient applications.

1. Introduction

Phase change materials (PCMs) have been widely studied for their ability to absorb energy without a significant increase in temperature during phase change (solid-to-liquid), storing it as latent heat. Although the use of PCMs is not new, for example, NASA has been doing research on PCMs since 1964 [1]; the use of PCMs has been emerging for widely different applications such as building thermal management [2] and electronics. Electronics have benefited by using PCMs as thermal buffers, especially those applications with intermittent loading profiles or transient power spikes [1,3]. Traditionally, organic PCMs have been the preferred class of materials for those purposes.

Organic PCMs' properties including high latent heat of fusion by unit mass, relatively low cost, and availability in a wide range of melting temperatures [1] make them the most commonly researched materials. Organic PCMs have been traditionally used in applications dealing with long timescales such as building thermal management and power generation [4]. Organic PCMs have been used in short pulse applications such as electronics cooling but the low thermal conductivity of these PCMs is a major concern for high heat flux applications such as power electronics [5,6] or computational sprinting [7,8]. Thermal enhancements like metal mesh [9,10], metal foams [11], heat sinks [12], carbon nanotubes [13] and metal honeycombs [14] have been used in an attempt, with limited success, to improve the effective thermal conductivity of organic PCMs. Most of the experimental demonstrations were still addressing thermal timescales on the order of many seconds to hours, demonstrating a need for other approaches to address fast transients.

Metallic PCMs, having an inherently high thermal conductivity and relatively high volumetric heat of fusion due to their high density, have been presented as a promising high heat flux, compact, fast action thermal solution. Several recent material reviews have highlighted metallic PCMs as likely candidates for phase change applications where system weight is less of a concern than high heat transfer rates [3,15]. In addition, recent PCM selection and figure of merit analyses have highlighted low melting temperature

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Nomenclature

T_m	melting temperature (°C)	R	resistance Ω
H	latent heat of fusion (J/g)	P	Power W
k	thermal conductivity (W/(m K))	ρ	electrical resistivity Ω m
ρ	density (kg/m^3)	w	width m
c_p	specific heat kJ/kg K	L	length m
V	voltage V		

metals as promising PCM candidates. Lu [16], Shamberger [17], and Shao et al. [7] all defined figures of merit for the cooling capacity of PCMs based on models of heat transfer through the material. All resulted in metallic PCMs having one to two orders of magnitude higher figures of merit than traditional organic PCMs primarily due to their higher energy absorption rate and resulting improved performance on short timescales.

Despite their seemingly ideal fit for faster transient loads, far fewer studies have been published using metallic PCMs. Of these, very few studies consider short timescales that would take advantage of the high heat rates enabled by metallic PCMs, and the majority of those were only simulations. Krishnan and Garimella performed simulations comparing metallic and thermally enhanced organic PCMs when subjected to conditions of 600 W for 25 s and 300 W for 50 s, showing metallic PCMs to perform better in all cases [5]. Evans et al., simulated the effect of using an unspecified metallic PCM as the die attach layer in an electronic package, showing with an ideal PCM melting model that such a configuration could reduce temperature rise on the millisecond timescale [6]. Finally, the authors recently used a 1-D nonlinear heat transfer analysis to numerically compare several organic and metallic PCMs in a standard power package-encapsulant configuration that showed that metallic PCMs outperformed other materials under 20 ms pulse loads [18].

Few experimental studies have been reported using metallic PCMs and their comparison versus organic PCMs. Fukuoka & Ishizuka experimentally investigated 49Bi/18Pb/12Sn/21In and 57.5Bi/17.3Sn/25.2In alloys integrated into an electronics package cavity, showing successful thermal suppression on timescales of 100s of seconds [19,20]. Fan et al. compared Bi/Pb/Sn/In and 1-octadecanol in reducing temperature rise in a PCM heat sink. The metallic PCM kept the maximum temperature 50 °C lower than the organic PCM over several minutes of heating [21]. Shao et al. demonstrated with a silicon thermal test chip the ability of 49Bi/18Pb/12Sn/21In to maintain a lower temperature compared to an organic wax PCM during a 0.6 s simulated computational sprint where the wax showed little to no thermal suppression [7]. Finally, Green, Fedorov and Joshi showed that silicon test chips with a 49Bi/21In/18Pb12/Sn alloy embedded in substrate micro-cavities exhibited phase change thermal suppression as quickly as 10 ms [22].

In order to exploit the high thermal conductivity of metallic PCMs, this work will focus on high heat fluxes and very short pulses scenarios. However, measuring temperature in such time scales using traditional methods, such as external thermocouples, is a known challenge. Therefore, a micro temperature sensor/heater device was designed and fabricated in an effort to measure temperature in the millisecond range. Micro-sensors have been widely used due their fast time response. In [23], Zhang et al. fabricated a thin film thermocouple which was capable of measuring temperature at the nanoseconds time scale. In our work, a Resistance Temperature Detector (RTD) was chosen as the temperature sensor because, while a thermocouple could provide the temperature of a very specific spot, the RTD can be designed such that it could give a representative temperature of the whole device. Phattanakun et al. [24] designed and fabricated a device using an aluminum heater and a nickel micro-sensor embedded in the same substrate that was used as a guide for our design.

2. Material selection

In [18] the authors used a 1-D heat transfer analysis with a constant heat flux boundary condition to study the performance of different organic and metallic PCMs and a dielectric gel under various pulse conditions. Under 20 ms pulses, metallic PCMs showed less temperature rise when compared to organic PCMs and a dielectric gel. This concurs with the work done by Lu [16] and Shamberger [17], where it was mentioned that metallic PCMs would perform better due to their properties, especially their high thermal conductivity. Organic PCMs showed little to no thermal suppression under the same conditions. The materials used in this work, shown in Table 1, were selected based on the result from [18].

3. Design, fabrication and packaging

The design objectives of the custom heater/RTD device include: (i) capable of generating high heat fluxes with minimal power input, (ii) capable of accurately measuring temperature at the milliseconds (ms) time scale, and (iii) capable of operating with a liquid metal PCM on the heat source. In order to address two of the objectives (i and ii), a low thermal conductivity borosilicate glass wafer was used as the chip material to minimize substrate heat loss. The metallic PCMs used in this study, Bi/Sn/In and Bi/Pb/Sn/In, have $\sim$16x and 28x higher thermal conductivity than the borosilicate glass substrate, respectively, which should force a significant fraction of heat into the PCM instead of the substrate. The organic PCMs have much lower thermal conductivity, but being on the similar order as the substrate more heat will be forced into the PCM than if a more conductive packaging substrate was used.

The RTD was designed to be as small as possible in an attempt to minimize the thermal inertia of the temperature sensor, hence having a faster response. Furthermore, the RTD was fabricated with a spacing of 10 μm from the heat source to minimize the temperature difference between the heater and the sensing element. A thin layer of silicon nitride was used as a dielectric/passivation to allow the direct depositing of liquid metal PCM without the risk of electrical shorting.

Copper was chosen as the material for both the heater and the RTD, not only because of its good linearity and sensitivity of resistance with temperature change, but also because making the heater and RTD of the same material simplified its fabrication. Copper is a commonly used RTD material in addition to platinum and nickel [29]. Another advantage is its low cost and high temperature coefficient of resistance (TCR) [$\alpha = 0.004$/°C], which provides high temperature/resistance resolution. A drawback to using copper as the heater material is that its variable resistance with temperature will cause some decrease in applied power as the heater warms and resistance increases during pulses according to Eq. (1). However, the positive change in resistance due to temperature can be