Sci. Bull. (2015) 60(7):701–706
DOI 10.1007/s11434-015-0760-9

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Article

**Engineering Sciences**

# Microfabricated ultra-thin all-polymer thermal ground planes

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Received: 22 December 2014 / Accepted: 12 February 2015 / Published online: 11 March 2015

**Abstract** Thermal ground planes, or planar heat pipes, can provide highly effective heat transfer by utilizing phase change of an encapsulated fluid. In this article, a flexible thermal ground plane (FTGP) was fabricated using polymer materials. Kapton was employed as a casing material while micropatterned SU-8 was used to provide both a liquid wicking structure and pillars to support the casing over a vapor core. An ultra-thin $TiO_2$ film was deposited over the SU-8 and Kapton via atomic layer deposition, which acted as both a moisture barrier and a hydrophilic coating on polymer surfaces. The assembled FTGP has a thickness of 0.30 mm, an active area of 20 mm × 60 mm, heater area of 20 mm × 10 mm, and can operate with a heat load up to 9.54 W, with an effective thermal conductivity up to 541 W/(m K).

**Keywords** Flexible electronics · Heat pipe · Electronics cooling · Thermal ground plane

## 1 Introduction

Micro heat pipes have been developed over the past two decades for thermal management of electronic devices [1–3]. Two-dimensional thermal ground planes (TGPs) or flat heat pipes have recently attracted great interests for mobile electronics. In such devices, heat enters a wicked evaporator section through the casing material, and the liquid permeating the wick absorbs the heat and evaporates. The vapor flows from the evaporator through an adiabatic section to the condenser, where it rejects the heat as it condenses. The condensate permeates the wicking structure and is pulled back to the evaporator by capillary pressure, completing the closed-loop thermodynamics cycle. Many previous TGPs have been fabricated by metal or ceramic microprocessing [4–6], but these prove challenging for flexible electronics applications.

Various polymer flexible thermal ground planes (FTGPs) have been developed, which use aluminized Mylar as the casing material and woven copper mesh bonded to electroplated copper micropillars as the wicking structure [7, 8], as well as silicone rubber as the casing material and multi-layer copper mesh as the wick [9]. All-polymer FGTPs are of great interests for wearable electronics and mobile computing, with potential enhancements in weight, flexibility, and manufacturability. An all-polymer FTGP based on extruded polypropylene was developed by McDaniels and Peterson [10], although the thermal performance of the device was not reported. Using commercial woven polymer mesh as the wicking structure, an all-polymer FTGP was developed by Oshman and reported in Ref. [11]. The FTGP was 1.1 mm in thickness. However, the reduction in thickness proved challenging due to the use of the commercial mesh structure. If the wicking structures in all-polymer FTGPs are defined by lithography, we can potentially optimize the device geometries with minimal overall thickness, as that have been done for ultra-thin TGPs made of metal and silicon substrates [5, 6]. Additionally, lithography enables a spatial gradient in the size of channels in the wick, which can potentially further optimize the device performance.

This article demonstrates the design, microfabrication, and testing of an ultra-thin, all-polymer FTGP. The design

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considers the size of liquid and vapor flow channels that maximize the difference between capillary pumping pressure and viscous pressure drop due to flow friction. Microfabrication is based on SU-8 patterning to define an array of micropillars as a liquid wicking structure. Additionally, posts of SU-8 are used to support the cladding material and keep it from collapsing when the system is under vacuum. An ultra-thin coating of $TiO_2$ deposited by atomic layer deposition (ALD) is used as both an impermeable moisture barrier and to render the surface hydrophilic. The assembled FTGP has an active area of 2 cm × 6 cm and a thickness of 0.3 mm. When tested with an evaporator measuring 2 cm × 1 cm and a condenser measuring 2 cm × 2.5 cm, the maximum heat load is 9.54 W with an effective thermal conductivity up to 541 W/(m K).

## 2 Experimental methods

### 2.1 Design

Figure 1a shows the cross-sectional schematics of the FTGP. The wicking structure of the FTGP is composed of an array of micropillars, as shown in Fig. 1b. Liquid flows through the channels between the micropillars, and such spacing provides the small radius necessary for high capillary pumping pressure. Vapor flows through a cavity between the wick and the vapor-side cladding; the height of this vapor core is defined by microposts. Additionally, a thin wick above the vapor posts prevents the accumulation of water along the vapor-side cladding. The posts are asterisk-shaped, creating channels for such accumulated water to return to the liquid wick. The design goals for this TGP is to achieve power dissipation of 5 W on an evaporator 1 cm × 2 cm in size with a total thickness of 300 µm over a TGP active area of 2 cm × 6 cm.

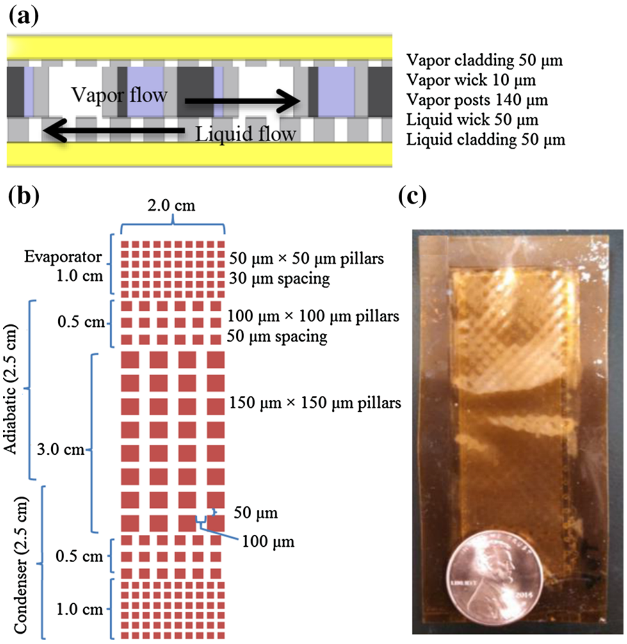

**Fig. 1** (Color online) **a** Cross-sectional schematics of FTGP, and **b** top-view schematic of the micropillar wick, **c** photograph of the complete FTGP

Careful consideration must go into the design of the FTGP microstructures in both liquid wicking structure and vapor core. Of particular concern is to ensure that the pressure drop due to viscosity is smaller than the capillary pumping pressure provided by the wicking structure so that the device will not operate under the capillary limit.

The pressure drop through the liquid channels can be calculated for laminar flow according to [12]

$$\Delta P_{\mathrm{l}} = \left(\frac{1}{6}L_{\mathrm{e}} + L_{\mathrm{a}} + \frac{1}{6}L_{\mathrm{c}}\right)\frac{\left(\frac{fRe}{2}\right)\mu_{\mathrm{l}}}{w_{\mathrm{T,l}}\delta_{\mathrm{l}}r_{\mathrm{h}}^2}\frac{\dot{Q}}{\Delta h_{\mathrm{fg}}\rho_{\mathrm{l}}}. \qquad (1)$$

Here, $L$ refers to the length, with the subscripts e, a, and c referring to the evaporator, adiabatic section, and condenser; *fRe* is the product of the friction factor and Reynolds number, which is a constant that depends on geometry for laminar flow; $\mu$ is the viscosity, $w_{\mathrm{T}}$ is the total flow width available to the liquid flow (TGP width less width of SU-8 pillars), $\delta$ the height of the flow channel, $r_{\mathrm{h}}$ the hydraulic radius of the flow channel, $\dot{Q}$ the power dissipated, $\Delta h_{\mathrm{fg}}$ the enthalpy change of vaporization, and $\rho$ the density. The subscript l refers to liquid-phase-specific quantities. The hydraulic radius of the flow channel is a function of the channel width ($w_{\mathrm{c}}$) and height, as $r_{\mathrm{h}} = \delta_{\mathrm{l}} w_{\mathrm{c}}/(\delta_{\mathrm{l}} + w_{\mathrm{c}})$.

In macro-scale heat pipes or TGPs, the pressure drop associated with vapor flow is often neglected; however, in ultra-thin TGPs, the friction resistance of vapor flow can be dominant. For parallel-plate flow, the hydraulic radius will be equivalent to the vapor core thickness; therefore, the pressure drop of the vapor will be given by

$$\Delta P_{\mathrm{v}} = \left(\frac{1}{6}L_{\mathrm{e}} + L_{\mathrm{a}} + \frac{1}{6}L_{\mathrm{c}}\right)\frac{\left(\frac{fRe}{2}\right)\mu_{\mathrm{v}}}{w_{\mathrm{T,v}}\delta_{\mathrm{v}}^3}\frac{\dot{Q}}{\Delta h_{\mathrm{fg}}\rho_{\mathrm{v}}}. \qquad (2)$$

The capillary pumping pressure is given by the Young–Laplace law for a fluid with surface tension ($\sigma$) and capillary radius; for channels between micropillars, the capillary radius will be given by half the channel width:

$$\Delta P_{\mathrm{cap}} = 2\sigma/w_{\mathrm{c}}. \qquad (3)$$

The sum of the pressure losses due to viscosity dissipation must be less than the capillary pressure. Note that the capillary pressure is independent of the heat load when thermophysical properties are assumed to be constant, while the viscous pressure drops have a linear relationship with heat load. Figure 2a plots the region of successful design in the parameter space for vapor core