The Fabrication and Characterization of Nanocarbon Foam as Novel Wick Material for Thermal Management of Electronics

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ABSTRACT

Flat heat pipe is a device for thermal management of electronics, in which wick is an important part. In this work, nanocarbon foams were prepared and their properties were investigated for their application as wick material. The nanocarbon foams are carbon nanotube based open cell porous material. The cell size is in microscale and the cell wall has pores in nanoscale. Capillary rise tests show that the nanocarbon foam with larger cells has better capillary performance than that with smaller cells. The capillary distance can reach 57 mm in 5 seconds. It is found that the thickness of cell wall is a key factor on foam's capillary performance. It is also found that the drying out could be eliminated when using nanocarbon foam as wick. The nanocarbon foam is a promising wick material for thermal management of electronics.

Keywords: nanocarbon foam, porous material, wick, capillary rise processes, thermal management

1 INTRODUCTION

Electronic devices have suffered large on-chip temperature gradients due to localized high heat flues resulting from the substantial non-uniformity in power dissipation. To solve the heat problems, the flat heat pipes (FHPs) are excellent candidates for cooling electronics as heat spreader [1]. A FHP consists of a working fluid, a wick structure, and a vacuum-tight containment unit (envelope). The wick material in FHPs plays a key role on the cooling performance. Conventional FHPs with uniform wick structures, such as micro grooves [3], sintered cupper mesh, or particles [4], are not suitable for high heat-flux applications [5]. In this work, we fabricated nanocarbon foams and evaluated their performance as wick material. It is found that the foams have capability and good performance on the capillary rise due to their low density and well controlled porous structure. Inaddition, the lightweight, high thermal conductivity, and great flexibility make nanocarbon foams be potential wick materials in heat pipes for the next generation of electronic devices.

2 EXPERIMENT

The materials used to fabricate nanocarbon foams are multi-walled carbon nanotubes (MWNTs), poly(methyl methacrylate) (PMMA) microspheres, polyacrylonitrile (PAN), and solvents. The PMMA microspheres served as a template for forming microscale pores in the foam and PAN was used as a precursor for forming graphitic carbon between MWNTs in the walls of the foam. The foam fabrication follows the following steps. First, PAN powder was dissolved in dimethylformamide (DMF) in 1 wt% concentration. The MWNTs and PAN/DMF solutions with PAN/MWNT weight ratio of 0.5 were mixed and well dispersed in isopropanol (IPA) by high power sonication. Then the PMMA microspheres with the PMMA/MWNT weight ratio of 20 were added and the resulting mixture was further sonicated in a bath sonicator for 10 minutes to achieve a uniform MWNT/PAN/PMMA suspension. A MWNT/PAN/PMMA composite was made by vacuum filtration of the suspension, followed by drying in a vacuum oven to remove the IPA and DMF completely. MWNTs and PAN were self-assembled around the PMMA microspheres. The foams were obtained through two heat treatments, at 300 °C in air for 3 hours and then at 1200 °C in nitrogen with 80 ml min^{-1} flow rate for 1 hour. During the first heat treatment, the PMMA microspheres were depolymerized and volatilized to form the microscale pores (cells), while the PAN was oxidatively stabilized. In the second heat treatment, the stabilized PAN was carbonized to form graphitic carbon to connect the MWNTs. The MWNTs and graphitic carbon form the cell walls in the foam [6, 7]. Three types of foams were made by using the PMMA microspheres with the diameter of ϕ20±3 μm, ϕ45±5 μm, and ϕ75±5 μm, respectively. The density of the foams are 35±3 mg/cm^3.

The structure of the nanocarbon foams was observed by using scanning electron microscopy (SEM). The capillary performance of the foams were evaluated, where acetone was used as the working fluid and infrared (IR) camera was used to track the movement of liquid during capillary process.

3 RESULTS AND DISCUSSION

The nanocarbon foam has a unique structure. The SEM images in Figs. 1a, 1b, and 1c show the structure of the nanocarbon foams made by using PMMA microspheres with diameter of ϕ20±3 μm, ϕ45±5 μm, and ϕ75±5 μm, respectively. It is clear that the micro-scaled pores are uniformly distributed and the nanocarbon foams have well controlled porous structure. The cell size of the foam is determined by the size of PMMA microspheres. Using polymer spheres as template allows for a better control over the size of the pores and also in minimizing the range in pore sizes. Because the density of the foams is kept the same, the foam with bigger cells has smaller cell density and thicker cell walls when compared with the foam with smaller cells. The cross-linked MWNT networks act as the walls of the cells while generating pores in nanometer scale within itself as shown in Fig. 1d [6-8]. The formation of cross-links at the junctions is made possible by the effect of capillary force that aids in transporting PAN to the intersections between the nanotubes during the drying process [9]. The nanocarbon foam is open cell foam and is highly porous.

For capillary rise test, all samples are in a rectangular shape and have the same size. The sample's thickness, width, and length are 1.5 mm, 5 mm, and 57 mm, respectively. Before the tests, the samples were dried and the temperature of the samples was room temperature. When one end of the sample was immersed into acetone solution, acetone moves along the sample due to the capillary force and evaporates from sample at the same time. Acetone was chosen as the working fluid in the tests because it wets nanocarbon foam well and has a fast evaporation rate. The evaporation of acetone from a surface of material causes the temperature drop, therefore, the temperature difference in a material can be used to indicate the location of the fluid and the flow of the liquid. IR camera was used to record the temperature profile of the sample by time, namely the capillary process. Figure 2 shows a typical IR image of a nanocarbon foam which was placed horizontally on a glass slide with one end immersed in acetone solution. In Fig. 2, the dark blue color shows the temperature about 10°C lower than room temperature (green color). Lower temperature indicates that there are more liquid in the sample and higher liquid evaporation happens there. The color profile in the sample is used to track the status of the capillary rise of the liquid. Typically, there are three regions in the foam: filled with liquid, wetted with liquid, and no liquid, which are indicated in Fig. 2 as saturation, wet, and dry, respectively.

The evaluation of capillary performance of nanocarbon foams was conducted when the foam was placed either parallel or perpendicular to the surface of the acetone solution. When one end of the foam is immersed into acetone solution, IR camera records the capillary process. The capillary rise height was extracted from the IR thermal image and the tip of the wicking front is chosen as the location of capillary rise height.

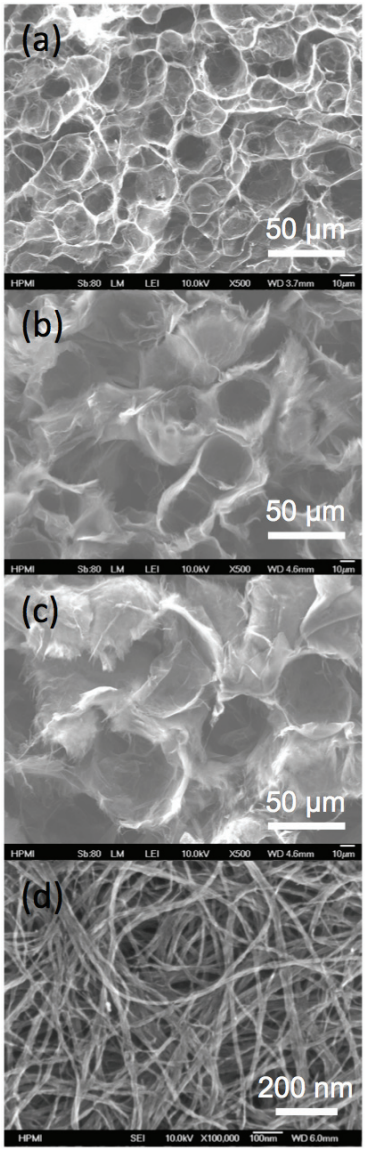

Figure 1. SEM images of nanocarbon foams with different cell sizes. The average diameter of microscale pores are (a) ϕ20 μm, (b) ϕ45 μm, and (c) ϕ75 μm. (d) SEM image of cell wall. The cell wall is formed by cross-linked MWNT networks

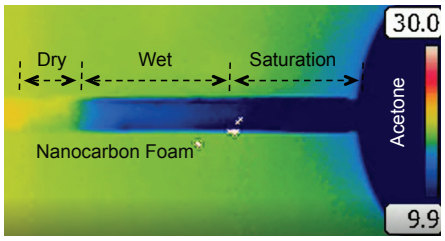

Figure 2. IR image of the capillary process of a nanocarbon foam placed horizontally on a glass slide.

Figure 3 shows the influence of the cells size on the capillary rise when the freestanding foams are places vertically. The foam with larger cell size has higher height and higher rate of capillary rise. It is because that the foam with larger cell size has thicker cell walls. The MWNT networks in the cell wall provide nanochannels for fast liquid transfer and larger cells lower the liquid flow resistance.

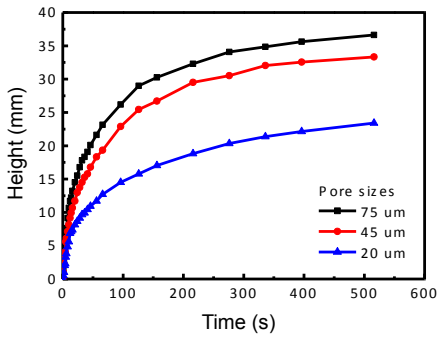

Figure 3. Capillary rise height of nanocarbon foams with different cell sizes. The foams are placed vertically to solution.

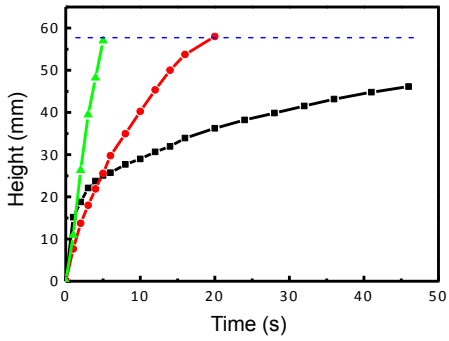

Figure 4. Capillary rise of the nanocarbon foam that is placed horizontally with one end in acetone solution. Three test setups: the foam is freestanding (black line), the foam is on a glass substrate (red line), and the foam is sandwiched between two glass substrates (green line). The cell size of the foam is ϕ75 μm.

The capillary rise in horizontally placed foam was tested in three different setups, which is freestanding, on a glass substrate, and sandwiched between two glass substrates. The foam has cell size of ϕ75 μm. The results are shown in Fig. 4. Comparing with the result showing in Fig. 3, it is clear that the capillary rise is faster when the foam is placed horizontally. With solid substrate in one side or both sides of foam, the capillary rise is even faster. The working liquid, acetone, can fill the whole foam samples in 5 s if there are substrates on both sides of the foam (green line in Fig. 4). Such fast capillary rise indicated that the nanocarbon foam would be an excellent wick material for flat heat pipes.

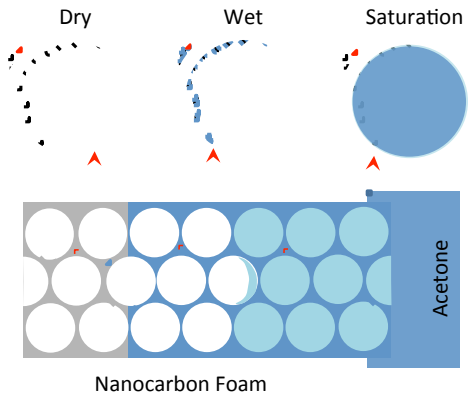

Figure 5. Model of the liquid transfer in the nanocarbon foam.

A model is generated to explain the capillary rise in the foam (Fig. 5). When one end of the nanocarbon foam sample immersed into the liquid source, the liquid will transfer in the foam in three steps. First, the liquid transfers along the cell walls, where MWNT networks with nanoscale porous provide high surface area and channels for the movement of liquid. The foam is wetted. As the liquid moves along the cell walls, the liquid starts to fill the cells. When the cells are full with liquid, this part of the foam is called saturation. The front lines of the wet and saturation in the foam are moving forward at the same time. The filled cells turn to be small liquid sources which help the liquid to transfer further. Compared with the wet part, the saturation part contains higher amount of liquid and higher evaporation rate which causes the bigger temperature drop in that area. Therefore, the wet part and saturation part have different temperatures, that are different colors in IR image.

The effect of nanocarbon foam on cooling was investigated. A small heat was used to stimulate a hot spot. One end of the freestanding nanocarbon foam was attached to the heater and another end was immersed in acetone solution (Fig. 6a). The heater was set at 106°C by applying constant DC current. Before the end of foam was immersed in acetone solution, the part of the foam attached to heater has the temperature closer to that of heater and most part of the foam is at room temperature (Fig. 6b). It is because the nanocarbon foam has high thermal conductivity and great heat dissipation too. When the end of foam was immersed in acetone solution, acetone flows towards the heater side due to capillary force (Fig. 6c). The capillary front can be seen clearly. Figure 6d shows the stable status. The most of the foam has a temperature lower than room temperature, while the part on heater has a temperature close to room temperature. It demonstrated that the working liquid flow continuously to the heater side and the evaporation there leads to the cooling of the heater. The weight change of the

samples before and after the capillary rise shows that ~90% pore space below the wicking front is filled with liquid, which indicates that the foam has very high capacity to store and transfer liquid due to its nano- and micro- wick structures.

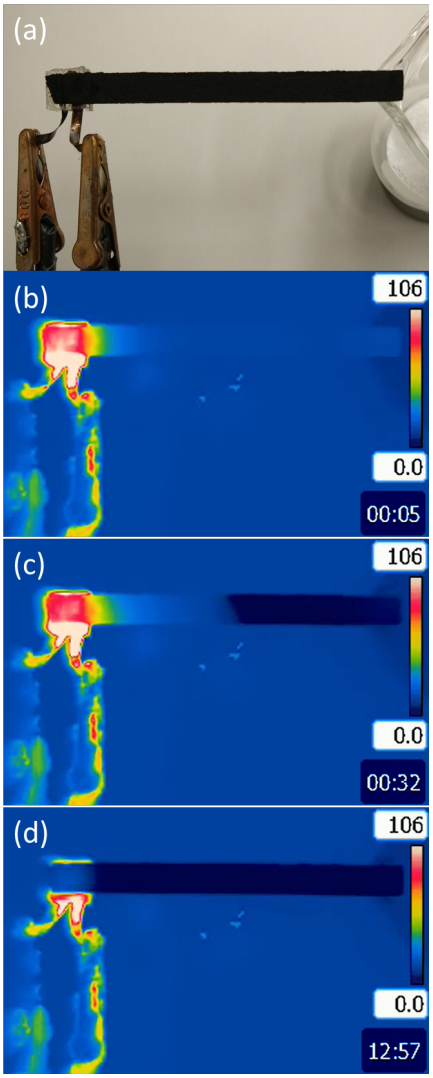

Figure 6. (a) Optical image shows the test setup. Freestanding foam is placed horizontally with one end stacked on a heater set at 106 C and another end was free and then immersed in acetone solution. (b-d) IR images of the foam (b) before and (c) a few seconds after one end was immersed in acetone solution. The color change of the foam indicates that acetone is moving toward the heated side due to the capillary force. (d) IR image of the foam which contacts both the heater and the acetone for long time. Acetone has arrived at the heat end and the heater is cooled.

Drying out is a serious issue in flat heat pipes, which causes failure of cooling. It happens when the amount of liquid evaporation at hot spot is larger than the amount of liquid transferred to the hot spot. The nanocarbon foam has much higher capability to store and transfer liquid than common wick materials. It is possible to eliminate the happening of drying out by using nanocarbon foam as wick material in flat heat pipes.

4 CONCLUSION

In this work, nanocarbon foams were fabricated and their performance as wick material for thermal management was evaluated. The nanocarbon foam has well controlled porous structure and the fabrication process is scalable. The foam cell size and porosity are factors to the capillary performance. The results shows that the nanocarbon foams have high potential to be novel wick material for thermal management of electronics. Nanocarbon foams are lightweight, electrically and thermally conductive, elastic, and stable. As a wick material, it will not only have excellent heat transfer function, but also provide flexibility and reliability.

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