Thermal dissipation media for high power electronic devices using a carbon nanotube-based composite

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Abstract
Challenges in the thermal dissipation of an electronic package arise from the continuous increase in power density of higher-power devices. Carbon nanotubes (CNTs) are known as the highest thermal conductivity material (2000 W mK$^{-1}$). This excellent thermal property suggests an approach in applying the CNTs in thermal dispersion materials to solve the aforementioned problems. In this work, we present an effect of thermal dissipation of the CNTs in the high-brightness light emitting diode (HB-LED) and micro-processor. For the thermal dissipation of the HB-LED, a vertically aligned carbon nanotube (VA-CNT) film on a Cu substrate was applied. Meanwhile, for the thermal dissipation of a micro-processor, the composite of commercial thermal paste/CNTs was used instead of the VA-CNTs. The experimental and simulation results have confirmed the advantages of the VA-CNT film and thermal paste/CNT composite as excellent thermal dissipation media for HB-LEDs, µ-processors and other high power electronic devices.

Keywords: thermal dissipation, thermal paste, µ-processor, multi-walled carbon nanotubes

Classification number: 5.14

1. Introduction
The problem of thermal dissipation material for high power electronic devices has attracted special interest from scientists and technologists. The temperature of high power electronic devices increases cyclically as a consequence of their operation. So, to improve the thermal stability and longevity of high power electronic devices, it is very important to find new materials and an appropriate configuration to celebrate the delivered thermal energy.

Carbon nanotubes (CNTs) are known as the highest thermal conductivity material compared to other metallic materials ($K_{\text{CNTs}} = 2000$ W mK$^{-1}$ compared to $K_{\text{Ag}} = 419$ W mK$^{-1}$ and $K_{\text{Cu}} = 380$ W mK$^{-1}$) [1]. Therefore, the CNTs are considered as an ideal material for thermal dissipation media in electronic devices in general and high power electronic devices in particular [2, 3]. In this paper, we present the experimental and simulation results of thermal dissipation efficiency using multi walled carbon nanotubes (MWCNTs) and vertically aligned carbon nanotubes (VA-CNTs) for a µ-processor and a high-brightness light emitting diode (HB-LED). In the thermal dissipation application for the µ-processor, the MWCNTs were used as an additive component in some types of commercial thermal paste with different concentrations of MWCNTs. To apply the VA-CNTs to a HB-LED, we developed a technique to transfer the VA-CNTs from Si to Cu substrates. Some initial results for using the VA-CNTs on a Cu substrate for LED chip testing are also reported.

2. Experimental results and discussion
2.1. Applying carbon nanotubes to a µ-processor
Nowadays, most computers use commercial thermal paste, such as silicon (for instance, Stars thermal paste with thermal
conducivity of 1.87 W mK$^{-1}$ or silver (for instance, AS5 thermal paste with thermal conductivity of 8.89 W mK$^{-1}$), to disperse the heat in the $\mu$-processor. To form CNT-based composite thermal pastes, we used the following materials:

- MWCNTs with diameters of 20–50 nm and lengths of several tens of $\mu$m.
- Commercial silicon thermal paste for computers (Stars Company), named Stars.
- Commercial silver thermal paste for computers, named AS5.
- Composite of commercial silicon thermal paste (Stars) and CNTs of different concentrations, named CNT/Stars.
- Composite of commercial silver thermal paste (AS5) and CNTs of different concentrations, named CNT/AS5.

The CNT-based composite thermal pastes were prepared and precisely coated on the surface of the $\mu$-processor; the volume and area of the thermal paste are fixed at 0.12 ml and 7 cm$^2$, respectively. The thickness of the thermal paste layer is approximately 170 $\mu$m. After coating the thermal paste on the $\mu$-processor surface, the CPU fan is loaded and fixed by four lockers of the computer [4].

To find the optimum concentration of CNTs, we mixed the CNTs into a commercial thermal paste with different concentrations from 1 to 7% weight (wt%). Figures 1(a) and (b) are typical SEM images of the MWCNTs and of 2 wt% CNT/AS5, respectively, used in this work.

**Figure 1.** Typical SEM images of (a) the MWCNTs and (b) the 2 wt.% CNT/AS5.

![Figure 1](image1)

![Figure 1](image2)

Figures 2(a) and (b) are the results of energy dispersive spectroscopy (EDS) analysis on the CNT/Stars and the CNT/AS5 thermal paste, respectively. We can see the presence of Si, Ca, O and C elements in the CNT/Stars thermal paste; and Ag, Zn, O, C elements in the CNT/AS5 thermal paste. This confirmed the presence of the CNTs in the CNT/Stars and CNT/AS5 thermal paste.

**Figure 2.** EDS spectroscopy of (a) 2 wt% CNT/Stars and (b) 2 wt% CNT/AS5.

![Figure 2](image3)

![Figure 2](image4)

Figure 3 is the measured temperature of the $\mu$-processor as a function of working time in the case using CNT/Stars thermal paste with different concentrations of CNTs: not using any thermal paste, utilizing Stars thermal paste, 1 wt% CNT/Stars, 2 wt% CNT/Stars, 3 wt% CNT/Stars, 5 wt% CNT/Stars and 7 wt% CNT/Stars. It is clear from figure 3 that without thermal matching media, the temperature of the $\mu$-processor reaches 85 $^\circ$C within 20 s and the computer was automatically shut down. This obviously confirmed the necessity of the thermal matching media for the device. By adding the CNTs (0, 1, 2, 3, 5 and 7 wt%) into the Stars thermal paste, the temperature of the $\mu$-processor decreased. In particular, the temperature increasing time and maximum temperature of the $\mu$-processor are 200 s and 63 $^\circ$C for the case of 2 wt% CNT/Stars, respectively, whereas these values are 75 s and 66 $^\circ$C for the commercial Stars thermal paste. When using AS5 thermal paste, the optimum concentration of CNTs was also 2 wt%. We have measured the temperature of the $\mu$-processor with an operation time of longer than 10 000 s (figure 4). The result in figure 4 shows that the temperature of the $\mu$-processor is almost saturated at 63 $^\circ$C when the operation time reaches 200 s. The thermal dissipation capability of CNT/Stars and 2%
When using Stars thermal paste, the heat resistance of the
µ-processor was 0.81 K W\(^{-1}\). When using Stars thermal paste, the heat resistance of the Stars thermal paste layer was 0.13 K W\(^{-1}\) and the thermal conductivity of the Stars thermal paste was \(k_{\text{STARS}} = 1.87 \text{ W mK}^{-1}\). By adding 2 wt% CNTs into the Stars thermal paste, the temperature of the µ-processor was 5°C lower compared to the Stars thermal paste itself, the heat resistance and thermal conductivity of the CNT/STARS thermal paste were \(R_{\text{CNT/STARS}} = 0.095 \text{ K W}^{-1}\) and \(k_{\text{CNT/STARS}} = 2.56 \text{ W mK}^{-1}\), respectively. When using AS5 thermal paste to disperse heat for the µ-processor, the thermal conductivity and heat resistance were \(k_{\text{AS5}} = 8.89 \text{ W mK}^{-1}\) and \(R_{\text{AS5}} = 0.027 \text{ K W}^{-1}\), respectively. When using the 2 wt% CNT/AS5 thermal paste, the heat resistance and the thermal conductivity were \(R_{\text{CNT/AS5}} = 0.015 \text{ K W}^{-1}\) and \(k_{\text{CNT/AS5}} = 16.2 \text{ W mK}^{-1}\), respectively. The simulation and experimental results showed that when using 2 wt% CNTs added thermal paste, the thermal conductivity of the thermal paste was more than 1.4 times larger than that when using commercial thermal paste.

### 2.2. Applying carbon nanotubes for a HB-LED

To apply the VA-CNTs for thermal dissipation in a HB-LED, it is necessary to have a VA-CNT layer on the Cu substrate of the device. We have developed a technique to transfer the VA-CNT layer from Si to Cu substrates. Firstly, we synthesize the VA-CNT films on a Si/SiO\(_2\) substrate. Then, we transfer the VA-CNT layer from the Si/SiO\(_2\) substrate to the Cu substrate. The VA-CNT films were synthesized on a Si/SiO\(_2\) substrate by the CVD method using Fe\(_2\)O\(_3\) particles as a catalyst. The Fe\(_2\)O\(_3\) nanoparticles were formed by a co-precipitation reaction of iron salts. The Fe\(_2\)O\(_3\) particles, having a diameter of 10–20 nm, were uniformly coated on Si/SiO\(_2\) substrate by spin-coating method.

The AFM image (figure 5(a)) indicated that the Fe\(_2\)O\(_3\) nanoparticles were located on the Si substrate at a high density of approximately 10\(^{10}\)–10\(^{12}\) cm\(^{-2}\) and the diameters of the Fe\(_2\)O\(_3\) nanoparticles were in the range of 10–20 nm.

Figure 5. (a) AFM image of the Fe\(_2\)O\(_3\) nanoparticles on the Si/SiO\(_2\) surface and (b) SEM image of the VA-CNT film grown for 30 min at a temperature of 750°C [6].
Figure 6. (a) Schematic view of the LED using thermal dispersive VA-CNTs; SEM images of (b) the vertical aligned CNT layer lifted off and pasted on the Cu substrates and (c) the LED chip adhered to the CNT film [7].

Figure 7. Light emission from the packaged LED operated at an input current of 100 (a) and 500 mA (b) using the VA-CNT film as the thermal dissipation medium [7].

layer, as schematically shown in figure 6(a). The LED chip used in this work was InGaN on sapphire with an active area, emitting light wavelength and working power of 0.5 mm × 0.5 mm, 460 nm and 0.5 W, respectively. Figures 6(b) and (c) are SEM images of the VA-CNT film on Cu substrate before and after packaging and wiring the LED chip on the CNT/Cu substrate, respectively [7].

The output light power of the LED packages should ideally maintain a linear relationship with the electrical input current if the heat generated from the LED modules can be effectively dissipated. However, heat arising from high input power would degrade the LED optical performance and result in a saturation of output light power. Normally, for the InGaN LED chip used in this experiment, the light power of the LED packages using the commercial thermal dissipation material starts to deviate from a linear relationship with the input current at about 300 mA and reaches a peak value at 350 mA. By using VA-CNTs instead of the commercial thermal dissipation material, the output light power of the LED packages retains a linear profile even if the input current can be higher than 500 mA. Figure 7 shows excited light emission from the packaged LED/VA-CNT/Cu that operates at 100 mA (a) and 500 mA (b). Our initial result confirmed that the VA-CNT film strong improves the thermal dissipation property and can be used in high power electronic devices.

3. Conclusion

We have successfully applied the MWCNTs in commercial thermal paste to effectively dissipate heat for a µ-processor of the PC. The SEM images, Raman and EDS analysis confirmed that CNTs were dispersed well in the CNT/Stars and CNT/AS5 thermal paste. The simulation and experimental results showed that when using 2 wt% CNT added thermal paste, the temperature of the µ-processor decreased by 5 °C and the thermal conductivity of the thermal paste was more than 1.4 times larger than that when using the commercial thermal paste. We also successfully synthesized the VA-CNT films on Cu substrates and successfully transferred the VA-CNT film from the Si substrate to the Cu substrate. The VA-CNT film on the Cu substrate was utilized as a thermal dissipation substrate for a 0.5 W InGaN LED package. For the LEDs, the VA-CNT film could maintain a linear relationship of the output light power with a high input current of more than 500 mA without reaching saturation for the LED chip of 0.5 W InGaN compared to the packaged device using commercial silver thermal paste. The initial results have confirmed the advantage of MWCNTs and VA-CNTs as excellent additive components for thermal dissipation media in the µ-processor of the PC, HB-LED and other high power electronic devices.

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