Nanoparticle coating in heat pipe design for miniaturised cooling

Size reduction and increasing processing power are driving forces in the development of modern electronic devices, from portable computers to smartphones and wearable devices. In all these applications, efficient cooling of the electronic components of a device is paramount. By exploiting novel design approaches based on the use of nanoparticle layers, Prof Tomio Okawa and Ms Menglei Wang (The University of Electro-Communications) are paving the way for heat pipes with enhanced heat transfer performance and reduced dimensions compared to traditional heat exchangers.

During the last few decades, the mass demand for and use of personal electronic devices has led to increased efforts to develop faster electronics containing large amounts of power in an increasingly reduced size. This has made the issue of cooling electronic circuits a crucial problem in the design of novel devices. The lifetime of an integrated circuit depends upon its operating temperature, and this leads to a design dilemma: either one increases the size of a device to accommodate additional cooling components, or one must sacrifice the lifetime of its integrated circuits. Furthermore, as consumers demand more and more functionality from their products, the number of integrated circuits tends to increase over time, further increasing the need for more efficient cooling.

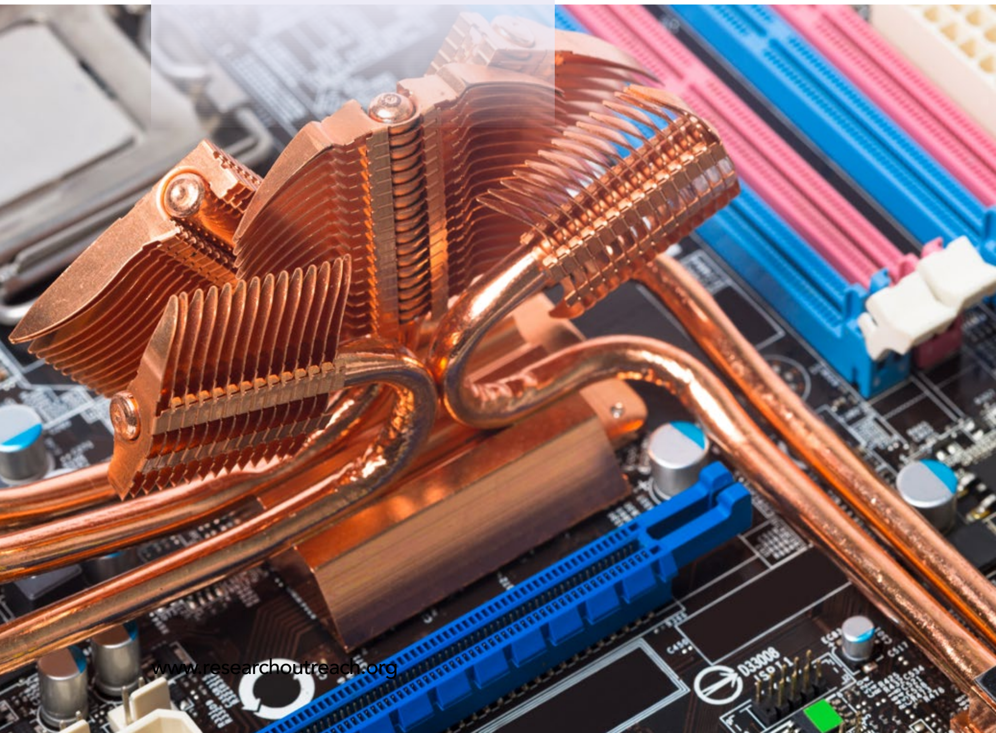
COOLING INTEGRATED CIRCUITS

In large consumer products, such as kitchen appliances and telephones, the market may accept a moderate increase in product size in return for additional functionalities. In these cases, cooling can be maximised by optimally arranging the electronic circuits within an air stream, or by adding thermal spreaders to transfer the heat to the exterior packaging. In personal devices – for instance, high-end notebook computers with powerful microprocessors, graphical processing units and advanced communication capabilities – more space-efficient cooling strategies need to be adopted. To maintain the small size and weight, notebook computers often contain lower-powered electronic components running at lower frequency and performance. High-end products using high-power components, on the other hand, suffer from a reduced lifespan, which is a trade-off caused by the lack of device enlargement for adequate cooling.

HEAT PIPES

The best cooling techniques for electronic devices must take advantage of every cubic millimetre of space available. Heat pipes – which have evolved since the late 1990s from specialised industrial heat transfer components to an indispensable consumer commodity in the design of high heat flux microcomputers – offer a convenient route to maximise cooling in a restricted space. They are in fact one of the most promising heat transfer devices for miniaturised electronic equipment.

A heat pipe acts as a heat transfer device, which effectively drives heat between a hot and a cold solid interface. It exploits the principles of thermal conductivity and phase transition in a cooling medium. At the hot end of a heat pipe, a



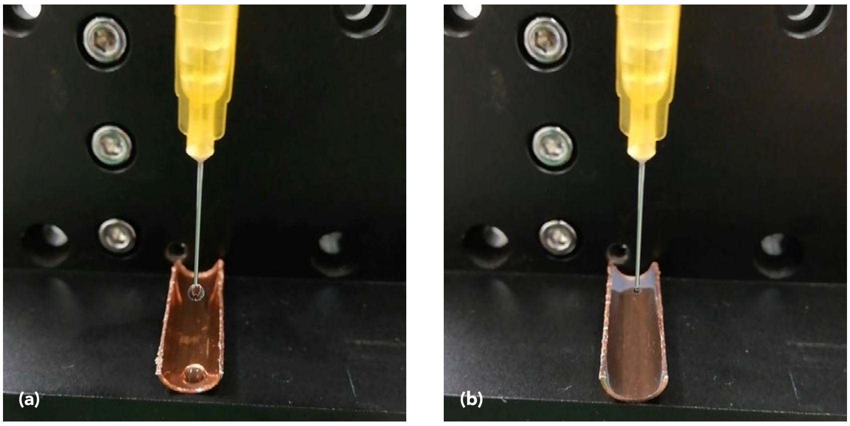


Figure 1. (a) Water on bare copper. **(b)** Water on nanolayer.

cooling liquid enters into contact with a thermally conductive solid material and is converted into a vapour. The vapour migrates inside the heat pipe to reach the cold interface, where it condenses back to its liquid state. Under the effect of gravity, a centrifugal force or capillary action, the liquid returns to the hot end, where it is again converted into a vapour and restarts the cooling cycle. Heat pipes act as extremely effective thermal conductors. Depending on their length, they can achieve a thermal conductivity approaching 250 times the value for pure copper. Unfortunately, the performance of heat pipes decreases as their diameter is reduced, or when they are flattened, which makes it difficult to use them efficiently in microelectronic devices.

Effective cooling is essential to increase the lifespan of integrated circuits in modern high-end electronic devices.

MINIATURISED HEAT TRANSFER: NANOPARTICLES

The work of Professor Okawa, in collaboration with Ms Menglei Wang, has been focusing on heat pipes that use capillary action to drive the diffusion of a cooling liquid, like water, from the cold to the hot end of the pipe after condensation. Capillarity is controlled by the presence of a wick within the pipe, and the heat transfer performance is largely determined by the structure and properties of the wick.

Extensive experimental work has been devoted, in particular, to heat pipes using water-based alumina (Al_2O_3) or copper nanofluids as cooling liquids. Nanofluids are colloidal suspensions of nanometre-sized particles, or nanoparticles, and they exhibit peculiar properties that make them useful in heat transfer applications, particularly in microelectronics. The use of nanofluid coolants has been shown to bring about an enhancement in the heat transfer performance of a heat pipe. This has been attributed to the deposition of nanoparticle layers at the evaporation section.

NANOPARTICLE LAYER COATING

Nanoparticle layers are thin, and therefore potentially ideal for miniaturised applications, and they exhibit strong capillarity. In addition, they are composed of easily obtainable, cheap and clean materials, which make them suitable for mass-produced products. Based on the results of previous work on nanoparticle deposition in heat pipes, Prof Okawa has put forward innovative ideas on how to engineer nanoparticle-based heat pipes for maximising their heat transfer capabilities.

He has proposed that the deposition of a nanoparticle layer in the condensation section and in the so-called 'adiabatic' section of the pipe, in which the condensed liquid travels back to the hot end of the pipe, in addition to the evaporation section, can be used to guarantee an even more efficient heat transfer within the pipe, without compromising the heat pipe structure or increasing its diameter. Furthermore, he has devised an efficient procedure to pre-coat all sections of the heat pipe, which is then filled, in operating conditions, with a suitable nanofluid.

SILICA NANOPARTICLE PRE-COATING

To demonstrate the importance of nanoparticle pre-coating on the performance of heat pipes, Prof Okawa examined the use of a silica (SiO_2) water-based nanofluid. In his experimental

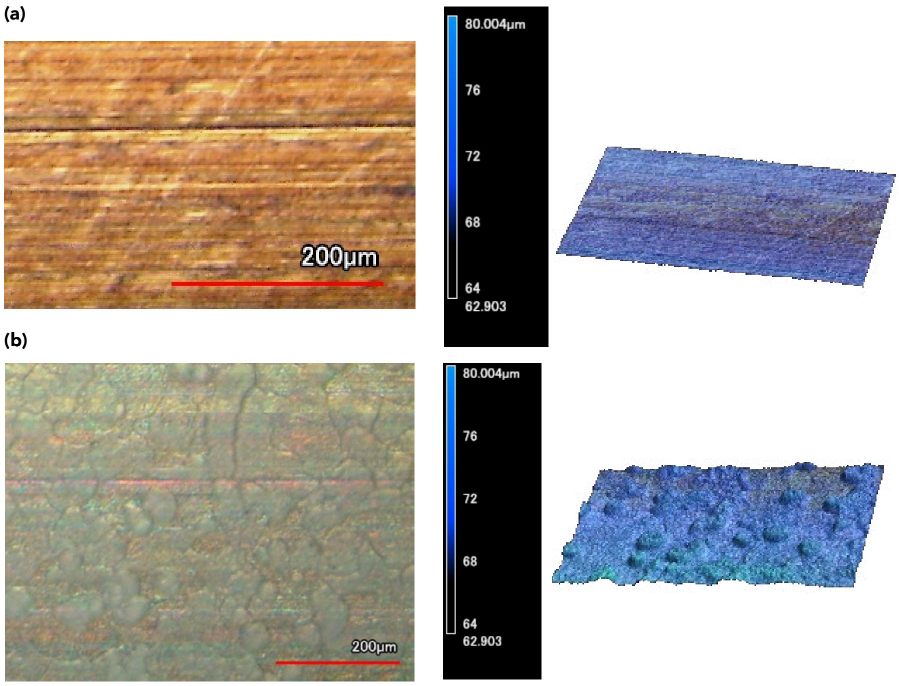


Figure 2. (a) Microscope image of bare copper tube surface. **(b)** Microscope image of nanoparticle-coated copper tube surface.

nanoparticle pre-coating. The creation of a nanoparticle layer on the wick is therefore an effective and accessible method for improving the heat transfer performance of the heat pipe. Even more intriguingly, excellent heat transfer was observed in the heat pipe even in the absence of a wick, provided the internal walls of the pipe were pre-coated with a nanoparticle layer. Effectively, if a sufficient number of nanoparticles have been deposited on the internal walls of the pipe, the resulting nanoparticle layer plays the role of a very thin and efficient wick.

This result is extremely promising, although further studies will be required to address issues concerning the durability of nanoparticle-layer coated heat pipes and the possible deterioration in heat transfer performance after experiencing dry-out. Nonetheless, Prof Okawa's findings are of crucial importance on the path toward smaller cooling systems for microelectronics, and they will stimulate further work aimed at exploring and exploiting the extraordinary properties of nanoparticle-based materials in a wide range of technological applications.

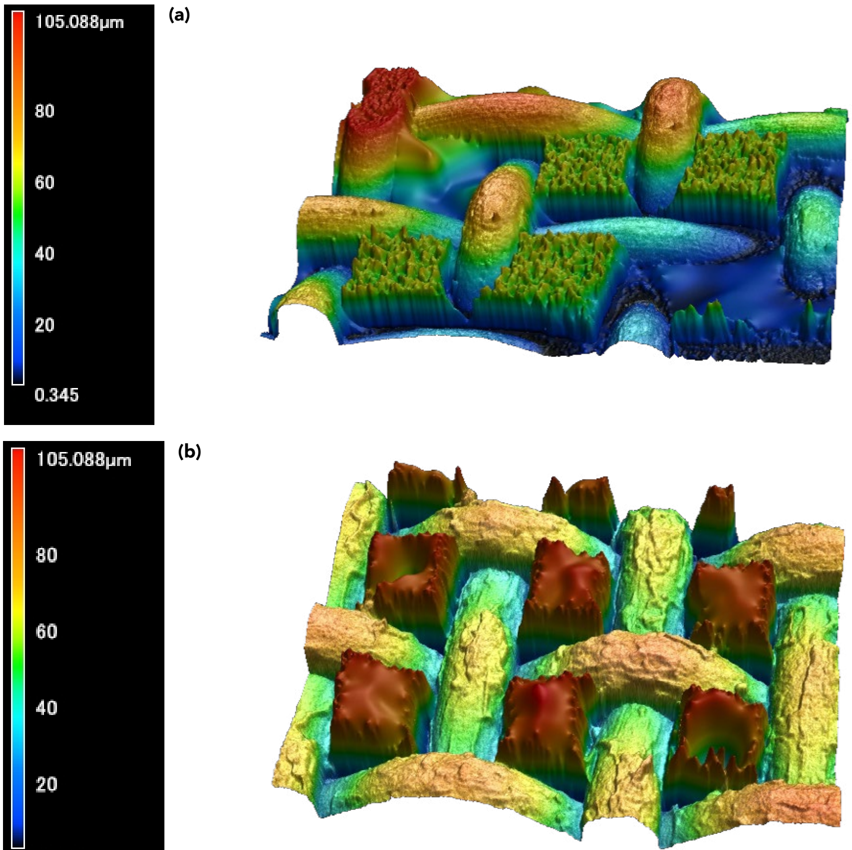


Figure 3. **(a)** Microscope image of metallic mesh (brass). **(b)** Microscope image of nanoparticle-coated mesh.

setup, a heat pipe was used consisting of a cylindrical copper container with a diameter of 8 mm, a wall thickness of 0.5 mm and a length of 100 mm. As a wick, a brass screen mesh was used, with a wire diameter of 85 μm and about 4700 strands per metre. The nanofluid consisted of silica nanoparticles suspended in distilled water, with a minimum size of 20 nanometres. Larger nanoparticle sizes (120-800) were also observed in the fluid, caused by the clustering of individual nanoparticles. The pre-coating of the screen mesh was accomplished by first heating it to 800 °C and then immersing it in the silica nanofluid repeatedly till its whole surface was covered by a nanoparticle layer. The internal wall of the copper pipe was also pre-coated by immersing and heating it in the nanofluid. Thickness measurements showed that the nanoparticle layer was as thin as ca. 9 μm.

Nanoparticle coating provides an efficient means to enhance the cooling performance of heat pipes and to decrease their size.

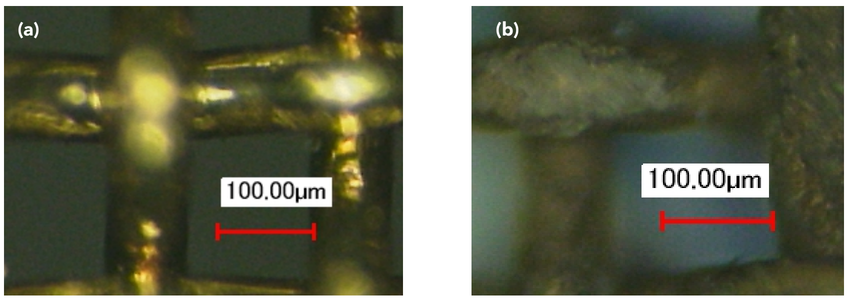


Figure 4. The photographs of screen mesh before and after nanoparticle layer coating. **(a)** Bare mesh. **(b)** Nanoparticle-layer coated mesh.

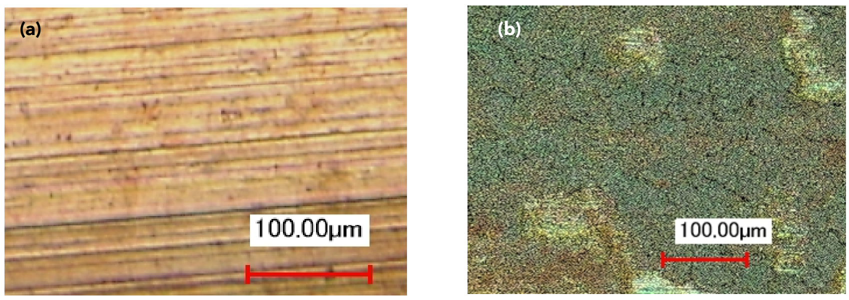


Figure 5. The photographs of copper tube before and after nanoparticle layer coating. **(a)** Bare tube. **(b)** Nanoparticle-layer coated tube.

INNOVATIVE HEAT PIPE ENGINEERING

In operating conditions, the experimental heat pipe used by Prof Okawa exhibited a 47% decrease in thermal resistance, which was attributed to an enhanced capillarity of the wick caused by the

Behind the Research

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Research Objectives

Prof Tomio Okawa and Ms Menglei Wang are researching the use of nanoparticle layers to enhance heat transfer performance and reduce dimensions in electronic devices.

Detail

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Personal Response

What are the remaining challenges that need to be addressed before making your method suitable for use in the mass production of microelectronic devices?

" Heat pipe was arranged horizontally in our experiments. Hence, the performance in vertical arrangement should be clarified and we are doing this now. Durability is another concern. Finally, for mass production, an efficient way to create a nanoparticle layer on the wire mesh and/or container inside wall must be developed. To achieve this, collaboration with a company partner may be indispensable. "