# Carbon Nanotube Bumps for Thermal and Electric Conduction in Transistor

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The continuous miniaturization of semiconductor chips has rapidly improved the performance of semiconductor products. However, thermal issues that affect semiconductor chips are becoming more serious. For example, heat transfer has become a very serious problem in the CPUs of personal computers; high-frequency high-power amplifiers (HPAs) of mobile communication systems; and power control units of hybrid-car motors. To solve this problem, Fujitsu has been developing semiconductor heat sinks that exploit the high thermal conductivity of carbon nanotubes (CNTs). This paper describes the CNT bumps we have recently developed for transferring heat and electrically connecting the source, gate, and drain of the high-power, flip-chip amplifiers of mobile communication base stations. CNT bumps can be used to achieve high gain and high thermal conductivity in high-frequency HPAs. This paper introduces some recent developments in CNT bump technology.

#### 1. Introduction

Since the discovery of carbon nanotubes (CNTs) in 1991, researchers have taken interest in their unique structure and physical properties. This interest is still continuing at present, and research into the practical application of CNTs has recently become popular.<sup>1)-3)</sup> Fujitsu is researching the application of semiconductor-type CNTs to transistors and the application of metal-type CNTs to wiring and heat transfer.<sup>4)-6)</sup> The high current capacity and low resistance of CNTs make them suitable for constructing the via interconnects that vertically connect the electrodes of multi-layer LSIs. In addition, Fujitsu is also researching ways to use the high thermal conductivity of CNTs to transfer heat from semiconductor chips.

Heat transfer technology has become much more important in the semiconductor field in recent years. Although the continuous miniaturization of semiconductor chips has rapidly improved the performance of electronic products, it has also caused thermal problems. For example, today's PC CPUs run so hot they could be used to fry an egg, and if the miniaturization of semiconductor chips continues, they are expected to reach the temperature of a nuclear reactor. Other devices that currently face a cooling problem are high-power amplifier modules used to convert electric power for hybrid cars and the high-frequency high-power amplifiers (HPAs) of mobile communication base stations. We think that the high thermal conductivity of CNTs make them one of the most useful technologies for solving these thermal problems in the semiconductor field.

This paper first describes the physical properties of CNTs that stem from their special structure. It then describes a flip-chip HPA that was developed for mobile communication base stations that uses CNT bumps as an example application of the high thermal conductivity of CNTs.

#### 2. Physical properties of CNTs

CNTs have a cylindrical structure made of a graphite sheet, with a diameter of 1 to 10 nm (**Figure 1**). This special structure provides various unique properties that are not found in conventional bulk materials. Semiconductor properties or metal properties are generated depending on the diameter and chirality (winding direction) of the cylindrical graphite sheet.

CNTs with semiconductor properties have



Semiconductor type

Metal type

Figure 1 Structure of CNTs.

an electron mobility that is at least 10 times that of silicon (Si). The bandgap of CNTs depends on their diameter. If semiconductors with the required bandgap can be created in the future by controlling the diameter and chirality of CNTs, CNTs will be widely used as a post-Si material because of their high electron mobility. Also, CNTs with metallic, electric conduction (also called its metal property) show unique properties. The current capacity of CNTs is very high because the very high covalent binding between carbon atoms greatly suppresses migration. The permissible current density is 10<sup>9</sup> A/cm<sup>2</sup>, which is 1000 times higher than that of copper (Cu). Therefore, the possibility of using CNTs instead of copper materials in the future is very high.

The thermal conductivity of a CNT is about 10 times higher than that of Cu and roughly equal to that of diamond. Therefore, CNTs are also highly expected to become the prominent heat transfer material in the future. The CNT shown in Figure 1 has a cylindrical structure made of a single graphite sheet, whereas the CNT shown in **Figure 2** — called a multi-walled carbon nanotube (MWNT) — is made of several graphite sheets. MWNTs always have a metal property and have property merits similar to



Figure 2 Multi-walled carbon nanotubes (MWNTs).

those of single-walled, metal-type CNTs. Because MWNTs can easily be grown at lower temperatures, we focused on MWNTs in our application development of metal-type CNTs. Specifically, we used clustered MWNTs to fabricate via interconnects and heat transfer paths.

# 3. Concept of flip-chip HPA using CNT bumps

This section describes the current status and problems of HPAs for mobile communication base stations and then explains the usefulness of CNT bumps in solving these problems.

To increase the data transmission rates of mobile communication devices, the operating frequency and output power of their HPAs must be increased. However, such increases will also increase the heat output of HPAs and make it harder to keep them sufficiently cool. For example, the output power of a high-power transistor chip for a mobile communication base station exceeds 100 W, but the chip is only several millimeters square, so it is very important to ensure a high rate of heat transfer from the chip. Conventional HPAs use the face-up structure for heat transfer shown in **Figure 3**.<sup>7)</sup> In this structure, a metal package is directly connected to a heatsink, the transistor chip is directly mounted on the metal package, and heat is transferred to the heatsink through the transistor chip. However, when the operating frequency is increased, the gain decreases due to the inductance of the bonding wire between the ground and chip. This gain reduction of the HPA directly reduces the system efficiency. To solve this problem, use of the flip-chip structure, in which the transistor chip is turned upside down and its electrodes are connected to the package electrodes through metal bumps (e.g., Au bumps), has been proposed. However, conventional metal bumps cannot sufficiently transfer the heat from the high-power transistors of an HPA. Therefore, it will be difficult to increase the gain and heat dissipation of HPAs in order to achieve the higher operating frequency and output power needed to increase the data transmission rate.

One of the solutions to this problem is to use a flip-chip HPA with CNT bumps (**Figure 4**).





Because CNT bumps can be formed by fine machining, they can be directly connected to the source, gate, and drain electrodes of a high-power transistor. Therefore, CNT bumps can be used for both heat transfer and electrical conduction.<sup>8)</sup> A high thermal transfer can be achieved by connecting a high thermal conductivity CNT bump to the source electrode near the transistor. Because the source electrode is connected to the ground electrode on the substrate through the CNT bump connected to the source, the ground-ing inductance is lower than in the conventional chip using a bonding wire. As a result, a high gain can also be achieved at a high frequency.

### 4. CNT bump production

This section describes the CNT bump production process and the fabrication of a flip-chip HPA with CNT bumps.

We used a very simple CNT bump production process. The catalytic metal needed to grow the CNTs is formed on the flip-chip mounting side of the wired substrate using photolithography. Then, the CNTs are grown on just the catalytic metal using the hot filament CVD method. We use an Al/Fe catalyst and an Ar-diluted acetylene gas source. The CNTs, which at 15 µm are sufficiently long to form bumps, can be grown vertically on the substrate. The size of the CNT bumps can be arbitrarily controlled using the catalytic pattern. Fine CNT bumps can be formed for electrode patterns of a high-power transistor that are 10 µm or narrower. **Figure 5** shows scanning electron microscope (SEM) images of CNT bumps formed on an aluminum nitride (AIN) substrate.

Each bump is made of clustered CNTs and has an area density of about  $10^{11}$ /cm<sup>2</sup>. The CNTs are MWNTs about 10 nm in diameter.

After growing the CNT bumps, the CNT surfaces are plated with gold (Au) to increase the adhesion between the transistor electrodes and CNT bumps during flip-chip bonding of the HPA chip. **Figure 6** shows the CNT bump structure after Au-plating. The thickness of the Au-plating layer is about 1 µm.

In the last step, the Au-plated CNT bumps are thermo-compressed onto the electrodes of the chip using a flip-chip bonder (**Figure 7**).

# 5. Characteristics of flip-chip HPA using CNT bumps

This section describes the characteristics of the flip-chip HPA that was fabricated using the developed CNT bumps.

For the high-power transistor, we used a GaN-HEMT that was being developed for mobile communication base stations. **Figure 8** 



Figure 4 Flip-chip HPA with CNT bumps.



Figure 5 SEM images of CNT bumps on AIN substrate.



Figure 6 SEM image of CNT bumps after Au-plating.



Figure 7 SEM image of flip-chip HPA.



Figure 8 I-V characteristics of face-up HPA and GaN-HEMT flip-chip HPA.

shows the current-voltage (I-V) characteristics of the conventional face-up HPA and those of a gallium-nitride-based high electron mobility transistor (GaN-HEMT) flip-chip HPA with CNT bumps.

The source-drain resistance, including the source and drain wiring resistances, contributes to the increased resistance seen in the I-V characteristics. However, this increase hardly differs between the face-up HPA and the flip-chip HPA, which indicates that the resistance of the CNT bumps is negligible. The negative resistance in the high-voltage, high-current region of the I-V characteristic is caused by self-heating of the transistor. The higher the thermal resistance in the mounted state, the greater the negative resistance. In the negative resistance region, there are no differences between the face-up HPA and the flip-chip HPA, indicating that the CNT bumps effectively transfer heat from the high-power transistors. From the thermal resistance of the mounted high-power transistors, we estimated that the thermal conductivity of each CNT is about 1400 W/m·K, which is 3 to 4 times that of Cu.

Next, we measured the S-parameters of the face-up HPA and flip-chip HPA to check the grounding-inductance reduction effect of the CNT source bumps and obtained the small-signal equivalent circuit parameters (Figure 9). The gate width of the transistor was 2.4 mm. The only differences between these HPAs are in the grounding inductance  $(L_s)$ , input capacitance  $(C_{gs})$ , and output capacitance (C<sub>ds</sub>). The input/output capacitance includes the parasitic capacitance between the wires and ground. The flip-chip HPA has a higher C<sub>ds</sub> than the face-up HPA, and this is probably because the distance between the drain electrode and ground surface is shorter in the flip-chip HPA.  $C_{ds}$  can be reduced by increasing the CNT bump length. L<sub>s</sub> of the face-up HPA was about 0.12 nH, whereas  $L_s$  of the flip-chip HPA was only 0.06 nH. The grounding inductance is reduced because the ground surface

is connected to the transistor source electrode through CNT bumps that are only 15 µm long.

Figure 10 shows the frequency dependence of the maximum available gain  $(G_{Amax})$  obtained from the measured S-parameters.

The difference in  $G_{Amax}$  between the face-up HPA and flip-chip HPA becomes pronounced at about 3 GHz and above. At 5 GHz and above, because of the lower grounding inductance,  $G_{Amax}$  of the flip-chip HPA is at least 2 dB higher than that of the face-up HPA. It can be considered that the gain of the flip-chip HPA can be increased by optimizing the CNT bump length and by reducing the input and output capacitances.

**Figure 11** shows the input/output characteristics of the flip-chip HPA with CNT bumps. The operating frequency is 2.1 GHz, the power voltage is 40 V, and the gate width is 2.4 mm. For comparison, this figure also shows the characteristics of the conventional face-up HPA. The power characteristics of the flip-chip HPA, which are acquired by effective heat transfer using the CNT bumps, are roughly the same as the power characteristics of the face-up HPA. When the gate width of the transistor is 2.4 mm, the saturation power is 39 dBm, the gain is 15 dB, and the power added efficiency is 68%, which are very good results. The other merit of the CNT bumps - greater amplifier gain due to the small grounding inductance — is not apparent because the 2.1 GHz operating frequency is too low. We expect that higher gain can be achieved in products operating at 3 GHz and above by using CNT bumps.

### 6. Conclusion

This paper introduced a CNT bump technology that provides high heat conductivity as an example application of CNT technology. It also described a flip-chip HPA for mobile communication base stations that uses CNT bumps.

We developed a technology for selectively growing CNT bumps vertically to a height of



measured data of  $S_{11}$  and  $S_{22}$ 



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Small-signal equivalent circuit model and comparison of model data with measured data.



Figure 10 Frequency dependence of maximum available gain (G<sub>Amax</sub>).



Figure 11 Power performance comparison of face-up HPA and flip-chip HPA using CNT bumps.

15 µm or more with a width of 10 µm or less. We were the first in the world to demonstrate that CNT bumps fabricated with this technology can be connected to fine electrodes of HPAs and used as flip-chip bumps. The thermal conductivity of each CNT bump is 1400 W/m·K, which is very high compared to that of metals, and the CNT bumps can be connected to a fine electrode very close to a heat source. By using these bumps, the grounding inductance can be reduced to about half or less while maintaining the same thermal conductivity as that of the conventional face-up structure. As a result, we increased the gain at 5 GHz and above to 2 dB or more.

In the future, we will attempt to improve the thermal conductivity by increasing the density of CNTs in a bump and will develop a practical, high-frequency HPA with CNT bumps for mobile communication base stations. This paper introduced only one example CNT thermal application; however, as described in the introduction, we expect that CNT technology will also be applied to PC CPUs, hybrid-car power modules, and other products with serious heat transfer problems.

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