

Review of Carbon Nanotube Wire-to-Metal Connection Methods: Techniques, Challenges, and Prospects

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Abstract: This paper reviews the connection technologies between carbon nanotube (CNT) wires and metal materials, analyzes the technical principles, advantages, limitations and application prospects of different connection methods. It mainly focuses on the electrical contact issues of CNT wires in the field of microelectronics, and how to achieve a high-performance, reliable combination of metal and CNT wires through emerging material processing and connection technologies. The article also discusses the challenges these technologies face in overcoming interface resistance, improving mechanical connection performance, and maintaining the characteristics of CNT wires.

Keywords: Carbon nanotube wire, Connection technology, Microelectronics, Contact resistance.

1. Introduction:

Carbon Nanotubes (CNTs) wires are wires made from carbon nanotube materials. Due to their unique structure and properties, CNT wires have a wide range of potential applications in various technological and industrial fields. CNT wires can exhibit conductivity similar to or even greater than copper under certain conditions, especially single-walled carbon nanotubes (SWCNTs). The thermal conductivity of CNTs is extremely high and can reach the thermal conductivity of diamond under certain conditions, making CNT wires very attractive for thermal management applications. The tensile strength of CNTs is tens of times higher than that of ordinary steel, but their weight is only one-sixth of it. CNT wires have a low density, making them suitable for creating lightweight structures with high electrical and mechanical performance. Carbon nanotubes are inert to most chemical reactions at room temperature, showing good chemical stability. CNTs can be used to manufacture amplifiers, radio receivers, digital logic circuits, and a variety of other electronic devices, replacing traditional copper or aluminum wires in microelectronics. Because of their superior conductivity, CNT wires can be used for power transmission and as conductive materials in batteries and supercapacitors to improve the performance of energy storage devices. As reinforcements in composite materials, CNTs provide a means to enhance other materials, and conductive composite materials using CNT wires can be used to create electromagnetic shielding, antistatic, and heating elements. Due to the high sensitivity of CNTs to chemical reactions, structures woven from CNT wires can be used as highly sensitive chemical and biological sensors. The strength and light-weight characteristics of CNT wires are of great significance to the aerospace industry, reducing the overall mass of airplanes or spacecraft, improving fuel efficiency, and thrust. In nanoscale electronic circuits, CNT wires can serve as components of extremely small scale. The flexibility and conductivity of CNT wires enable them to be woven into textiles, creating wearable devices and smart clothing[1-4].

Despite the many advantages and broad potential applications, CNT wires also face challenges in real-world

applications including production costs, production consistency, and interface contact strength. These challenges hinder the commercialization process of CNT wires. Connection of Carbon Nanotube (CNT) wires to metals is critical in the application of electronics, energy, and some specific fields. This connection refers primarily to the interface between CNT wires and metal electrodes or metal components, which directly affects the performance of electronic devices[5-6].

To ensure efficient current transfer and reduce energy loss, the contact resistance at the connection should be as low as possible. A good connection between metal and CNT can achieve this. The overall performance of electronic devices relies heavily on the performance of the materials that make up the device, including the performance of the interface between CNT wires and metals. A good connection ensures efficient device operation. When the device operates for a long time or is used in harsh environments, the connection between CNT and metal needs to remain stable and durable to prevent material detachment or degradation. Metals are commonly used as electrodes and interconnects in microelectronic devices, and stable connection with CNTs allows for the integration of these materials[7].

The contact area between metal and CNT wires is often smaller than the size of CNTs, which may lead to higher contact resistance, affecting device performance. Many metals have poor chemical compatibility with the surface of CNTs, and may not form stable chemical bonds, leading to insufficient contact stability. There may be significant differences in thermal expansion between CNTs and metals, which can increase mechanical stress at the connection in the presence of large temperature differences, affecting the stability of the connection. CNTs have diameters on the nanoscale, making precise control of the connection between CNTs and metals at the microelectronic detail level a challenge. The region where metal and CNT connect might form interface states capable of trapping charge, affecting the transmission of carriers and the performance of electronic devices. The reliability of CNT wire-to-metal connections has not been widely tested, and there is a lack of standardized methods and evaluation guidelines[8-9].

To overcome these challenges, researchers are exploring a variety of methods, such as using intermediary layer materials to improve the chemical affinity between CNTs and metals, employing various chemical and thermal treatment techniques to lower contact resistance, and precisely controlling CNT layouts with advanced micro and nano fabrication technologies. As these techniques develop, it is anticipated that more effective connections between CNT wires and metals will be realized in the future, further advancing the application of CNT wires in practical electronic devices. In past decades, research on CNT wires has focused on their unique electrical, thermal, and mechanical properties. Regarding the connection between CNTs and metals, researchers have paid particular attention to the following aspects: Researchers have found that the magnitude of contact resistance significantly affects the performance of CNT-based electronic devices. To reduce this resistance, different metals (such as silver, palladium, copper, etc.) have been used to establish connections with CNTs; Surface engineering methods include assembly of organic monolayer (SAMs) to enhance the interface properties between metal and CNTs; Metal can be deposited on the CNT surface through Atomic Layer Deposition (ALD) technology to form a uniform, controllable metal layer; Various methods have been used to improve interface compatibility between CNTs and metals, including chemical modification and thermal treatment; The reliability of connections between CNT wires and metals has been studied, and accelerated life tests have been conducted to evaluate the durability of connections under different conditions; The development of micro and nano fabrication techniques, such as electron beam lithography (EBL), has made it feasible to form connections at precise locations, advancing the integration of CNTs in semiconductor devices and other microelectronic systems[10-11].

Precision interface engineering at the nanoscale: Using techniques like molecular-level self-assembly, nanoparticle embedding, and optimization of electrode design to control the contact properties between CNTs and metals; Coating CNTs with conductive polymers such as polyaniline and polypyrrole to enhance the connection strength and electronic coupling between metal and CNTs; Combining CNT wires with metals to prepare composite materials that have both excellent mechanical properties and outstanding electrical conductivity; Investigations are underway into the quantum confinement effects of CNTs and their potential applications in quantum computing, which require high precision metal-CNT connection techniques. Utilizing the sensitive nature of CNTs and the stability of metals to design innovative smart materials and sensitive sensors. Researchers are utilizing multidisciplinary approaches, leveraging knowledge from chemistry, physics, material science, and electrical engineering, to collectively advance the technology of connecting CNT wires to metals. With the development of new materials and new process technologies, the realization of efficient CNT wire-to-metal connections and their application in practice has become an increasingly close goal[12].

2. Types and Principles of Connection Technologies

CNT wire-to-metal connection technologies can be realized through several different methods, each with its unique principles and characteristics: This involves directly

connecting metal to the ends of CNTs. Metal atoms form covalent bonds with the ends of CNTs, usually achieved through chemical adsorption or molecular bonding. This connectivity method can reduce contact resistance because electrons can be directly transferred from metal to CNT through the covalent bond. In this configuration, metal contacts the side of CNT, forming a larger contact area. Lateral contact can be formed through physical adsorption or van der Waals forces between materials. Although this contact method may produce higher contact resistance, it facilitates the overall layout of metal and CNT composite wires[13].

Introducing dopant atoms into CNTs (such as boron or phosphorus) to alter their electronic properties can facilitate the transfer of electrons between CNTs and metals. Doping can improve interface properties and reduce the Schottky barrier at the interface, allowing electrons to travel more easily between metal and CNT. This method involves depositing a metal thin layer of atomic-level thickness on CNTs. This highly controlled method can achieve uniform coverage and help reduce contact resistance. ALD technology can also be used to prepare metal catalyst nanoparticles on the surface of CNTs, thereby forming tighter metal-CNT connections[14].

Using non-contact energy sources such as lasers or microwaves to locally heat the contact points between metal and CNTs to establish a connection without harming the CNT structure. This technique can precisely control thermal input on a microscopic scale, achieving a high-quality weld. Using conductive polymer materials, such as polypyrrole or polyaniline, to fill the gaps between metal and CNTs. Such a filler material can not only improve the mechanical strength of the interface but also facilitate the transfer of charge between metal and CNTs[15].

Printing metal inks onto CNTs to form metal-CNT connections. Using microcontact printing can create pre-defined metal patterns on the surface of CNTs, thus creating connections where needed. The choice of the above technologies depends on the specific application's requirements, including the stability of the connection point, resistance, mechanical strength, and the complexity of the manufacturing process. As research deepens, we can expect more innovative methods to improve connections between CNT wires and metals. In some cases, to establish connections between CNTs and metals, researchers use micromanipulation techniques and nanomechanical tools. This includes physically placing them by pushing or rotating CNTs to contact metal electrodes. Although this technique can achieve high precision in positioning, the operation process is cumbersome and difficult to mass-produce[16].

In this method, the chemical functionality of the CNT surface is designed to automatically align and connect with metal electrodes. This typically relies on molecular recognition and specific surface interactions, facilitating self-assembly processes at the nanoscale. CNTs can grow directly on predefined metal electrodes through techniques such as Chemical Vapor Deposition (CVD). By controlling growth conditions, such as gas flow, temperature, and catalysts, the growth direction and positioning of CNTs can be precisely controlled to form the ideal metal-CNT connection[17].

This method uses a focused electron beam to cut CNTs, generating active endpoints, which are then connected by bonding to the metal surface. Electron beam technology can provide extremely high spatial resolution, suitable for precision operations, but also requires high levels of

professional operations and costs. Using pressure to press CNTs against metal structures to form connections through the action of physical forces. Although this method may not provide very firm adhesion, it allows rapid, reversible connections, suitable for some removable devices or testing schemes. By winding CNTs around metal structures to create contact. This creates a physical wrap on the metal surface, providing a good contact area and can be strengthened by pressure or thermal treatment to enhance the stability of the connection[18].

The ideal CNT wire-to-metal connection should have low contact resistance, high mechanical stability, and be able to withstand long working environments. Stable, low-resistance contact between CNTs and metals is crucial for promoting CNT applications in electronics, energy storage, and sensing, among others. However, some challenges remain, such as irregular factors at the interface between CNTs and metals, batch production and standardization issues of manufacturers, and aging and reliability issues at the contact interface. Future research will continue to focus on improving connection technologies, such as optimizing cost-effectiveness, enhancing performance and stability, and integrating into electronic devices on a large scale. With advances in nanotechnology and the development of new materials, we can expect more efficient and reliable CNT to metal connection solutions[19].

3. Evaluation and Comparison of Connection Technologies

Contact resistance is an important evaluative criterion because it directly affects the performance of the overall circuit. End-bonded contacts usually have lower contact resistance due to their good chemical bonding. Side contacts and other forms of contact (such as pressure contact or self-assembly) may have higher contact resistance and need to be minimized through design optimization. Connection technologies must be robust enough to withstand external stress and fatigue. In addition, the structural stability is crucial for durable and reliable electronic applications. Mechanical techniques such as machining and winding can offer good mechanical performance but may sacrifice some electrical performance. Some techniques such as direct growth and electron beam confinement require precision equipment and operations, which may increase production complexity and costs. In contrast, non-destructive welding and ALD technologies have the capacity to precisely control at the nanoscale, but may also be more complicated and costly. Conversely, self-assembly and pressure contact are more suited for simple and rapid application scenarios. For industrial-scale production, the ability to scale to mass production is a key consideration. Some techniques, like microcontact printing, may be more easily expanded to batch production. However, for more precision-intensive techniques (such as machining and electron beam confinement), batch production may be a challenge. Different metals and types of CNTs may require specific connection methods to maintain performance and stability, which involves selecting suitable catalysts and chemical treatment methods. Compared with traditional manufacturing technologies, CNT wire connection techniques may be more costly. Raw materials, manufacturing equipment, and operational complexity all affect the final cost. Long-term stability and reliability are key considerations in the

evaluation of connection technologies. Interface aging, thermal cycling, and electric current carrying capacity need to be considered. Good contact stability can prevent performance degradation, increasing device lifespans[20].

Each technology has its advantages and limitations, so they should be chosen according to the specific requirements of the application. For example, in situations requiring high current density and low contact resistance, end contacts and direct growth may be preferable. For applications requiring low cost and high-volume production, microcontact printing and self-assembly may be more appropriate. For high-end electronic devices that demand precise positioning and control, ALD and non-destructive welding can offer higher performance. When selecting CNT wire-to-metal connection technologies, a balance may need to be struck between performance, cost, and manufacturability. As technologies continue to develop and more experimental data accumulates, future evaluations and comparisons are likely to include an increasing number of standards and dimensions for consideration[21].

4. Expansion of Application Fields

In microelectronic devices, CNT wires are used as interconnects to replace traditional copper wires. Copper's conductivity on the nanoscale is limited by quantum effects, while CNTs have higher conductivity and current carrying capacity. For example, CNTs can be directly grown on a silicon-based substrate using Chemical Vapor Deposition (CVD) technology and connected to metal electrodes using micromanipulation techniques. This method can achieve lower contact resistance and higher current carrying capacity[22].

CNT wires are used in the development of new types of high-sensitivity sensors. The high surface area, high electrical conductivity, and small size of CNTs make them very attractive for use in biological and chemical sensor applications. For example, CNTs can be integrated onto electrodes and connected to metals using self-assembly technology, allowing CNTs to efficiently capture target molecules and produce detectable electrical signals[23].

In the electrodes of supercapacitors and batteries, CNT wires are used to enhance conductivity and mechanical strength. Coupling CNTs with metals can increase the charging and discharging capabilities and the cycling life of batteries. By depositing CNTs onto metal electrodes using microcontact printing technology, the conductivity of the electrodes can be improved, enhancing the overall performance of the battery[24].

In NEMS devices, the extremely fine size and high elastic modulus of CNTs make them ideal materials for making moving parts such as actuators and switches. CNT wires can be precisely connected to metal electrodes using electron beam confinement technology to construct nanoscale mechanical devices. Flexible electronics and wearable devices require flexible wiring and connection technologies. CNTs, with their exceptional flexibility and electrical and mechanical properties, are one of the ideal materials for such uses. For example, winding techniques can be used to wrap CNTs on a bendable metal substrate to form flexible connections, suitable for bendable circuit boards and wearable devices[25].

When analyzing these cases, it is necessary to consider the needs of specific applications to evaluate the CNT wire-to-metal connection technologies used. Each technology's advantages and disadvantages must be considered, as well as

whether they can meet performance requirements and cost-effectiveness. Additionally, the expected lifespan of the devices, operating conditions (such as temperature, humidity, etc.), and reliability requirements are important factors in determining which technology to choose. As CNT technology develops, we can expect more innovative application cases to emerge, offering advanced solutions for various industries.

5. Technological Challenges and Prospects

Carbon Nanotube (CNT) wire-to-metal connection technologies have enormous potential in electronics and nanotechnology, but they also face a series of challenges. The following are the key challenges and future prospects: The interface between CNTs and metals often has contact resistance, which can impact the performance of the entire electronic device. Reducing the resistance at the contact point between CNTs and metals is a current research focus. The stability of CNT-to-metal contact may degrade at different temperatures and current densities, limiting their use in high-power or high-temperature applications. Existing CNT growth and connection methods are often incompatible with current semiconductor manufacturing processes, making it difficult to achieve scalable and mass production. Achieving high-quality, consistent, and reproducible CNT growth and connections is crucial for commercial applications but remains a challenge. The production cost for high-purity, high-quality CNT materials is high, limiting their market competitiveness. CNT wire-to-metal connection technologies often require complex process steps and specialized equipment, increasing production difficulty and costs. There is a lack of industry standards and testing protocols to measure and ensure the reliability and performance of CNT wire-to-metal connections[26].

With the development of new catalysts and better CNT positioning and directional growth techniques, improvements in contact resistance and interface stability are expected. Utilizing advanced connection technologies such as microcontact printing and self-assembly to achieve simple, reliable, and cost-effective CNT wire-to-metal connections. Developing CNT growth and connection technologies compatible with existing semiconductor processes to achieve large-scale commercial production. Researchers and engineers from the fields of physics, chemistry, and material science co-operate to address the technical challenges faced. Seeking a broader range of application cases in microelectronic devices, sensors, energy storage, flexible electronics, and others to expand market demand. Accelerating research development and technology transfer with policy incentives and research funding support. Developing industry standards and reliable testing methods to provide accurate, standardized performance evaluations. As research deepens and technology matures, CNT wire-to-metal connection technologies are expected to overcome existing challenges and be widely applied in multiple fields. With innovative designs, material synthesis, and manufacturing processes, we can expect CNTs to play a more critical role in future microelectronics and nanotechnology[27].

6. Conclusion

The technology of connecting carbon nanotube (CNT) conductors with metals is an evolving field that harbors the potential to drive revolutionary advancements in

microelectronics, nanotechnology, energy storage, and many other domains. Nevertheless, the commercialization path of this technology faces numerous challenges. CNT conductors are highly regarded for their exceptional electrical, thermal, and mechanical properties, as well as their higher current density capacity compared to traditional materials, which gives them the potential to reshape the future of electronic devices. While the performance of CNT conductors is attractive, effective connections with metals still present issues, particularly in terms of contact resistance, interfacial stability, and batch production. Future research must focus on improving the interfacial quality at the CNT-metal junction, optimizing manufacturing processes, and developing methods that are compatible with current semiconductor fabrication technologies. Successful commercialization will require reducing production costs, which necessitates breakthroughs in material preparation, CNT growth, and connections with metals, as well as the ability to achieve large-scale manufacturing and integration. Close collaboration across different disciplines is extremely important for the development of CNT conductor technology, demanding the collective expertise of physicists, chemists, materials scientists, electrical engineers, and others. It is necessary to establish industry standards and reliable testing methods to ensure the quality, reliability, and performance of CNT conductor and metal connection joints meet application requirements. To ensure the practical application value of CNT conductor technology, expanding market demand is critical. This means that tailored and optimized solutions must be designed for specific industries. In summary, despite challenges, the technology of connecting CNT conductors with metals remains optimistic for the future due to its immense developmental potential and unique performance advantages. With relentless research efforts, technological innovation, industrial collaboration, and policy and economic support, CNT conductor and metal connection technology has the potential to become a considerable scientific force, propelling the advancement of the electronics sector and related application areas.

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