

Development of nanomaterials in flexible electronics

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Abstract. Flexible electronics, with its excellent flexibility, leading-edge and lightweight, has become a frontier technology capability in the field of electronics, which integrates well with the characteristics of nanomaterials for applications in various disciplines such as sensors, information, medical, and energy. This paper systematically summarizes the main structures of flexible electronics featuring flexible substrates with their outstanding flexibility as well as mechanical and electrical properties. Afterwards, it delves into the four major properties of nanomaterials along with their extensive applications aboard flexible electronics. In particular, the development applications of carbon nanotube films in sensors and electronic devices by means of their great flexibility and electrical conductivity are mainly outlined. Then the practical applications of graphene in the domain of electronic display through its superior heat dissipation are introduced. In the final part, an exploration is made on how the advantages of flexible electronics and nanomaterials can be further used in frontier fields such as aerospace, smart medicine, and automated science if we combine them more effectively. However, as an emerging field, the development process of flexible electronics is still fraught with challenges. Two major challenges are still facing the field: mechanics, packaging, and cost. There is a long way to go for flexible electronics combined with nanomaterials, which can open numerous possibilities for electronic technology.

Keywords: Nanomaterials, Flexible electronic, graphene, Carbon nanotubes.

1. Introduction

With the rapid development of intelligent terminal and chip technology, the famous Moore's Law [1] is increasingly close to its limit, when the width of the lines on the silicon wafer reaches the nanometer scale, the properties of the material change radically, so we need to think about changing the structure of the chip better, flexible electronics is a good choice because of the stretchable, flexible properties of its devices. Now, flexible electronics are widely used in many fields, such as information, energy, medical, aviation because its portable, thin, scalable, and high efficiency, etc. But currently based flexible electronic devices can't meet our requirements, so we need to further improve the performance of it.

As a part of the field of flexible electronics, nanotechnology has become a hot topic due to its good flexibility, transparency, conductivity, etc. At present, there are many backgrounds about the application of nanomaterials in flexible electronic devices, such as carbon nanotubes, graphene, graphene/copper nanosheet composites. many materials have been preliminaries applied and developed in flexible electronic devices.

In this paper, we first introduce the structure and properties of flexible electrons and nanomaterials, such as the components of flexible electrons, the physical properties of flexible electrons, the quantum properties of nanomaterials and so on. Then, we summarize the application status and examples of nanomaterials in the field of flexible electronics. Among them, we mainly discuss the related application examples of carbon nanotubes and graphene in the field of flexible electronics, such as carbon nanotubes flexible sensor, graphene flexible display, graphene composite materials and so on. These nano flexible electronic devices have strong application potential by virtue of their high adaptability to the environment, good thermal stability, and excellent electrical conductivity.

However, the technology of nanomaterials in the field of flexible electronics is not mature enough, so we briefly discuss the difficulties about mechanics, packaging, and cost of nanomaterials in the field of flexible electronics. In the end, we briefly analyze the prospect of nanomaterials in the field of flexible electronics.

2. Flexible Electronics

Flexible electronic [2] is a generic term for a technique that refers to the new electronic technology of fabricating organic and inorganic material electronic devices [3] on flexible, ductile substrates. Compared to traditional electronics, flexible electronics are more flexible and adaptable to different environmental operating conditions and the deformation needs of device facilities.

2.1. Flexible electronic technology structure

Flexible electronics technology has a relatively similar basic structure, although the areas of application vary substantially, all of them contain at least four parts: electronic components, flexible substrate, interconnect, and adhesive layer, as shown in Figure 1. The upper covering layer is used to shield the circuit and electronic components from moisture and oxidation. Compared to conventional electronics, the flexible substrate is the most distinctive structural difference in flexible electronic systems.

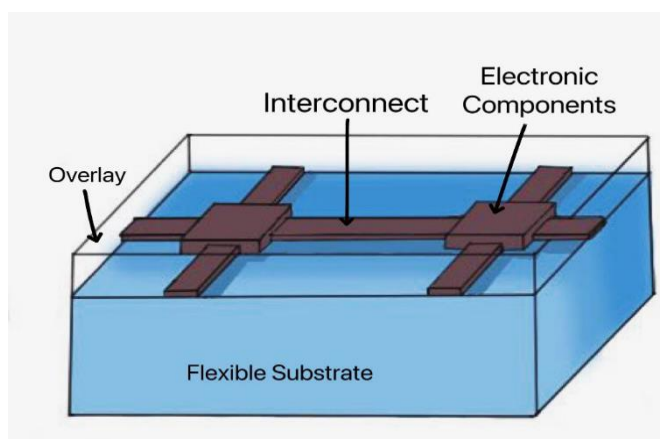


Figure 1. Fundamental structure of flexible electronic systems

2.1.1. Electronic components

Electronic components have been defined as the basic elements of electronic circuits together with the components of small machines and instruments. It is also the basic building block of electronic products. They are frequently composed of certain parts that can be used in the manufacture of similar products. Thin-film transistors and sensors, which are commonly used in conventional technology, can be used in flexible electronics too. These electrical components are not fundamentally different from those used in traditional electronics, but as flexible electronics are uniquely flexible and ductile, some components made of inorganic semiconductor materials [4] are easily damaged during deformation, resulting in the need for special carriers to be mounted on flexible substrates, such as microcellular element islands. As some thin film transistors can operate normally under a certain degree of deformation due to their specific characteristics, these electronic components can be mounted directly on the flexible substrate without regard to the problem of brittle breakage caused by deformation or ductility.

2.1.2. Flexible substrate

Flexible substrate is the decisive factor in determining the elastic deformation performance of flexible electronic devices. Flexible substrates are commonly known as "soft boards", which are the achievement of substrates made from flexible insulating substrates, and traditional electronic devices

are commonly based on silicon materials, while flexible substrates feature many excellent advantages not possessed by rigid substrates. The most prominent feature is its high-level flexibility, which can be freely bent, folded, etc. Because of the flexibility of the flexible substrate, meeting the needs of flexible electronic devices scalable, high density, miniaturization, high-reliability direction of development; secondly, the flexible substrate folded with lightweight, small volume, good heat dissipation, more like a thin film (usually only 1mm thick). It has been prepared using polymer, not only to reduce the cost of electronic products, to ensure the economy of the material but also to limit the product thickness and weight, which is more in line with the development needs of high-density miniaturization.

As the " foundation " of flexible electronic technology, flexible substrates, like traditional rigid substrates, have a high level of insulation requirements. Flexible electronic devices have enormous potential in the fields of displayers, flexible display technology, and smart technologies, where the consequences of electrical leakage in electronic devices can be extremely serious. An insulated flexible substrate [5], on the other hand, ensures that the electronics work properly, eliminating accidents such as leakage and safeguarding the security of the users and the flexible electronics.

In order to achieve the key properties of thin, transparent, flexible, and stretchable flexible electronics, materials with high chemical stability, thermal stability, and transparency are necessary, specific materials will be described in subsequent sections. Flexible substrates have many deformation types in the application and act as energy storage with energy harvesting. The common types of deformation involve bending, plastic deformation, stretching, biaxial, radial, and electroactive deformation (Figure x).

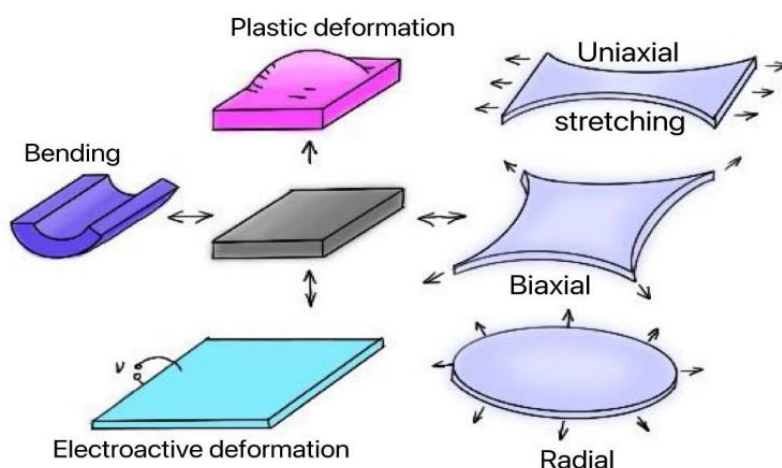


Figure 2. Deformation of flexible electronic sensing substrate materials

2.1.3. Interconnect

As mentioned above, components made of partially inorganic semiconductors are brittle and easily damaged if the device is bent or deformed. Therefore, they are placed on rigid cell islands and interconnect are attached to these individual cell islands like wires by means of metal films, as shown in Figure x. A complete, flexible, and extensible flexible circuit becomes feasible.

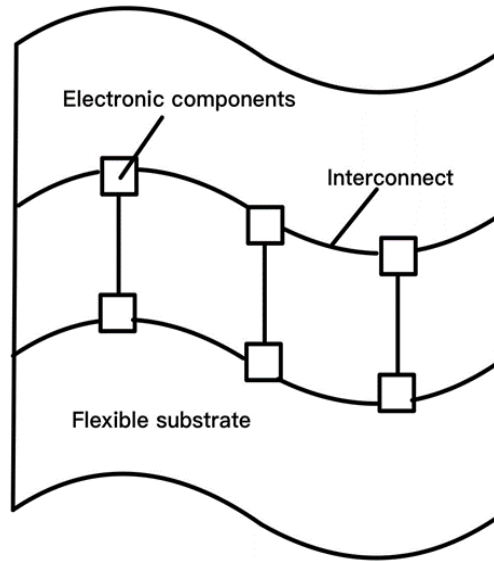


Figure 3. Schematic diagram of a flexible electronic circuit

2.1.4. Adhesive layer

The adhesive layer [6] acts as the " binder " for the various parts of the flexible electronic system, also connecting the flexible substrate to the superstructure, playing a key role in the integration of the respective parts of the system, and especially the connection between the flexible substrate and the interconnect.

2.2. Characteristics of flexible electronics technology

The obvious characteristics of flexible electronics include mechanical flexibility and electrical instability.

2.2.1. Mechanical properties

Compared with traditional electronics, flexible electronics is characterized by its excellent flexibility and ductility. Traditional electronics typically use silicon wafers for integrated manufacturing, which are so hard and brittle that electronic devices are almost impossible to extend or bend, and even the slightest deformation can cause devastating damage to their structure and performance. However, flexible electronics technology is designed by a unique flexible substrate, which makes flexible electronics highly flexible and malleable. Through the analysis of the ductility structure of monocrystalline silicon on an elastic substrate, Zhang et al [7] deduced the expressions of wave wavelength and amplitude under static conditions, and determined the pre-strain level that the flexible electronic system could bear. Meanwhile, Song et al [8] research on flexible materials shows that the ductility of flexible materials can be improved by increasing the bridge length. All the above studies show that flexible materials have good flexibility, which is more in line with the needs of electronic equipment development in the new era and can greatly improve the quality of flexible electronics. Electrical characteristics

2.2.2. Electrical characteristics

Electrical conductivity is the most important property of flexible electronic materials, and the electrical parameter to measure electrical conductivity is resistance. When the shape of the flexible conductive material changes, the change of its resistance can be expressed as:

$$R = \rho \frac{L}{S} \quad (1)$$

Where ρ is the resistivity of the conductor, L is the length of the conductor, and S is the cross-sectional area of the conductor. The experiments of Morsi et al [9] show that the resistance of flexible

electronic materials increases with the increase of deformation. If there are cracks on the surface of the flexible electronic conductor, its resistance will be further increased. When the flexible electronic material breaks, the conductive material loses its conductivity. The deformation of flexible electronic materials will cause the instability of their electrical conductivity.

3. The application status of nanomaterials in flexible electronics

3.1. Introduction to nanomaterials

Materials with one or more of the three dimensions smaller than 100nm are called nanomaterials [10], according to this, this can be divided into zero-dimensional, one-dimensional, and two-dimensional nanomaterials. On the other hand, based on their chemical composition, nanomaterials can be divided into nanocrystalline [11], nano-polymer [12], nano-composite [13] and so on. Besides, nanomaterials also have four physical properties [11], next, we'll look at each of them.

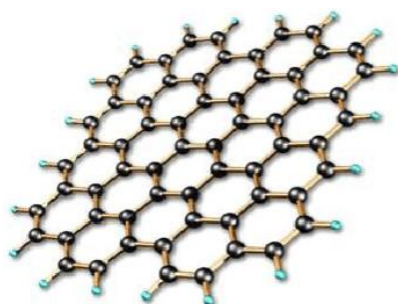


Figure 4. Graphene, a two-dimensional Nanomaterial

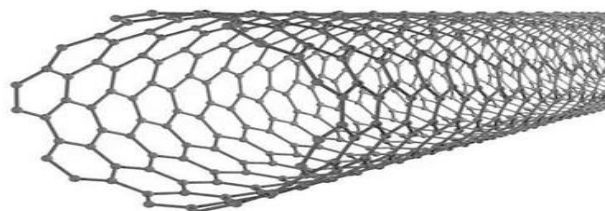


Figure 5. Carbon nanotubes, a one-dimensional nanomaterial

Surface effect—The ratio of atomic number to total atomic number on the surface of nanomaterials increases with the increase of its size. This makes nanomaterials so reactive that they are oxidized by oxygen in the air even when they are standing still in the air, so they are generally kept in liquid. *With this property, nanomaterials can be used as nano powder additives to increase the toughness of the material and reduce the specific gravity of the material.*

Small size effect—As the size of nanomaterials has reached the nanometer scale, their macroscopic physical and chemical properties have undergone significant changes. For example, copper is a good conductor in real life, while copper nanomaterials are insulating at low temperatures.

Because of its small size effect, nanomaterials can be used as functional materials combined with industrial technologies, applied in infrared stealth technology, sintering promoting materials, magnetic fluid field and so on.

Quantum size effect—For nanomaterials, continuous energy bands split the energy levels of components, and the energy level spacing increases with the decrease of particle size. Therefore, nanoparticles exhibit anomalous properties in the fields of electric energy, magnetic energy, and heat energy, which are completely opposite to those of macroscopic objects. For example, nanocrystalline materials have high magnetic permeability and high magnetic sensitivity due to their quantum size effect.

Macroscopic quantum tunneling—Tunneling [14] is one of the fundamental quantum phenomena, so nanomaterials are no exception. Macroscopic quantum tunneling refers to the fact that some nanoparticles can still cross a barrier when the total energy of the nanoparticles is not enough to do so. In the early time, people used the macroscopic quantum tunnel effect to explain nickel nanoparticles [15] can keep superparamagnetic at low temperature.

Quantum size effects [16] and macroscopic quantum tunneling effects will lay the foundation for future developments in microelectronics and optoelectronic devices. These quantum effects define the limits to which existing microelectronic devices can be further miniaturized.

After Moore's Law became saturated, flexible electronics became one of the most important technologies we needed to master and nanomaterials with its own excellent characteristics can make flexible electronic devices to get further development, So mastering nanotechnology is especially important.

3.2. Current situation and application of nanomaterials in flexible electronics.

Now nanomaterials have been used in flexible electronics. Carbon nanotube films [17], for example, can be used as substrates for flexible sensors because of their flexibility and toughness. Or graphene [18], which has good conductivity and flexibility, can be used to make flexible electronic displays, and graphene can also be used as a sandwich material to make nanocomposites, so it has a lot of application examples of nanomaterials.

Next, we will mainly introduce two examples, one is the application of carbon nanotubes thin films in the field of flexible electronics, and the other is the application of graphene nanomaterials and their composites in the field of flexible electronics.

3.2.1. Application of carbon nanotube thin films in flexible electronic devices

Carbon nanotube films have been widely used in the field of flexible electronic devices due to their excellent electrical conductivity, flexibility, thermal conductivity, and mechanical stability. Like flexible sensors, flexible energy components, flexible conductive film materials and so on.

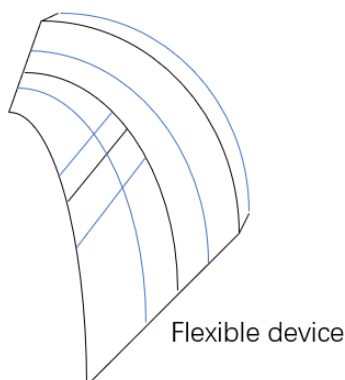


Figure 6. Flexible device

a) Carbon nanotubes thin film-based flexible sensor

Flexible sensor [19] is a more adaptable sensor. Such as pressure sensors [20], strain sensors, temperature sensors and so on, they have good flexibility, tenacity, ductility, can freely bend and even fold, and their structure is also very flexible and changeable. In theory, they are ideal sensors for monitoring the body's biomedical signals, movement, and environment. The flexible sensor is easy to carry and wearable, which can better meet the needs of our daily life. In addition, flexible sensors are highly adaptable to the environment and can be arbitrarily arranged according to the requirements of measurement. They have been widely used in many fields such as medical care, electronic skin [21], medical care, electronics, sports equipment, aerospace, environmental monitoring and so on.

b) Carbon nanotubes thin film based flexible energy devices

Flexible energy devices have attracted wide attention in the emerging fields of flexible electronic devices. For example, flexible battery [22] with long life, flexible nano generator [23] with high power and so on. As a new one-dimensional material, carbon nanotubes have many advantages, such as higher specific surface area, thermal stability, good chemical properties, and high electrical conductivity. Therefore, to a large extent, carbon nanotube films have more advantages in mechanical properties than other materials used to prepare flexible energy devices, it can not only be directly used as a flexible material to prepare flexible energy devices, but also can be used as a component of flexible materials to improve the performance of devices.

c) Other carbon nanotube thin film based flexible electronic devices

Carbon nanotubes film can be used to fabricate flexible touch screen, flexible transistor, flexible photodetector, and other flexible electronic devices due to its excellent electrical conductivity.

For example, flexible transparent conductive material [24]. The transparent conductive films we commonly use are prepared by a certain method on a glass substrate, and the conductive glass can be flexible, but when the glass is thinner, Glass itself is a rigid and fragile material, so it cannot be bent and folded freely for long periods of time, And the cost of glass is high. As a conductive film, carbon nanotubes have good flexibility and can be bent and extended freely, so the thin film material has a great development space in transparent conductive materials, and it can help us solve the above problems.

3.2.2. Application of graphene in flexible electronics

As a two-dimensional material, graphene has good flexibility of nanomaterials, electrical conductivity, and has a good stability, it can now be used as a conductor to facilitate electricity exchange [25], or as a laminated nanomaterial to form composite structures, like graphene and copper nanosheets. It has good sheet shape and electrical conductivity, can be used as flexible printing electronic conductive filler. In the field of flexible electronic devices, graphene can be used to make graphene capacitive touch screen through its flexibility, which can be applied to mobile phone screens, flexible displays, and other fields.

Graphene can be used to make flexible electronic displays for mobile phones because of its good electrical conductivity, transparency, and flexibility. The flexible graphene touchscreen [26] can achieve the function of bending and folding, which can greatly improve the conductivity and the performance of the phone, but also easy to carry. Flexible display screen has an important application prospect in future electronic display devices.

Graphene is almost completely transparent, it absorbs only about 2.3% of light [27], and its electron mobility exceeds $1,500 \text{ cm}^2/\text{V}\cdot\text{s}$ at room temperature, that's higher than carbon nanotubes or silicon crystals, and its resistivity is only 10 to the minus 8, smaller than copper or silver, making it one of the least resistive materials in the world. It is because of its low resistivity, so through graphene make it flexible electronic device has good electrical conductivity.

In addition, graphene can also be used as a sandwich material to prepare nanocomposite materials. Here we mainly take graphene and copper nanosheet [28] as an example to do a simple introduction.

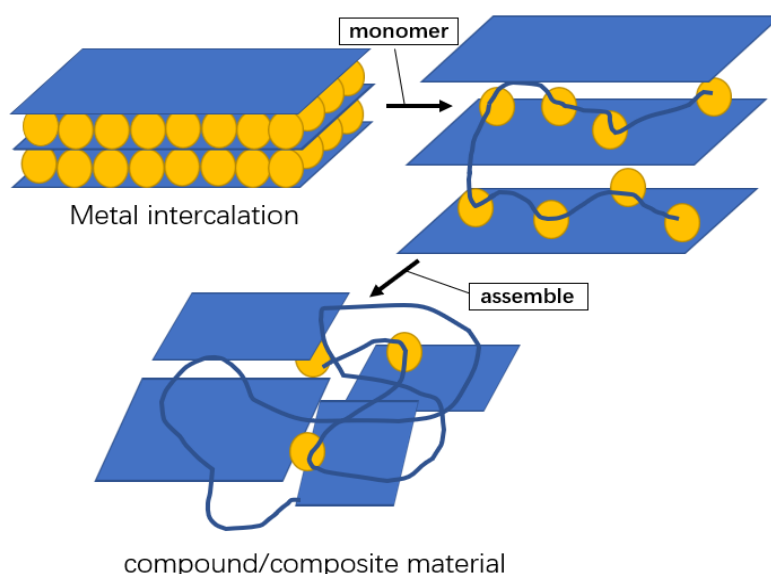


Figure 7. Structure and formation of composite materials

The composite of graphene and copper nanosheets can keep the sheet shape better, and the resistivity of graphene/copper nanosheets [29] is $3.36 \text{ m}\Omega\cdot\text{cm}$, which is an excellent conductive material and can be used as conductive filler for flexible printed electronics. Besides, in the practical

application of the product, the composite material of graphene and copper nanosheet as conductive filler can make the flexible electron still maintain good contact during flexible deformation, which can ensure the smoothness of the circuit.

4. The difficulties of nanomaterials in the field of flexible electronics and the prospect of its application

4.1. Difficulties encountered at present

At present, flexible electronic technology is still in its infancy, and many researchers are constantly trying to break through the traditional thinking and create new fields and industries.

Although flexible electronic devices can be bent, but flexible electronic devices will continue to withstand alternating stress after repeated folding and bending, so it is easy to crack and problems over a long time, so at present, we need to improve the structure or material to solve the problem.

Nano materials as a new material can indeed make the life and stability of the flexible electronics improve, but due to the lack of experience at this stage, especially in the field of nanotechnology, so we are still unable to lead to large-scale preparation technology. although the integration of nano materials technology the performance of flexible electronics has improved theoretical, but if we don't overcome the problems of processing, we can only stay in the experimental stage.

Secondly, the cost of nanomaterials is also a problem worthy of our consideration. Due to the structural characteristics of nanomaterials, it is very difficult to prepare and obtain them, so the cost of preparation is very high, which is beyond our range of affordability. Therefore, it is difficult to promote flexible electronic devices in the market, so it is impossible to promote the development of flexible electronic devices.

4.2. Development prospect of nanomaterials in flexible electronics field

Nanomaterials have many strange properties in chemical and physical properties. If we can systematically use the excellent properties of nanomaterials in the field of flexible electronics, then we can further use them in the frontier fields of aviation, intelligent medicine, automatic science and so on.

In addition, flexible electronic devices made from nanomaterials can be made smaller and thinner, and the performance of electronic devices can be further improved. As we know, Moore's Law is slowly failing in integrated circuits, so using two-dimensional nanomaterials could help us get past that bottleneck, this allows us to make lighter, faster electronics. The mobile phones we carry around with us, for example, will be able to watch video faster if flexible electronics and nanotechnology are incorporated into them.

5. Conclusion

Flexible electronics with its good flexibility and mechanical properties can lay a certain foundation for the development of electronic devices in the future, the application of good conductivity and extensibility of nanomaterials in the field of flexible electronics is our best choice. At present, there have been many applications of nanomaterials in the field of flexible electronics. We mainly describe the application examples of carbon nanotubes and graphene in the field of flexible electronics. Among them, carbon nanotubes as one-dimensional nanomaterials have good conductivity, flexibility, and mechanical stability, which can be applied in flexible sensors, flexible energy devices, flexible transparent conductive materials, thus further applied in detection, aviation, national defense, medical and other infrastructure construction. Besides, as one of the materials with the lowest resistivity, graphene can be used in flexible conductive devices. And with its flexibility, graphene can be used to make flexible display screens, which brings convenience to our life. On the other hand, graphene can be used as a sandwich material to prepare nanocomposites, such as graphene-copper nanocomposites which can be used as conductive filler for flexible printed electrons. For now, due to mechanical

properties, mass production, cost and other problems, the application of nanomaterials in the field of flexible electronics is not mature, but its development prospect in the field of flexible electronics is worth looking forward to.

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