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Overview of Flexible Electronic Encapsulating Technology

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1.1 Flexible Electronics Overview

Flexible electronics, with its unique flexibility, ductility and high efficiency and low cost manufacturing process, have wide application prospects in information, energy, medical, national defense and other fields. As with traditional integrated circuit (IC) technology, manufacturing processes and equipment are also the main drivers for the development of flexible electronics technology. Flexible electronics manufacturing technology level indicators include chip feature size and substrate area size; the key is how to create a smaller feature size of flexible electronic devices on a larger format substrate at a lower cost.

Compared to traditional electronics, flexible electronics have greater flexibility and can adapt to a certain extent to different working environments to meet the requirements of the device's deformation. Flexible electronics covers organic electronics, plastic electronics, bioelectronics, nanoelectronics, and printed electronics, including radio frequency identification (RFID), flexible display, organic electroluminescent (Organic Light-Emitting Diode, OLED) display and lighting, chemical and biological sensors, flexible photovoltaics (PVs), flexible memory or storage, flexible batteries, wearable devices, and many other applications. With its rapid development, the involved fields have been further expanded, and now it has become one of the research hotspots in cross-disciplinary research (Figure 1.1) [1].

In recent years, with the further improvement of flexible electronic technology, we have seen some unimaginable products. For example, the current attention is on folding-screen (Figure 1.2) and wrap-around-screen cell phones. In fact, whether it is a folding screen or a wrap-around screen, the essence of the use of flexible screen technology is that it is a form of flexible electronics technology. The flexible screen, flexible chip, and flexible electrode are only the tip of the iceberg of flexible electronics technology. In fact, information technology involves a variety of sensing, information transmission, information processing, energy storage, and other links that are expected to achieve flexibility [2].

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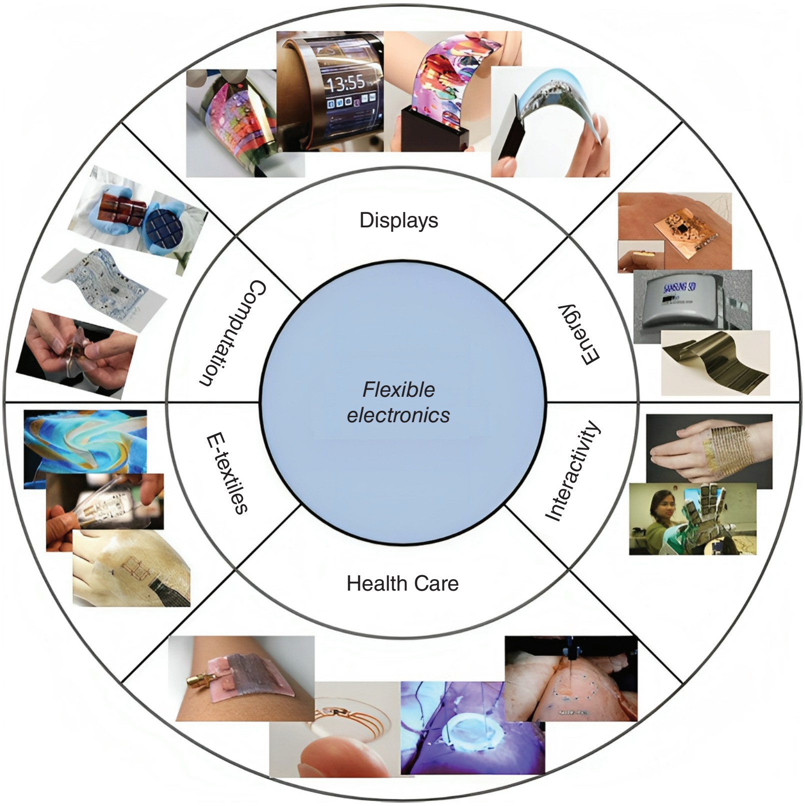


Figure 1.1 The fields of flexible electronics.

So, how exactly is flexible electronics achieved?

First, let us understand the materials used in flexible electronics. Common materials for flexible electronics include flexible substrates, metallic materials, organic materials, inorganic semiconductor materials, and carbon materials represented by graphene (Figure 1.3).

After the raw materials are available, let us look at how flexible electronic devices are manufactured. There are three common flexible electronics fabrication methods: transfer printing, inkjet printing, and fiber structure formation. Among them, transfer printing is a series of functional arrangement techniques used to deterministically assemble micromaterials and nanomaterials into spatially organized structures with two- and three-dimensional layouts [4]. Inkjet printing, on the other hand, as the name implies, allows the direct deposition of functional materials to form patterns on substrates [5]. Flexible electronics fabrication methods based on fiber structures are well suited for wearable electronics that are lightweight, durable, flexible, and comfortable [6].

Since, as mentioned above, flexible electronics have so many advantages and broad application prospects, why has their development been slow to open up?

Figure 1.2 Folding-screen phone.

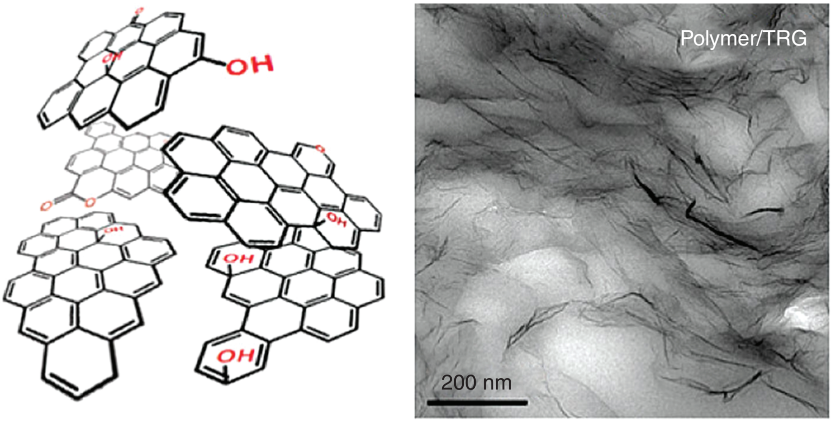


Figure 1.3 Thermally reduced graphite oxide (TRG). Source: Kim et.al. [3]; © 2010, Reproduced with permission from American Chemical Society.

Two major obstacles impede the development of flexible electronics: mechanics and encapsulation. Shen Yang, vice president of the School of Materials at Tsinghua University, has said that the first challenge in the development of flexible electronics is the mechanics of the problem: flexible electronic components in repeated folding and bending will be constantly subjected to alternating stress over time, making them easy to crack. This problem can be overcome mainly through structural design. The second challenge is the problem of electronic encapsulating, which is to integrate the components on the flexible substrate tightly encapsulated together and achieve the desired function.

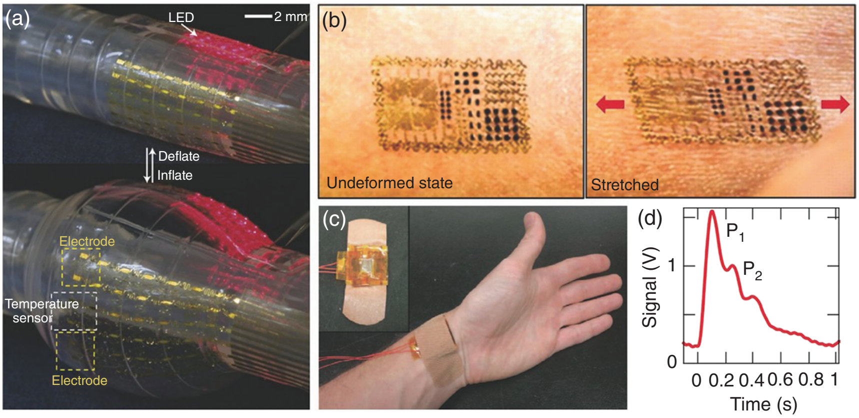


Figure 1.4 Flexible sensors. Source: Hammock et al. [7]; 2013, Reproduced with permission from John Wiley and Sons.

Furthermore, the slow progress in the development of flexible electronics can be attributed to the absence of a significant “viral effect” in terms of application scenes. In other words, the folding-screen cell phone is not an industry pain point. However, another application of flexible electronics – flexible sensors – may be the real revolutionary change in the industry application scene.

Using flexible sensors and conductors, scientists can convert the external force or heat into electrical signals, which are transmitted to the robot’s computer for signal processing, so that it can be made transparent, flexible, extensible, freely bendable, foldable, and wearable electronic skin in order to monitor the human body indicators in real time and accurately [7], as shown in Figure 1.4.

Recently, the Institute of Mechanics of the Chinese Academy of Sciences, in cooperation with researchers from Dalian University of Technology and Beijing University of Aeronautics and Astronautics, has developed a thin-film patch-type flexible curvature sensor for wearable devices from the mechanical structure design (see Figure 1.5). This sensor can accurately measure the dynamic bending curvature and bending angle of the measured surface, and its bending measurement results are not affected by tensile deformation. So, in practical application, it does not require the sensor to be perfectly bonded to the measured surface but simply fit, so it is no problem at all even with gloves or tights on. Also, this sensor is very suitable for integration with wearable apparel and can be applied to flexible smart wearable devices such as joint flexion monitoring, gesture recognition, and sitting posture monitoring [8].

Currently, there are two main approaches to the selection of flexible electronic materials internationally. One approach is to shift from traditional inorganic materials to organic materials, such as polymer materials and organic semiconductors, for flexible electronic applications. Another approach involves the combination of organic and inorganic materials, utilizing composite materials to develop flexible electronic devices.

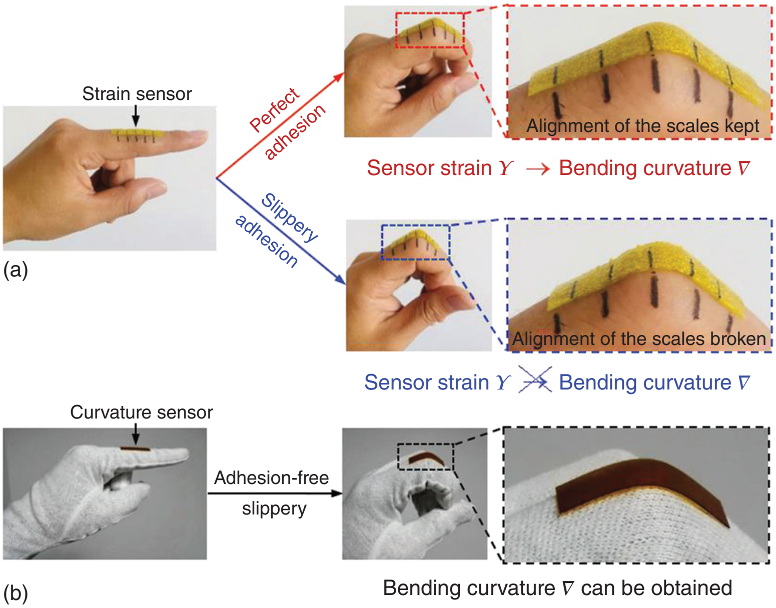


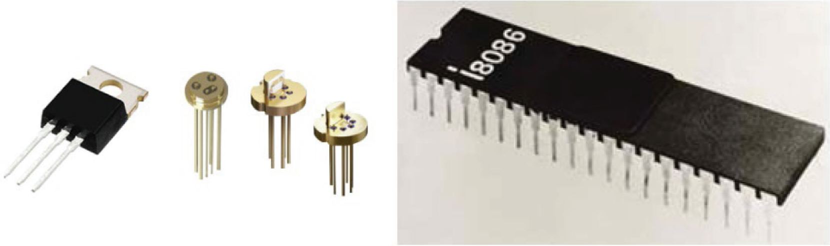
Figure 1.5 Curvature sensors for joint flexion deformation, gesture recognition, and sitting posture monitoring. (a) Strain sensor. (b) Curvature sensor. Source: Liu et al. [8]; © 2018, Reproduced with permission from John Wiley and Sons.

Since the discovery of graphene, two-dimensional materials consisting of single layers of atoms, such as boron nitride, molybdenum disulfide, and black phosphorus, have garnered attention from the semiconductor industry. Research related to these two-dimensional materials holds promise for the advancement of flexible electronics.

The successful application of flexible displays, flexible sensors, and other flexible electronic components signifies the transition of flexible electronics from theory to practice. This advancement may herald a new era of electronic device revolution, bridging the gap between humans and machines and fostering closer interactions.

1.2 Development of Flexible Electronic Encapsulating Technology

One generation of encapsulating, one generation of products. One generation of encapsulating, one generation of products. After the flexible electronic device is manufactured, before it is brought to market as a product, it needs to be packaged to isolate water vapor to ensure its stable operation and complete function. The encapsulating of flexible electronic devices is the same as the encapsulating of traditional electronic devices and is a branch of the encapsulating of electronic devices. When it comes to the word encapsulating, it first originated from the encapsulating of ICs,



(a) (b)

Figure 1.6 TO-type encapsulation (a) and double inline encapsulation (b). Source: Reproduced with permission from huangye88.com / http://yiqiyibiao.huangye88.com/xinxi/5529un9e0ef8b2.html / last accessed 02 August 2023.

and the development of IC encapsulating was developed along with the development of IC chips. The history of the development of encapsulating is also the history of the continuous improvement of chip performance and the continuous miniaturization of the system. As the size of IC devices shrinks and the operating speed increases, new and higher encapsulating requirements are placed on ICs.

Therefore, before introducing flexible electronic device encapsulating, we review the development history of the IC encapsulating industry, which will inspire us to learn as well as develop flexible electronic device encapsulating. The history of the IC encapsulation industry can be divided into two stages: traditional encapsulation and advanced encapsulation, with the year 2000 serving as a crucial boundary [9].

Traditional encapsulating: The development of traditional encapsulating technology can be further subdivided into three phases.

Phase 1 (before 1980): This phase corresponds to the through hole (TH) era, characterized by jack mounting to printed circuit boards (PCBs), pin counts below 64, fixed pitch, a maximum mounting density of 10 pins/cm^2, and encapsulation types such as transistor outline (Transistor Outline Encapsulation, TO) and dual inline (Dual Inline Encapsulation, DIP), as represented in Figure 1.6.

Phase 2 (1980–1990): This phase marks the surface mount technology (SMT) era, characterized by the use of leads instead of pins, wing-shaped or ding-shaped leads, two-sided or four-sided leads, pitch ranging from 1.27 to 0.44 mm, suitable for 3–300 leads, mounting density of 10–50 pins/cm^2, and encapsulation types such as small outline encapsulation (SOP) and quad-edge flat Packaging (QFP), as depicted in Figures 1.7 and 1.8.

Phase 3 (1990–2000): This phase corresponds to the area array encapsulation era, represented by ball grid array (BGA) and chip scale encapsulation (CSP). In this phase, solder balls are used for encapsulation, greatly reducing the distance between the chip and the system. Moreover, the multi-chip module (MCM) represents the integration of multiple chips on a high-density multilayer interconnected substrate using SMT, enabling the assembly of various electronic components and subsystems, as shown in Figure 1.9.


(a) (b) (c)

Figure 1.7 Narrow pitch small outline encapsulation (SSOP) (a), thin small outline encapsulation (TSOP) (b), and thin shrink small outline packaging (TSSOP) (c). Source: Reproduced with permission from Guangzhou Nuode Electronics Co., Ltd / https://www.nodpcba.com/news/2769-cn.html / last accessed 02 August 2023.

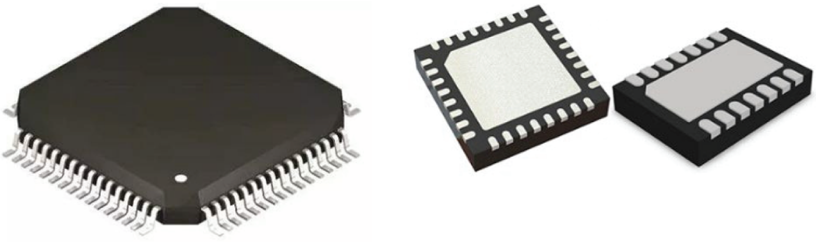
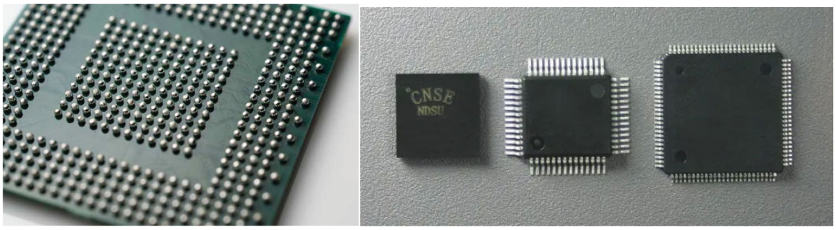

(a) (b)

Figure 1.8 Quad-edge flat encapsulation (QFP) (a), Quad (dual) edge pinless flat encapsulation QFN/DFN (b). Source: Reproduced with permission from Guangzhou Nuode Electronics Co., Ltd / https://www.nodpcba.com/news/2769-cn.html / last accessed 02 August 02 2023.



(a) (b)

Figure 1.9 Solder ball array encapsulation BGA (a), chip level encapsulation (CSP) (b). Source: Reproduced with permission from biyuzg / http://www.biyuzg.com/ / last accessed 02 August 02 2023.

Advanced encapsulation: Since the mid-1990s, driven by the demand for multifunctional system products and advancements in CSP encapsulation and multilayer substrate technology, the IC encapsulation industry has entered the era of three-dimensional (3D) stacked encapsulation. The key features of advanced encapsulation include: (i) the evolution from encapsulating components to encapsulating systems; (ii) the shift from single-chip to multi-chip development; (iii) the transition from multi-chip module (MCM) flat encapsulation to 3D encapsulation; and (iv) the adoption of flip chip (FC) connection and

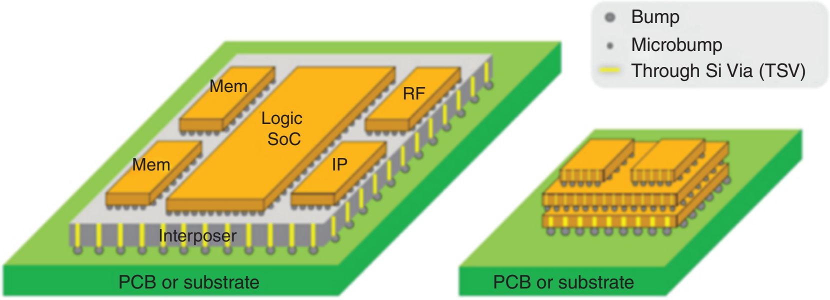


Figure 1.10 2.5D IC encapsulation (a), 3D IC encapsulation (b). Source: Reproduce with permission fromANSYScorporation.

silicon through-hole connection (Through Silicon Vias, TSV) as the main bonding methods. Advanced encapsulation technologies include FC, wafer-level encapsulation, and encapsulation-on-encapsulation (PoP)/system-in-a-encapsulation (Sip)/TSV, which exhibit the following characteristics.

3D encapsulating technology: Multi-chip component planar encapsulating technology integrates multiple IC chips to achieve the integration of encapsulated products in terms of area, then allows chip integration to achieve vertical integration, which is the main efficacy of 3D encapsulating technology. 3D encapsulating can be achieved in two ways: die stacking and encapsulation stacking within the encapsulation. 3D encapsulating is a combination of FC, wafer-level, and POP/Sip/TSV encapsulating technologies, and its development is divided into three stages: the first stage uses lead and FC bonding technology to stack chips; the second stage uses encapsulation body stacking (POP); and the third stage uses through-silicon-via technology to achieve chip stacking (Figure 1.10).

FC technology is not a specific encapsulation type but a circuit interconnection technology that facilitates direct connection between the chip's bare face and the substrate. Unlike wire bond (WB) and tape automated bonding (TAB) technologies that restrict the chip pads to the periphery of the chip, FC technology allows for better electrical performance by utilizing the entire chip area, eliminating the need for interconnection leads. The general structure of FC encapsulation is illustrated in Figure 1.11.

Wafer-level encapsulation (WLP) technology is a product of the combination of FC technology with surfacemount technology and solder ball array encapsulating technology under the continuous pursuit of miniaturization in the market and is an improved and enhanced chip-level encapsulation. WLP is very different from the traditional encapsulating method (first cut and then sealed, after the encapsulation area is at least greater than 20% of the original chip area). WLP technology is first applied to the whole wafer at the same time for many chip encapsulations, testing, and finally cutting into a single device and directly mounted on the substrate or PCB, so the volume after the encapsulation is equal to the original size of the chip, and production costs are also significantly reduced. WLP technology can also be called standard WLP (fan-in WLP) and then evolved into diffusion WLP (fan-out

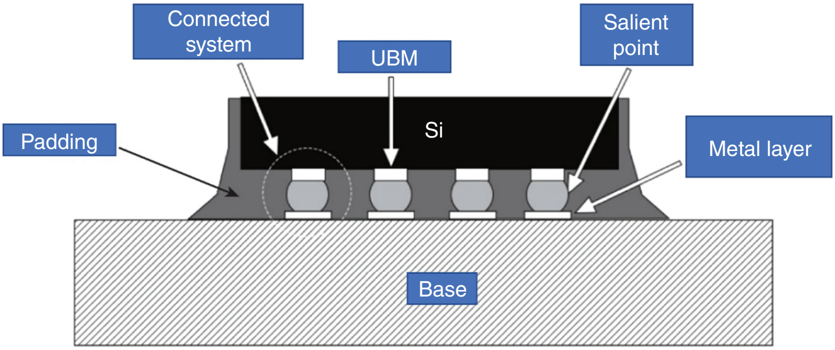
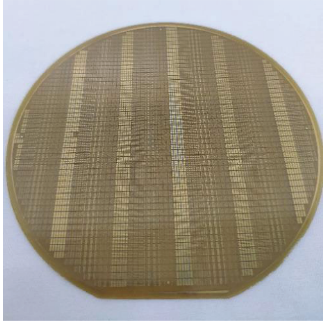


Figure 1.11 General structure of flip chip encapsulation body. Source: Reproduced with permission from www.dymek.cn.

WLP), which is based on wafer reconfiguration technology, rearranging the chip on an artificial wafer and then following similar steps to the standard WLP process for encapsulating, as depicted in Figure 1.12.

PoP is an out-of-encapsulation encapsulation, which refers to the longitudinal arrangement of logic and storage components of the IC encapsulation form. It uses two or more BGA stacks with generally strong resistance under the logic operation located at the bottom and storage components located in the upper, using solder balls to combine the two encapsulations. It is mainly used in the manufacture of advanced portable devices and smartphones used in advanced mobile communication platforms, as shown in Figure 1.13.

Figure 1.12 Wafer-level encapsulation devices. Source: Reproduced with permission from Daimei Instrument Technology Service (Shanghai) Co., Ltd / https://www.dymek.cn/ / last accessed 02 August 2023.



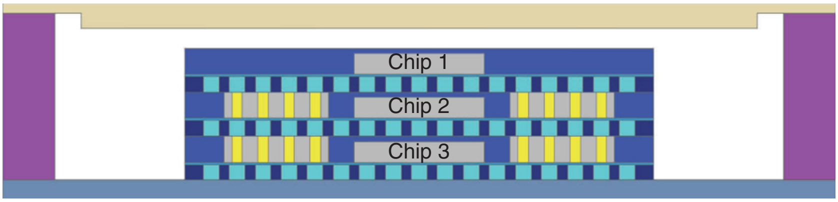


Figure 1.13 Three-dimensional chip stacking structure. Source: Reproduced with permission from www.dymek.cn.

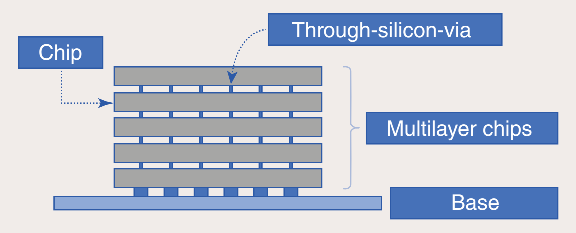
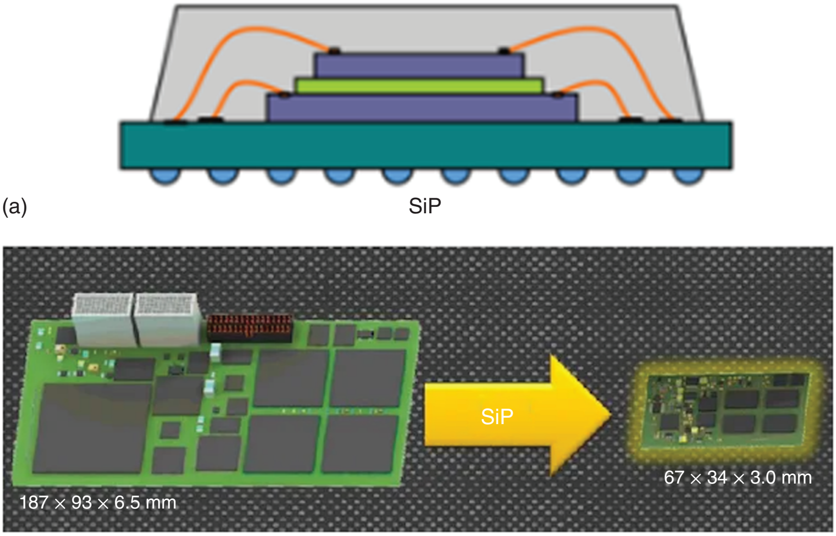


Figure 1.14 3D encapsulation structure using silicon through-hole technology. Source: Reproduced with permission from https://zhuanlan.zhihu.com/p/396703245.



(b)

Figure 1.15 System-level encapsulation structure schematic (a) and system-level encapsulation devices (b). Source: Reproduced with permission from https://smartwear.zol.com.cn/458/4582055.html.

TSV technology is also a circuit interconnection technology that interconnects chips by creating vertical conduction between chip and chip and wafer to wafer. Unlike previous IC encapsulation bonding and stacking techniques that use bumps, TSV enables the highest density of chip stacking in the three-dimensional direction, the smallest form factor, and greatly improves chip speed and low power performance. TSV is a key technology for 2.5D and 3D encapsulations, as illustrated in Figure 1.14.

System in a encapsulation (SIP) technology is the integration of multiple functional chips, including processors, memories, and other functional chips, into a single encapsulation to achieve an essentially complete function. It corresponds to a system on a chip (SOC). The difference is that SOC is an encapsulation in which different chips are encapsulated side by side or stacked, while SOC is a highly integrated chip product (Figure 1.15).

Overall, encapsulating technology has evolved from traditional encapsulations (DIP, SOP, QFP, PGA, etc.) to advanced encapsulations (BGA, CSP, FC, WLP, TSV, 3D stacking, SIP, etc.). In terms of structure, encapsulations have evolved from the early transistor outline encapsulation (TO) to DIP and to SMT in the 1980s. The SOP was derived from SMT in the 1980s, and gradually the small outline J-lead (SOJ), Thin Small Outline Encapsulation (TSOP), and Very Small Outline Encapsulation (VSOP) were derived. SOP, Shrink Small Outline Encapsulation (SSOP), Thin Shrink Small Outline Encapsulation (TSSOP), Small Outline Transistor (SOT), SOJ, TSOP, VSOP, SSOP, SOT, small outline integrated circuit (SOIC), etc., and the later plastic leaded chip carrier (PLCC), QFP. After the IC function and the number of I/O pins gradually increased, Intel took the lead in updating the QFP package to the ball grid array package (BGA) in 1997. The recent mainstream packaging methods are chip scale package (CSP) and overlay package or flip chip package (Flip Chip). From the encapsulating materials, including metal, ceramic, plastic, and other materials used for encapsulating, many high-intensity working conditions of the circuit such as military and aerospace level still have a large number of metal encapsulating. Therefore, the general development process of IC encapsulation can be summarized as follows:

Structure: TO-DIP (Dual In-Line Encapsulation) – PLCC – QFP – BGA – CSP.
Material aspects: (metal, ceramic) – (ceramic, plastic) – plastic.
Pin shape: long-lead direct insertion – short-lead or leadless placement – ball-and-bump soldering.
Assembly method: TH cartridge – surface assembly – direct mounting.

The current global mainstream encapsulating technology of ICs is the third-generation encapsulating technology, namely BGA encapsulation, chip-level encapsulation (CSP), and FC. Among them, FC encapsulating technology, which is considered necessary to promote low-cost, high-density portable electronic device manufacturing process, has been widely used in the consumer electronics industry. The fourth-generation encapsulating technologies, such as WLP, silicon through-hole technology (TSV), and system-level encapsulating (SIP), are still being promoted on a small scale, but they will become the mainstream of future encapsulating methods under the technology upgrade.

In the encapsulating of flexible electronics, the above encapsulating technologies are borrowed and improved, and now the following two processes are mainly used in flexible electronics encapsulating.

1.2.1 Flip Chip Process

FC technology is widely used in traditional microelectronic encapsulating, which has the following characteristics [10]: (i) provides a good point connection for the signal, which can make more effective use of the chip area and has an ultrahigh encapsulating density; (ii) has light mass and small form factor; and (iii) the lead inductance becomes smaller, crosstalk becomes weaker, the signal transmission time is shortened, and thus has excellent high-frequency performance. In flexible electronic encapsulating, FC technology also has these characteristics, and because of the flexible substrate as a carrier, making the product bendable and flexible can

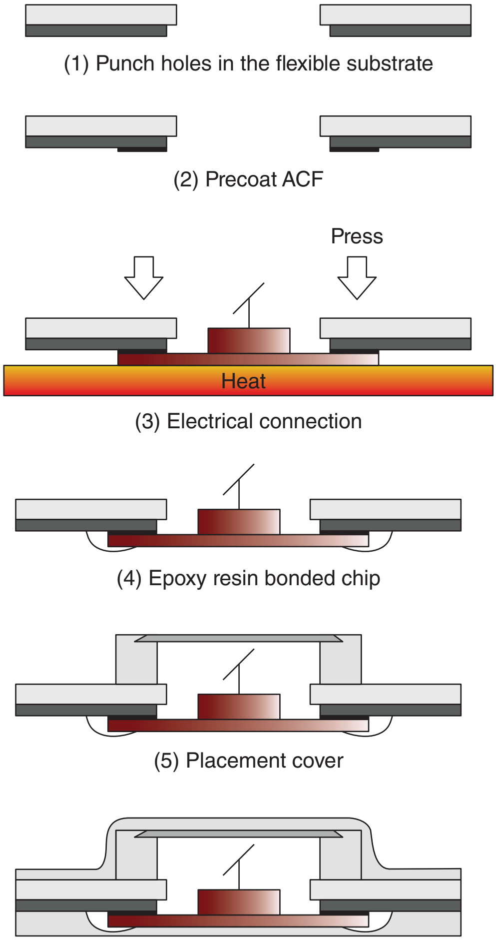


Figure 1.16 The encapsulating process of flip chip. Source: Reproduced with permission from Zhang and Pan. [11]; © 2010, Springer-Verlag.

make full use of space to reduce the size. FC encapsulating methods are solder bump method and conductive adhesive bonding. The former uses the reflow process between the chip and the substrate to form a solder ball, but the reflow requires a high temperature, and commonly used flexible substrate materials including polyimide and polyester (PET) are only suitable for low-temperature (less than 200 °C) bonding technology, so flexible electronic encapsulating is often used in the conductive adhesive connection. Figure 1.16 shows an application of FC technology for flexible encapsulating, and its main process includes [11]: (i) cutting a hole in the flexible substrate that has been made to place the chip; (ii) pasting the anisotropic conductive film (ACF) to the substrate pad for subsequent electrical connection; (iii) adjusting the chip pad so that it is aligned with the pads on the substrate and realizing the physical and electrical connection of the assembly through heating and compression; (iv) filling the side of the chip with epoxy resin to strengthen the structural strength of the assembly to prevent cracks when bending;

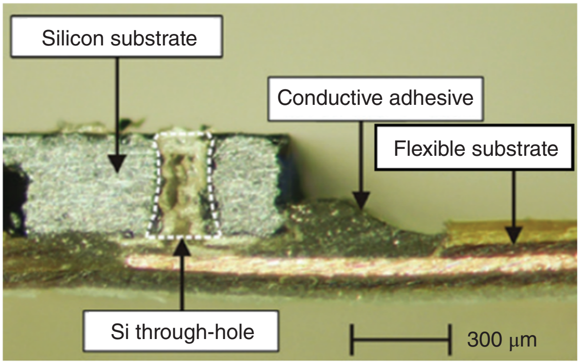


Figure 1.17 Cross-sectional micrograph of MEMS connected to FPCB. Source: Reprinted with permission from Hocheng et al. [12]; © 2012 The Institute of Physics.

(v) placing the mask above the chip, and the gap between the mask and the chip provides space for the chip to move, which is suitable for certain moving parts. The mask is made by injection molding process and its materials are epoxy resin and polydimethylsiloxane; (vi) polydimethylsiloxane is coated around the whole device to seal it, completing the whole encapsulating process. Benfield et al. [12] used FC technology to realize micro-electro-mechanical system (MEMS) and the electrical and structural connection between the MEMS and the flexible printed circuit board (FPCB) is shown in Figure 1.17. The combination of the silicon through-hole design on the chip can effectively reduce the encapsulation size by up to 33%.

1.2.2 Progress of CIF-Based Flexible Electronic Encapsulating Technology

Chip in Flex (CIF) is a kind of structure that fixes the driver IC on the flexible circuit board with die flexible film, which uses a flexible additional circuit board as a carrier to encapsulate the chip and the flexible substrate circuit together. The chip can be encapsulated in a flexible substrate with a thickness of less than 100 μm chip. Flex-on-flex assembly technology, making it more versatile and reliable. At the same time, its cost will be further reduced, both in terms of raw materials and process, which has great significance for its mass production. These advantages make it gradually become a new trend in the current flexible electronic encapsulating.

Compared with embedded encapsulating and CIP (Chip In Plastic) encapsulating, especially when combined with wafer-level encapsulating technology, the main advantages of CIF include [13]: (i) the process temperature is lower and can reach below 200 °C, which is more favorable for the curing of ACFs; (ii) the process steps are also greatly reduced, mainly in the form of certain ACF process steps can be omitted, such as ACF cutting and pre-lamination; (iii) the mechanical and electrical connection between the chip and the flexible substrate is more reliable; and (iv) a certain degree of integration and flexibility can be achieved.

As shown in Figure 1.18, the CIF encapsulation consists of an ultrathin silicon wafer (40 μm thick), a FPCB, and an ACF. PI in the figure is polyimide. The CIF structure has excellent bending performance, and Kim et al. [14] demonstrated that no chip fracture was observed for a minimum bending radius of 5 mm.

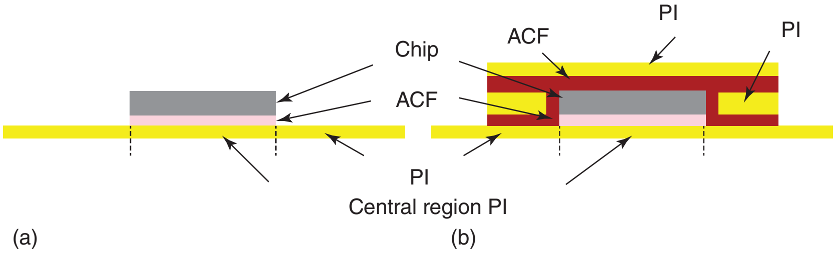


Figure 1.18 Schematic diagram of COF encapsulation and CIF encapsulation. (a) COF encapsulation and (b) CIF encapsulation. Source: Adapted from Suk et al. [14].

Figure 1.19 shows the steps of CIF encapsulation, mainly including: (i) pre-coating a layer of ACF on a 50 μm thick wafer; (ii) cutting the pre-coated thin ACF wafer into small units; (iii) placing the pre-coated thin ACF wafer on the first layer of flexible substrate for COF encapsulation; (iv) bonding the second layer of substrate with ACF; (iv) bonding the third layer of substrate with ACF; and (iv) finishing the encapsulation with FOF process CIF encapsulation. It should be noted that parameters such as encapsulation temperature, time, and force must be taken into account in the FOF encapsulation process. The optical image and cross-section of the finished CIF encapsulation are shown in Figures 1.20 and 1.21, respectively.

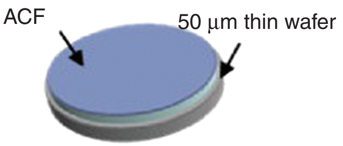
1.3 Encapsulating Technology of Several Important Flexible Electronic Devices

1.3.1 Organic Light-Emitting Diode

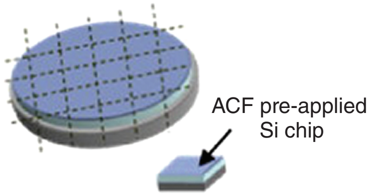
Organic light-emitting diode (OLED) is favored by the market for its advantages of surface light source, cold light, energy savings, fast response, flexibility, ultra-thinness, and low cost, etc. OLED technology is also known as the third-generation display and lighting technology. At present, global manufacturers continue to invest in technology research and development. OLED flat panel display technology is tending toward mass production technology and is increasingly mature with market demand for high-speed growth stage, but because of its poor stability, water, oxygen, and heat are extremely sensitive, and encapsulating technology is particularly critical. For flexible OLED devices, rigorous encapsulating to achieve longer life and improved stability is a must for their mass production (Figure 1.22) [16].

The key core material of flexible OLED devices is an ultrathin organic electroluminescent layer, which is extremely sensitive to water, oxygen, and heat and is responsible for its poor stability [17]. Oxygen quenches the trilinear excitons, which directly leads to a significant decrease in the luminescence quantum efficiency. It also oxidizes the organic materials of the hole transport and light-emitting layers, leading to the opening of unsaturated double bonds and a decrease in the device's luminescence efficiency and electron–hole transport capacity. Water vapor tends to make the organic semiconductor in the light-emitting layer through hydrolysis reactions. The metals used in the electrodes are very reactive and are susceptible to both

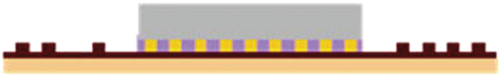
Figure 1.19 CIF encapsulating process steps. Source: Adapted from Kim et al. [14].



(1) ACF lamination on a 50 μμ thin wafer



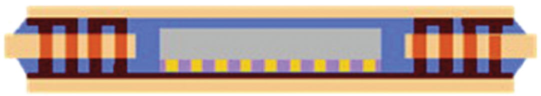
(2) ACF pre-applied wafer dicing



(3) COF assembly using ACF pre-applied chip

(4) 2nd PI alignment using ACF

(5) 3rd PI alignment using ACF



(6) CIF packages by FOF bonding

oxidation and hydrolysis by reaction with the water vapor that penetrates [18]. Due to the special characteristics of the substrate material, the water and oxygen barrier ability of flexible devices is worse than that of rigid materials, and the requirements for encapsulating are higher. Strict encapsulation of flexible OLED devices is necessary to extend device life and improve device stability, which is the key to mass production of flexible OLED devices.

OLED devices have extremely demanding requirements for encapsulating, and practical OLED devices usually require a water vapor transmission rate (WVTR) of

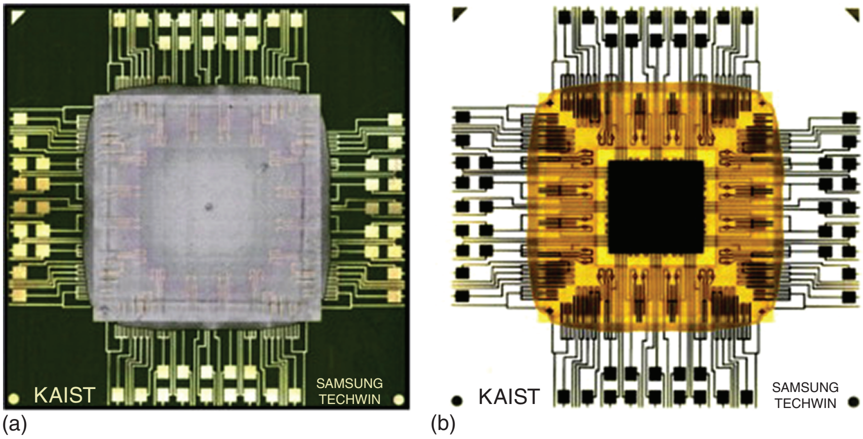


Figure 1.20 Optical image of CIF. Source: Suk et al. [15]; © 2015, Reproduced with permission from Elsevier.

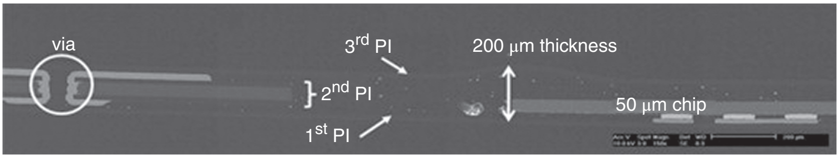


Figure 1.21 Cross-sectional view of the CIF encapsulation. Source: Reprinted with permission from Ref. [15]; © 2015, Institute of Electrical and Electronics Engineers.

less than 10^{-6} g/m^2/day and an oxygen vapor transmission rate (OVTR) of less than 10^{-5} cm^3/m^2/day [19, 20].

Currently, there are two methods for encapsulating flexible OLED devices. One method is in-line encapsulation, where the metal electrode surface of flexible OLED devices is directly coated with an alternating inorganic–organic barrier layer [21], as shown in Figure 1.23. This encapsulation method is widely used and offers the advantage of avoiding the process of breaking the vacuum seal of the OLED device, preventing the metal electrode from coming into contact with water, oxygen, dust, and other impurities, thus ensuring the long-term performance requirements of the OLED device. However, in-line encapsulation is a more complex process overall, making it challenging to achieve roll-to-roll production. The in-line processing temperature ($\geq$90 °C) during the preparation of the barrier layer can also cause damage to the OLED device, affecting its lifespan. Currently, most domestic and foreign companies employ in-line encapsulation technology.

Another method is embossed encapsulation, where the metal electrode surface of OLED devices is laminated with a high barrier film through an adhesive/film layer, as shown in Figure 1.24. The embossed encapsulation process is relatively simple, allowing for separate optimization of the OLED device and the high barrier layer preparation process. However, during encapsulation, the OLED device may be exposed to water, oxygen, and dust, and the encapsulation material may also be

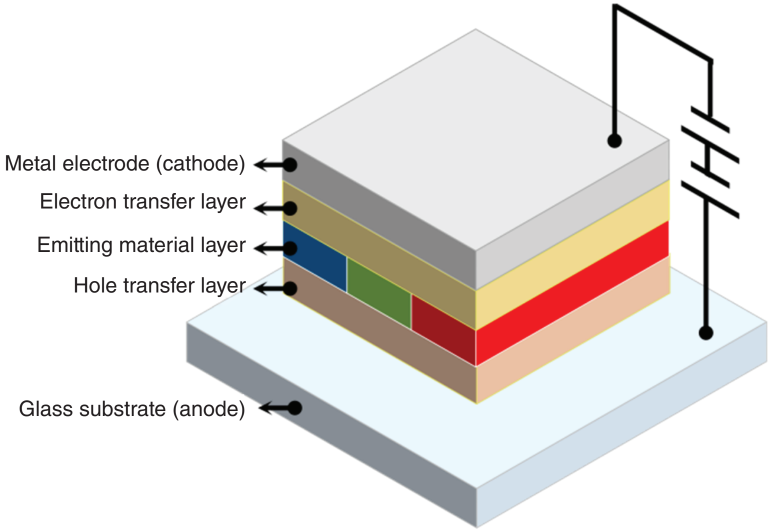


Figure 1.22 OLED light-emitting element structure diagram. Source: Reproduced with permission from http://bushu.swdkcc.com/home/result/info/id/444/catId/56.html.

Figure 1.23 In-line encapsulating structure of flexible OLED devices. Source: Adapted from Park et al. [21].

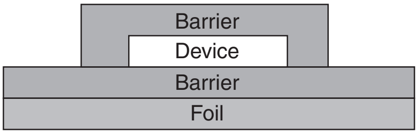
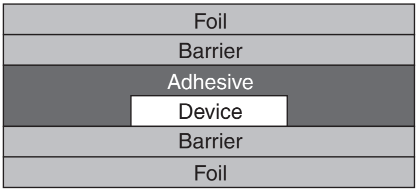


Figure 1.24 Structure of embossed encapsulation for flexible OLED devices. Source: Adapted from Park et al. [21].



destructive to the metal electrode. Additionally, the use of adhesive films that are not highly resistant can result in side leakage issues, allowing water and oxygen to penetrate the device through the adhesive layer and cause damage. Furthermore, under-reacted adhesives can react with OLED devices, impacting their lifespan.

Representative in-line encapsulation technologies include:

Barix encapsulation technology was first developed in Vitex System, United States of America, which is an inorganic–organic overlapping multilayer encapsulation structure [22, 23]. In the process of preparing large-size flexible OLED devices, some unavoidable small raised particles have appeared on the surface of the film layer before cathode plating [24]. Because the cathode metal layer is very thin, these small raised particles are enough to pierce the cathode, causing pinholes in the cathode metal layer, which eventually lead to hydroxide entering the device along the pinholes and causing damage to the device. The Barix encapsulation is coated with an

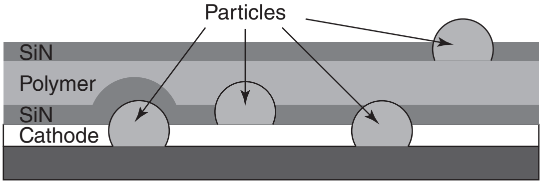


Figure 1.25 Schematic diagram of cross section of multilayer structure. Source: Reproduced with permission from Brand et al. [26]; © 2014, Elsevier.

organic layer on top of the inorganic layer, which not only fills the pinholes in the inorganic layer but also improves the bending resistance of the device [25]. With this inorganic–organic overlapping multilayer encapsulation structure, the water permeability can reach 10^{-4}–10^{-6} g/m^2/day and the oxygen permeability can reach 0.005 cc/cm^2/day.

The Dutch Holst [26] adopted the Barix encapsulation method, and the device structure is shown in Figure 1.25. Although the SiN film can cover the pinholes of the metal layer, the SiN film itself will form new pinholes. Coating an organic polymer layer on the SiN to flatten the interface can effectively fill the defects of the SiN layer and extend the path of water and oxygen into the OLED device, and the organic polymer can also effectively improve the bending resistance of the device. Then a layer of SiN film is plated to reduce the impact of pinholes on the device by increasing the channel length, thus achieving the purpose of improving the barrier properties of the device. As shown in Figure 1.26, the device encapsulated with the SiN/organic polymer/SiN structure can reduce the number of black spots by three orders of magnitude at the same time compared to one layer of SiN alone, significantly improving the barrier performance and further enhancing the device's resistance to water and oxygen. This process can be produced by roll-to-roll and strip-seam coating processes, providing more options for the industrialization of large-size OLED device encapsulation.

Samsung Display uses an inorganic/organic/inorganic Barix structure, followed by a layer of adhesive resin, and finally a coated hybrid encapsulation. This five-layer encapsulation structure also makes the encapsulation effect much better.

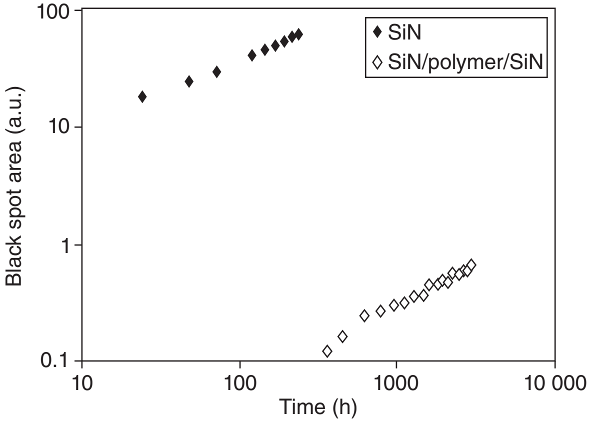


Figure 1.26 Relationship between the number of black spots and time. Source: Reproduced with permission from Brand et al. [26]; © 2014, Elsevier.

Atomic layer deposition (ALD) is considered an extension of chemical vapor deposition (CVD) technology, which is a controlled chemical reaction [27, 28]. Unlike CVD, the ALD technique breaks down the chemical reaction into two steps, allowing the parent material to separate after a certain level of reaction with a sudden charge of a large amount of inert gas, which removes the excess parent material from the chamber and prevents the process from proceeding further. Most ALD techniques are binary reactions, and the above method enables controlled and quantitative deposition of both reactants, allowing the preparation of smooth, continuous, and defect-free films. Lee [29] proposed a hybrid barrier layer in which a layer of graphene was first deposited by chemical vapor deposition and then a layer of Al_2O_3 was deposited by ALD. Compared with the Al_2O_3 layer alone, the water resistance and bending resistance of the hybrid barrier layer were superior. Lee's group pioneered the use of electrode materials and inorganic materials together as a barrier layer, providing a broader idea for OLED device encapsulation. The group has pioneered the use of electrode materials and inorganic materials as a barrier layer, providing a broader idea for OLED device encapsulation. In the literature [30], it is described that the water permeability of OLED devices was reduced to 0.058 $g/m^2/day$ by using ALD to deposit 20 nm Al_2O_3 followed by 200 nm SiN_x as the barrier layer, and the lifetime of OLED devices reached 260 hours. In the literature [31], the water permeability of OLED devices could be as low as 4.75×10^{-5} $g/m^2/day$ by using ALD to deposit Al_2O_3 and ZrO_2 as the barrier layers, and the OLED device lifetime could be extended to 10,000 hours.

Vacuum thermal deposition is one of the traditional vacuum coating techniques that requires equipment to reach at least 10^{-3} Pa. Wei Bin [32] proposed the use of MgF_2 and ZnS films grown by vacuum thermal deposition as a hybrid barrier layer, and the device's water barrier capability was greatly enhanced. The yellow OLED devices encapsulated with three pairs of MgF_2/ZnS had a lifetime of more than 500 hours at 2000 cd/m^2 initial luminance with a 56% luminance drop without UV resin sealing. With UV resin sealing, the device's half-life could reach 245 hours. Using MgF_2/ZnS as the passivation layer with good light transmission, this encapsulation method is simple to prepare and inexpensive for the encapsulation of OLED devices with top light-emitting structures. In general, the in-line encapsulation process is developing toward simplicity, controllability, and low cost.

The off-line encapsulating technology is a high-barrier film laminated to the metal electrode surface of flexible OLED devices using encapsulant/film, which is overall less difficult to prepare than the in-line process. The advantage of off-line encapsulating technology is that the performance of the encapsulant/film and high-barrier film can be optimized separately, but in the process of encapsulating flexible OLED devices may be exposed to water and oxygen or dust, which may cause damage to the flexible devices and is not conducive to achieving the goal of high efficiency and long life.

The first-generation flexible barrier film materials used for flexible electronic encapsulating are mainly organic films, such as polyethylene (PE), PET, and polyvinylidene chloride (PVDC). The structural properties of these materials themselves determine their limited water barrier capacity. The second-generation flexible barrier materials uses aluminum foil and aluminized film as a barrier layer because of its excellent barrier performance and simple preparation process, but the aluminum foil needs to have a certain thickness to achieve the water barrier requirements, and the cost of barrier materials rises. The aluminum foil material is brittle and easy to crack at the folds, which affects its barrier properties. In addition, aluminum foil and aluminized films are opaque, which limits their applications [33]. The development of third-generation high-barrier films started in the mid-1980s when Mitsubishi Plastics in Japan prepared barrier films by vaporizing inorganic silica onto polyvinyl alcohol, PET, polyamide, and other substrates. In 2001, with the help of a 100 kW high-power electron gun developed in Germany, a technological breakthrough was achieved in the silicon oxide barrier layer, which led to the rapid development of oxide barrier film applications. From 2007 onward, high-barrier film research began to be applied to solar cell encapsulating, OLED, and quantum dot display industries.

The barrier film layer has undergone the evolution of single-layer, double-layer, and multilayer structures. Single-layer barrier film has a simple structure, mature technology, and high light transmission rate, but poor barrier properties; double-layer barrier film has simple technology, high light transmission rate, but the barrier properties still cannot meet the requirements of the encapsulating OLED index; multilayer barrier film structure and process is complex, the polymer layer and organic layer overlapping structure makes its barrier properties high, generally on the surface of the flexible substrate PET, PEN or PI first flattening treatment, i.e. coating a layer of organic flattening material, and then making silicon nitride, silicon oxide, or alumina inorganic barrier layer by PECVD or ALD process; followed by cycling the organic flattening layer/inorganic barrier layer, which can be compared to the water and oxygen barrier performance of glass and can meet the index requirements of OLED encapsulating. Cho et al. [34] deposited AlN_x/UVR/AlN_x on the PEN substrate as a barrier layer and used it as a flexible substrate for OLED encapsulating. Aging tests were performed at 85 °C and 85% RH, and it was found that the brightness of the encapsulated OLED devices decreased by only 9% after 750 hours compared with those encapsulated on standard glass substrates.

The encapsulant used for flexible electronic encapsulating generally refers to liquid encapsulation adhesive, and the encapsulation film is mainly encapsulation adhesive film. Liquid encapsulation adhesives are usually divided into solvent-based and solvent-free types. The solvent is easy to damage the metal electrode, the light-emitting layer and the carrier transport material in the flexible OLED device, so the packaging adhesive is solvent-free, UV-curable, neutral and cannot corrodes the metal electrode. Encapsulation adhesive film is divided into hot-melt adhesive film and room-temperature pressure-sensitive adhesive film. To use hot-melt adhesive film for encapsulation, the adhesive film needs to be heated to 140 °C or more, so that it can be heated to a molten state to bond the battery to the high-barrier film. However, the 140 °C process temperature will cause thermal deformation of the substrate and will also damage the OLED light-emitting layer film and other functional layer materials, resulting in significant degradation of the device's optoelectronic performance. The pressure-sensitive adhesive film has a protective film on both sides and can be bonded to the barrier film and the OLED device after removing the protective film. Compared with hot-melt adhesive film, the process temperature of pressure-sensitive adhesive film is very low, and the lamination can be done at room temperature to avoid deformation and decomposition of the substrate and functional layers by heat. To prevent water vapor leakage from the edges of OLED devices in hot and humid environments, high-barrier pressure-sensitive films can be used. Therefore, the use of pressure-sensitive adhesive film requires that the encapsulation film can be laminated at low or normal temperatures, the lamination process is free of air bubbles, and the film should have barrier properties.

1.3.2 Flexible Solar Cell Encapsulating

Flexible solar cells will be one of the most important mainstays of future PV applications due to their lightweight, bendability, and low installation cost. It has a wide application space in building integrated photovoltaic (BIPV), building attached photovoltaic (BAPV), mobile objects, portable devices, and aerospace. Flexible solar cells generally have the following types: flexible inorganic solar cells, flexible organic solar cells, flexible calcium titanite solar cells, and flexible dye-sensitized solar cells. Flexible inorganic solar cells include flexible amorphous silicon solar cells and flexible copper indium gallium selenide solar cells. This book mainly introduces the encapsulation of flexible amorphous silicon solar cells and flexible chalcogenide solar cells.

1.3.3 Flexible Amorphous Silicon Solar Cells

In the early days of solar cells, the main raw material was crystalline silicon, but the cost was high, so it was only used in space exploration. Due to the high cost of crystalline silicon, crystalline silicon solar cells consume more silicon materials, and due to the development of technology, finally in 1974 Carlson developed the earliest amorphous silicon solar cells in the laboratory. An amorphous silicon cell (a-Si) is a solar cell made of amorphous silicon film deposited on a conductive glass (non-flexible) or stainless steel and special plastic substrate.

In 1977, Carlson and his team successfully developed an amorphous silicon Schottky barrier cell with an energy conversion efficiency of 5.5%. Following this, in 1978, Osaka University in Japan achieved a conversion efficiency of 4.5% with the development of an amorphous silicon PIN cell. In the fall of 1981, Osaka University further improved the technology by preparing an a-SiC:H/a-Si:H PIN heterojunction solar cell, which surpassed an energy conversion efficiency of 8%. This cell utilized a P-type broadband a-SiC:H as the window material. By 1982, the efficiency of this a-SiC:H/a-Si:H PIN heterojunction solar cell exceeded 10%. Subsequently, in 1987, the conversion efficiency of amorphous silicon cells reached 12%. Sanyo in Japan achieved a milestone in 1990 by developing an amorphous silicon cell with a conversion efficiency of 15.8%. In 1994, amorphous silicon cells with a back surface field structure, prepared using the PECVD method, were introduced in Japan with a conversion efficiency of 18.9% [35].

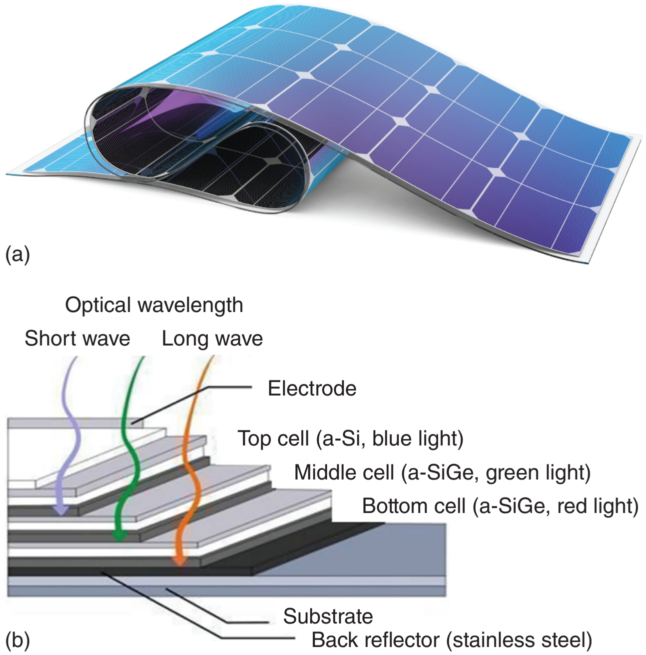


Figure 1.27 Flexible amorphous silicon solar cell (a) Source: iaremenko/Adobe Stock and its general structure (b). Source: Reprinted with permission from Yin and Jiang. [37]; © 2012, Guangzhou Chemical Industry.

Flexible amorphous silicon solar cells are mainly made of stainless steel and special plastics as substrates [36]. As shown in Figure 1.27, flexible amorphous silicon solar cells are mostly designed with sandwich structure, divided into three light-absorbing layers: the top layer using amorphous silicon material with an optical energy gap of 1.8 eV, which facilitates the absorption of blue light; the middle layer using amorphous silicon and 10–15% germanium alloy material with an optical energy gap of 1.6 eV, which facilitates the absorption of green light; and the bottom layer using amorphous silicon and 40–50% germanium alloy material with an optical energy gap of 1.4 eV, which facilitates the absorption of green light. The optical energy gap is 1.4 eV, which can absorb red light and far-red light and absorb different solar spectrum bands in different layers. The high PV conversion rate makes up for the low conversion rate of amorphous silicon compared to polycrystalline silicon and monocrystalline silicon panels in sunny weather. The light that is not absorbed when the light source enters is reflected back by the back reflection layer (Ag/ZnO) of the substrate and is absorbed on the way out, thus converting and outputting more electricity than normal solar products. The cell is covered with a protective layer of ethylene vinyl acetate (EVA) polymer and encapsulated with a transparent, highly inert fluoroplastic film. The surface of the film is patterned to absorb light from all angles, effectively preventing sunlight loss. The flexible amorphous silicon solar cell can work normally in an environment from −40 to 80 °C, and even if a part is pierced by a bullet, the rest of the cell can still generate electricity without being affected by it [37].

1.3.4 Flexible Perovskite Solar Cells

Perovskite solar cells, which are solar cells using chalcogenide-type organometallic halide semiconductors as light-absorbing materials, belong to the third-generation solar cells. Among them, the most commonly used light-absorbing layer is a hybrid organic–inorganic lead or tin halide-type material, such as methylammonium lead halide, which is cheap and easy to produce.

The term “chalcogenide solar cell” is derived from the chalcogenide crystal structure of the light-absorbing layer material ABX_3. Chalcogenide crystals exhibit an ABX_3 structure, typically cubic or octahedral. As illustrated in Figure 1.28, in a chalcogenide crystal, B ions occupy the central position of the cubic cell and are surrounded by six X ions, forming a coordination cuboctahedron with a coordination number of 6. A ions are located at the top corner of the cubic cell and are surrounded by 12 X ions, forming a coordination octahedron with a coordination number of 12. A ions and X ions have similar radii, creating a dense cubic stack when combined [38].

Chalcogenide solar cells have rapidly gained attention as a research hotspot for new solar cell technologies, owing to their high light absorption properties and excellent carrier separation and transport characteristics. In just a decade, their efficiency has increased from 3.8% in 2009 to the current level of 25.8%. These solar cells utilize common and inexpensive materials with high abundance and high tolerance for raw material purity and defects.

One of the significant advantages of chalcogenide solar cells is that they do not require the vacuum and high-temperature processes associated with traditional crystalline silicon cells. Instead, they can be manufactured using solution-based methods. This feature makes them highly promising for mass production and the application of low-cost, high-efficiency flexible solar cells. They have the potential to rapidly supplement the market and address applications that cannot be covered by traditional crystalline silicon solar cells.

However, it should be noted that the materials used in each functional layer of chalcogenide solar cells are sensitive to water vapor, oxygen, ultraviolet light, and pressure in the air. These environmental factors can significantly reduce the service life of the cells. Encapsulation technology offers an effective solution to isolate the working components from the external environment, preventing pollution and corrosion from various impurities. It is a method employed to improve the service life of precision electronic components (Figure 1.29).

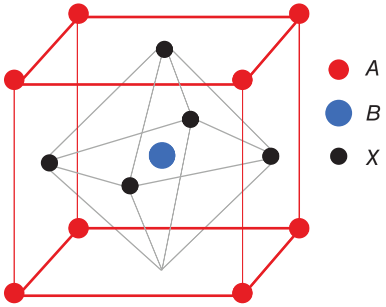


Figure 1.28 Crystal structure of chalcogenide. Source: Reproduced with permission from Rongrong et al. [38]; © 2019, Chinese Physical Society.

Figure 1.29 Calcium titanite solar cell device. Source: Reproduced with permission from Guo et al. [39]; © 2018, Royal Society of Chemistry.

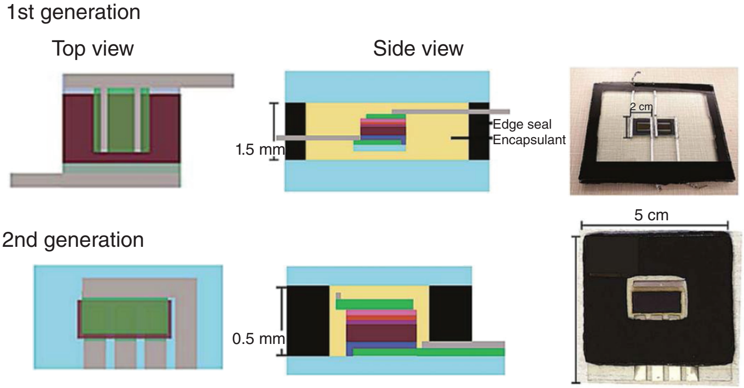


Figure 1.30 Top view, side view, and physical view of the first-generation encapsulating technology and the second-generation encapsulating technology. Source: Reproduced with permission from Juarez-Perez and Haro [40]; © 2016, Elsevier.

Currently, there are two common cell encapsulation techniques for chalcogenide solar cells [40], as illustrated in Figure 1.30.

The first-generation encapsulation technique involves the use of evaporative metal injectors and welded metal strips to conduct current from the cell to the outside. The edges of the strips are sealed, with the device positioned in the center of the closed cavity.

The second-generation encapsulation technique utilizes transparent indium tin oxide (ITO) electrodes to separate the chalcogenide from the metal electrodes. This ensures a lateral gap between the electrodes and the calcium titanite solar cells, with the ITO electrodes positioned directly on one side of the encapsulation. This approach allows for better sealing of the entire device. Both techniques are known as “edge sealing“ encapsulation techniques.

Polymer materials are commonly used for encapsulation due to their excellent insulation, thermoplasticity, and mechanical strength. The dense encapsulation layer effectively isolates water and oxygen from the air, enabling cost-effective

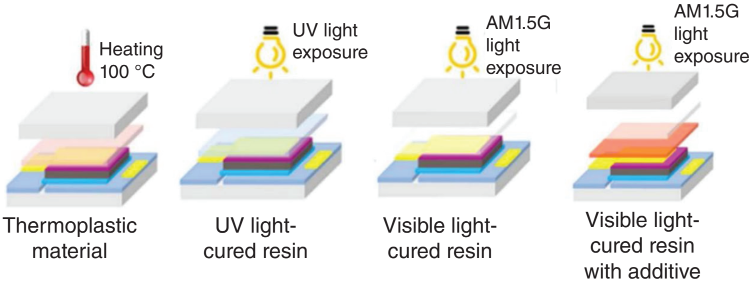


Figure 1.31 Several operating conditions for the preparation of polymeric encapsulation layers. Source: Reproduced with permission from Shi et al. [41]; © 2020, American Association for the Advancement of Science.

large-area encapsulation. Common materials used for encapsulation include polyisobutylene, PE, thermoplastic polyurethane, EVA, and cyclized perfluoropolymers. Various preparation methods for encapsulation layers are available, such as thermal curing, UV curing, and visible light curing, as shown in Figure 1.31 [41].

Recently, Dr. Lei Shi from the Australian Centre for Advanced Photovoltaics and Prof. Anita Ho-Baillie from the University of Sydney [40] investigated the encapsulated chalcogenide solar cell system using gas chromatography–mass spectrometry (GC–MS) and found that the polymer-glass "blanket-cover" encapsulation technique can form an absolutely hermetic system and greatly improve the operating life of chalcogenide solar cells. The polymer-glass encapsulation technique allows the efficiency of chalcogenide solar cells to remain above 95% after 4000 hours of operation under IEC 61215:2016 standard test conditions. The (GC–MS) technique reveals that the absolute hermetic encapsulation effectively prevents the diffusion of various decomposition gas molecules and maintains the equilibrium of the system, and the residual vapor can promote the regeneration of chalcogenide at night, which increases the cycle life of the cell. The "blanket" encapsulation technique, in which the entire device is encapsulated with a polymer so that the device is in close contact with the polymer and there are no cavities inside. Interestingly, the authors added a layer of Cover Glass to the encapsulated cell, which effectively prevents the escape of CH_3Br and NH_3 from the decomposition of chalcogenide, an effect that cannot be achieved with polymer encapsulation alone. The polymer acts not only as a water vapor barrier but also as a strong binder between the chalcogenide solar cell and the cover glass, further enhancing the hermetic performance of the system (Figure 1.32).

For the encapsulation of calcium titanite solar cells, the researchers employed polyisobutylene and polyolefin. They subjected the cells to hygrothermal and humidity freeze tests within a temperature range of −40 to 80 °C. Remarkably, the cells encapsulated with this technique showed no degradation after 1800 hours of operation, surpassing the 1000-hour requirement stipulated in the test standard. The short-circuit current density and open-circuit voltage of the cells remained stable even after the test, a characteristic commonly observed in calcium titanite solar cells containing methylamine ions.

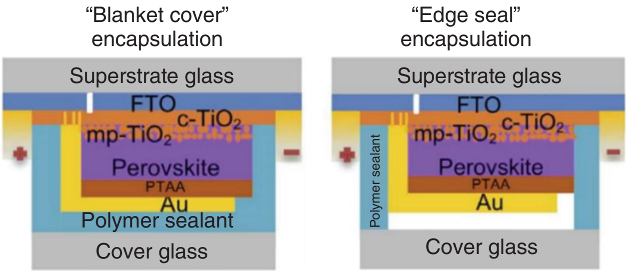


Figure 1.32 Cross-sectional diagram of "blanket cover" and "edge seal" encapsulations. Source: Reproduced with permission from Juarez-Perez and Haro [40]; © 2020, American Association for the Advancement of Science.

This study demonstrates that the use of simple and cost-effective polymer-glass combination encapsulation techniques, such as polyisobutylene or polyolefin-based encapsulation, can confer exceptional durability to organic–inorganic hybrid chalcogenide solar cells. Notably, these cells exhibited remarkable resilience against severe humidity freeze tests, despite the known low thermal stability of methylammonium ions, which has typically been a challenge in achieving highly stable chalcogenide solar cells. The polymer-glass "blanket-cap" encapsulation technology ensures absolute hermeticity, creating a stable operating environment that prevents decomposition products from escaping the system and significantly extending the lifespan of chalcogenide solar cells. This work offers new insights for designing more stable chalcogenide solar cells and greatly advances the commercialization of this technology [40].

1.4 Flexible Electronic Encapsulating Materials

1.4.1 Selection Principle of Flexible Electronic Encapsulating Materials

Flexible electronic encapsulating materials are utilized to support and protect flexible electronic devices, as well as establish interconnections between devices and external circuits. They play multiple roles, including mechanical support, environmental sealing, signal transmission, heat dissipation, and shielding. These materials consist of substrates, wiring, frames, interlayer media, sealing materials, and more. Among them, flexible electronic encapsulating substrate materials primarily provide mechanical support and airtight protection and facilitate heat dissipation for flexible electronic devices and their interconnections.

The selection of flexible electronic encapsulating materials should consider the following aspects:

(1) **Thermal expansion coefficient**: Matching the thermal expansion characteristics of the substrate and flexible electronic devices
(2) **Dielectric properties (permittivity and loss)**: Ensuring fast response and minimal delay in electrical signal transmission within the circuit

(3) **Thermal conductivity**: Facilitating heat dissipation from the working circuit
(4) **Mechanical properties**: Possessing adequate strength, hardness, and toughness.

Flexible electronic encapsulating substrate materials are commonly composed of plastic encapsulating materials, typically thermosetting materials such as epoxy, caseinate, polyester, and silicone. Among these, epoxy resin is the most widely used. Plastic encapsulating materials are popular in the electronic encapsulation industry due to their low cost, maturity, and simple production processes. However, they also have notable drawbacks. Most plastic materials lack sufficient density, exhibit poor thermal conductivity, possess thermal expansion coefficients that do not match flexible electronic devices, have high dielectric loss, and tend to be brittle. Plastic encapsulating materials are susceptible to moisture absorption, which leads to expansion and the potential for device failure, particularly with epoxy materials being highly affected by moisture. This significantly impacts the reliability of encapsulation, making them unsuitable for industries with higher reliability requirements, such as military and aerospace. Through ongoing research on encapsulating materials, these issues can be effectively mitigated by adjusting the ratio of plastic encapsulating materials and optimizing processing methods. Ideally, plastic encapsulating materials should possess the following characteristics: high raw material purity, low viscosity, minimal impurities, low water absorption, good heat resistance, high thermal conductivity, matching thermal expansion coefficients, ease of processing and molding, minimal raw material waste, good flame retardant properties, and excellent environmental performance without toxicity or pollution.

1.4.2 Desirable Properties of Flexible Electronic Encapsulating Materials

To minimize the impact of environmental factors such as water, oxygen, and dust on flexible electronic devices, flexible electronic encapsulating materials must meet the performance requirements specified in national standards. General performance indicators include insulation, breakdown strength, heat resistance, mechanical strength, and WVTR.

(1) **Insulation**: Flexible electronic encapsulating materials should exhibit high insulation resistance, typically exceeding 30 MΩ under normal conditions.
(2) **Breakdown strength**: When the electric field strength exceeds a certain threshold, flexible electronic encapsulating materials may experience a breakdown, leading to a loss of insulation properties. Generally, the breakdown strength requirement for flexible electronic encapsulating materials is above 10 KV/mm.
(3) **Heat resistance**: With increasing temperature, the resistance, breakdown strength, and mechanical strength of flexible electronic encapsulating materials tend to decrease. Therefore, flexible electronic encapsulating materials should maintain stable and reliable insulation and sealing performance while operating within specified temperature ranges for extended periods.

(4) **Mechanical strength**: Depending on specific requirements, different mechanical strength indicators such as tensile strength, compressive strength, bending strength, shear strength, tear strength, and impact resistance may be specified for different flexible electronic encapsulating materials.

(5) **Water and oxygen transmission rates**: Water and oxygen transmission rates, including WVTR and oxygen transmission rate, are measured in grams per square meter per day ($g/m^2/day$) and cubic centimeters per square meter per day ($cm^3/m^2/day$), respectively. As water vapor molecules are smaller than oxygen molecules and are more difficult to block, the WVTR is used to evaluate the encapsulation's effectiveness. The WVTR indicates the weight of water vapor that passes through a unit area of material under specific time, temperature, and humidity conditions. The oxygen transmission rate, on the other hand, measures the volume of oxygen that permeates through a unit area of material within a given time under constant temperature and pressure differences. Typically, flexible electronic encapsulating devices require a WVTR below 10^{-6} $g/m^2/day$ and an oxygen transmission rate below 10^{-5} $cm^3/m^2/day$.

(6) **Other characteristics**: Certain flexible electronic encapsulating materials may exist in liquid form, such as various resins. Their properties include viscosity, fixed content, acid value, drying time, curing time, and more. Additional characteristics of flexible electronic encapsulating materials may encompass permeability, oil resistance, elongation, shrinkage, solvent resistance, arc resistance, and others.

1.5 Overview of the Development of Flexible Electronic Packaging at Home and Abroad

The development of flexible electronic packaging has seen significant progress both domestically and internationally. Currently, Japanese companies such as Sumitomo Chemical, Shin Kong Electric, Toppan, Tanaka, and Mitsui High-tec hold a substantial market share of around 25% globally. DuPont, a global leader in fluorine material development and production, is also a key player in the future competitive landscape of electronic encapsulating materials, with its market share steadily expanding. DuPont's involvement in the field has provided new development ideas for other fluorine material companies. Given the numerous advantages of fluorine materials and their experience in fluorine encapsulating technology, it is anticipated that fluorine materials will play a significant role in the field of flexible electronic encapsulation.

China represents the main application market for flexible electronic encapsulating materials, accounting for approximately 40% of the global market demand, followed by the United States with a share of around 15%. However, China currently lacks well-known enterprises focused on the development and production of functional materials in the field of flexible electronic encapsulating, unlike DuPont and Sumitomo Chemical. Although domestic fluorine chemical giants such as Juhua and San Aifu have shown interest in this area, they are still in the initial stages and cannot yet compete with international giants like DuPont. Therefore, flexible electronic encapsulating materials could be another area where foreign companies have a competitive advantage over domestic ones.

The global encapsulating industry has experienced single-digit growth, with statistics indicating that Taiwan accounts for 53% of sales, occupying half of the global encapsulating industry. Mainland China and the United States follow with shares of 21% and 15%, respectively, ranking second and third. Malaysia, South Korea, Singapore, and Japan each hold shares of 4%, 3%, 2%, and 2%, respectively. In terms of market share, domestic encapsulating companies have entered the global top tier and possess a certain level of international competitiveness.

Over the next five years, the competition pattern in the electronic encapsulating materials market is expected to be established. Leading global companies in this field include DuPont, Evonik, EPM, Mitsubishi Chemical, Sumitomo Chemical, Mitsui High-tech, Tanaka, Shin Kong Electric, Panasonic, Hitachi Chemical, Kyocera Chemical, Gore, BASF, Henkel, AMETEK Electronics, Toray, Maruwa, Lida Fine Ceramics, NCI, Chaozhou Sanhuan, Nippon Micrometallic, Toppan, Dainippon Printing, Germany Posel, and Ningbo Kangqiang, among others. Various authorities predict that the global electronics encapsulating market will experience rapid growth with a stunning CAGR from 2023 to 2028.

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