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The Application of Polyimide used in Semiconductor Industry: A Review

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Abstract: The polyimide (PI) and photosensitive polyimide (PSPI) were always regarded as protecting layer or insulation layer in semiconductor industry due to its high-temperature resistance, outstanding mechanical properties, chemical and radiation resistance, and excellent dielectric properties. The PI and PSPI had various usage methods and applications in organic light-emitting diode (OLED) display, integrated circuit (IC) and IC packaging based on its specific performance advantages. This paper introduced the usage method and application of PI film and PSPI in OLED display, IC fabrication and IC packaging. For PI film, the usage method including transfer patterning from a PR patterning layer and the laser for patterning technology, the PI was usually regarded as flexible substrate in OLED devices and insulation layer in IC packaging. For PSPI, the usage method including forming patterning based on photolithography technology, the PSPI was usually regarded as planarization layer, pixel definition layer and pixel supporting layer in OLED display, the PSPI was also regarded as protecting layer and insulation layer in IC fabrication and packaging.

Key words: Polyimide, photosensitive polyimide, usage method, protecting layer, insulation layer

1. Introduction

As known, polyimide had extensive applications in the separation membrane, aerospace industry, microelectronic and optoelectronic engineering, organic light-emitting diode (OLED) display, integrated circuit (IC) and IC packaging due to its high-temperature resistance, outstanding mechanical properties, chemical and radiation resistance, and excellent dielectric properties.[1-3] Polyimide is a polymer containing imide structure in the main chain of molecular structure. The main chain of polymide with high performance is usually made up of a main structural unit, which contains aromatic ring and heterocyclic ring.[4-6] Polyimide had the highest grade of flame retardant, good electrical insulation properties, mechanical properties, chemical stability, aging resistance, radiation resistance, with a dielectric constant of 4.0 at 103 Hz, dielectric loss is only 0.004 ~ 0.007, belonging to F to H class insulation, and these properties will not change significantly in a wide temperature range (-269℃ to 400℃). The performance of polyimide is at the top of the pyramid of polymer materials, is the best performance of thin film insulation materials.[7-10] The polyimide film,

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carbon fiber polyimide and aramid fiber polyimide have been considered as the three bottleneck key polymer materials, which restrict the development of China's high-tech industry.[11-15]

Polyimide materials (mainly in the form of polyimide film) can be used as interlayer dielectric materials for multi-layer metal interconnection structures in multi-layer wiring technology.[16-19] Multilayer wiring technology is a key technology for developing and producing ultra large scale, high-density, and high-speed integrated circuits with three-dimensional cross structure.[20-23] The use of multi-layer metal interconnection on chips can significantly reduce the connection density between devices, reduce the RC time constant and chip occupied area, and significantly improve the speed, integration degree, and reliability of IC chip.[24-26] The multi-layer metal interconnection process mainly used high-performance polyimide film as the dielectric insulation layer, copper or aluminum as the interconnection wire.[27-30] The main advantages of this technology were using the high conductivity and anti-electromigration properties of copper, adding the low dielectric constant and planarization performance of polyimide.[31-34] Polyimide has the characteristics of high insulation strength, high and low temperature resistance, low thermal expansion coefficient, radiation resistance, flame retardant self-extinguishing and high stability.[35-38] The polyimide could be classified into five kinds based on the specific performance advantages, which were polyimide film, polyimide fiber, polyimide foam, polyimide composite material and photosensitive polyimide (PSPI).[39-42] Polyimide film was the earliest commercialized, most mature, and largest market capacity product form of polyimide, with applications covering multiple industries such as flexible circuit boards, consumer electronics, high-speed rail transit, wind power generation, electrical insulation, 5G communication, flexible displays, aerospace and other industry.[43-44] Polyimide fiber was mainly used in the military market, while the civilian market is in a rapid development stage. Polyimide fiber has excellent heat resistance and mechanical properties, making it a core accessory material in important fields such as aerospace and military aircraft. It also has broad market space in environmentally friendly high-temperature filter materials, fire-resistant materials, and other fields. At present, polyimide foam was the most important application in thermal insulation and noise reduction materials for naval ships. Polyimide composite materials were composite materials that combine high temperature resistance with high-strength substrates, mainly used in industries such as aerospace, high-speed rail transit, and automobiles. PSPI mainly had two major applications of photoresist and electronic packaging.[45-46] Compared to painless photoresist, PSPI does not require the application of light blocking agents and can respond to visible processing procedures. PSPI is also an important electronic packaging adhesive for packaging block integrated circuits and multi-chip packaging components.[47-48]

In this paper, the author introduced the application of polyimide used in semiconductor industry. An overview of polyimide used in semiconductor industry was showed in Figure 1. The polyimide was usually classified into the non-photoresist polyimide (PI) and PSPI. For the application of PI, it was widely used as flexible substrate in the array structure during the preparation of OLED device. The PI was also introduced as a passivation layer during the IC packaging process. For the application of PSPI, it was widely used in the process of OLED device, IC fabrication and IC packaging. The PSPI was usually introduced as a planarization layer (PLN) and pixel definition layer (PDL) in the array structure of OLED display. The PSPI was also introduced as passivation layer during the process of IC fabrication and IC packaging.

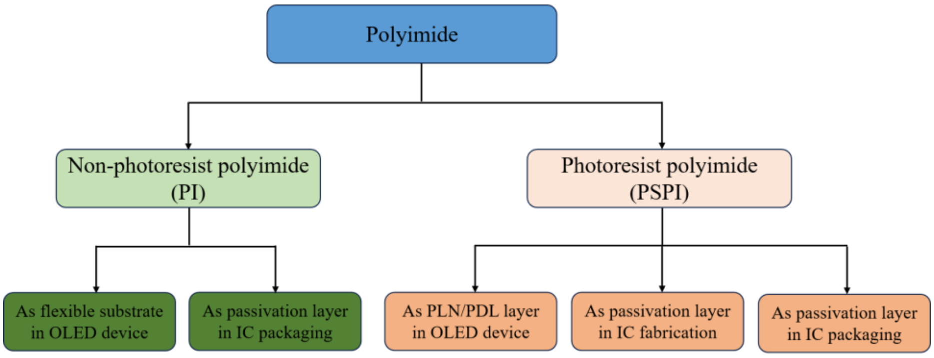

Figure 1. An overview of polyimide used in semiconductor industry.

2. The introduction of polyimide

According to its chemical structure, applications and the type of molecular bonds within the chain, PI has mainly been divided into three categories, which included thermosetting polyimide (PI-s), thermoplastic polyimide (TPI) and modified polyimide. Based on its high-temperature resistance, outstanding mechanical properties, excellent dielectric properties, chemical and radiation resistance, PI has been widely used in many high-tech fields such as aerospace, aviation, space, automotive, electronics and electrical appliances.[49]

PI-s is high-performance polymer with cross-linked molecular structures formed through irreversible curing, which also contain imide rings (-CO-N-CO-) in their backbone to enable its extreme thermal and chemical stability. The temperature resistance of PI-s made it possible for operating continuously at 300-426° C (even a short-term up to 550° C). The mechanical strength of PI-s usually had a tensile strength up to 414MPa and a compressive strength about 190MPa. For the electrical properties of PI-s, the dielectric constant and volume resistivity were usually about 2.4 and above 1015Ω • cm. The characteristic of cross-linking limited the reprocessing of PI-s, which also enhanced its stability. For the classification & material design, the subtypes of PI-s was usually including bismaleimide (BMI) type, phenylethynyl-terminated (PETI) type, benzocyclobutene (BCB) based type and soluble PI-s.[50-51]The BMI type PI-s was usually used as aerospace composites with high glass transition temperature (Tg >250° C). The PETI type of PI-s had superior toughness and can be processed with via resin transfer molding technology. The BCB based type of PI-s was widely used as ultra-low dielectric loss material for 5G/mm wave ICs. The soluble PI-s, the fully imidized powders could enable for solvent-based coatings without curing voids. For the application and market dynamics, PI-s was widely used in aerospace, electronics and energy industry. For example, PI-s was usually used as engine parts and ablative shields in aerospace and used in the fabrication of flexible PCB substrates and IC encapsulation in electronics. Meanwhile, PI-s was was also used as gas separation membranes (for H_2/N_2 selectivity) and fuel cell components in energy industry.

TPI refers to a linear polyimide with good melting properties that can be processed and formed by using conventional plastic molding processes such as compression molding, extrusion and injection molding. Comparing with PI-s, TPI resin has many advantages such as good toughness, large damage tolerance and repairability, which can also be used as the matrix resin for continuous carbon fiber reinforced resin based composites. The prepared prepreg by TP-s does not require low-temperature storage, which can also significant reduce the manufacturing cost of composite materials and improve their impact toughness. Based on the difference of organic dianhydride and organic diamine monomers durint the preparation, the TPI can be divided into six types, which included bisphenol A-type TPI, maleic anhydride type TPI, ether anhydride type TPI, ketone anhydride type TPI, phthalic anhydride type TPI and fluorine anhydride type TPI.

Modified polyimide is engineered to overcome inherent limitations (such as high dielectric constant and poor solubility) while retaining its core advantages. The key development of modified polyimide is its application in electronics & 5G field, aerospace & energy field, emerging frontiers field. For example, the ultra-low dielectric constants (<2.5) of modified polyimide is critical for high-speed printed circuit board (PCBs) and mmWave antennas.52 The PI modified by polyoxyalkyleneamine could be used for bonding ICs at low temperature (⩽180° C) based on an industry standard of 250°C in flexible circuits field.[53] The PI foams with thermal conductivity of 0.03W/m • K) was used to replace ceramics as lightweight insulation material in cryogenic tanks in the field of aerospace & energy. The classification of modification strategies mainly included structural modification, composite modification and morphological modification. The common method of structural modification was altering the chemistry of PI backbone with copolymerization or monomer designing. The fillers (nanoscale to micron) was usually incorporated in PI matrices for composite modification. The dielectric constants of Silica-filled PI can achieve a dielectric constants of 2.2-2.8, while the dielectric constants of pure PI was 3.2. The typical strategy for morphological modification is controlling the engineering porosity or cross-linking density.

2.1 The introduction of PI

The passivation layer and buffer inner coating polyimide of microelectronic devices are widely used in the microelectronics industry. PI coating can effectively block electron migration and prevent corrosion. The components protected by the PI layer have a very low leakage current, which can increase the mechanical performance of the components, prevent chemical corrosion, and effectively enhance the moisture resistance of the components. PI layer has a buffering function, which can effectively reduce circuit cracking and circuit breaking caused by thermal stress, and reduce damage to components during subsequent processing, packaging, and post-processing. Although polyimide coatings can effectively prevent the cracking of plastic encapsulated devices, the effect is closely related to the performance of the polyimide material used. Generally, polyimide with good adhesion performance, glass transition temperature higher than welding temperature, and low water absorption is an ideal inner coating material to prevent device cracking. For example, during the fabrication of OLED display, polyimide was used to form PI layer as flexible substrate based on its flexibility, its thermal stability can also expend the lifetime of OLED device.[54] Based on the flexibility and thermal stability of polyimide when used as flexible substrates for OLED displays, the structured analysis of their impacts mainly included the enabling robust bendability of flexibility and the ensuring process compatibility of thermal stability. For the mechanical resilience of using as flexibility substrates in OLED display, PI films exhibited high tensile strength (typically 180-530MPa) and elastic recovery with allowing OLED substrates to withstand repeated bending (>100000 cycles in 2-5 mm radius) without any cracking.[55] By Engraving patterning or filler integration on PI surface could enhance the stress dissipation and reduce delamination risks in multi-layer OLED structures. For the ensuring process compatibility of thermal stability, PI substrates could maintain structural integrity at high temperature (>350° C) is enabling critical for OLED fabrication steps of OLED display based on other process that ITO electrode was sputtered at 300℃, the TFT layer was deposited at 280~350℃ by plasma-enhanced chemical vapor deposition (PECVD) technology and the organic light-emitting layer was annealed at 250℃. PI with a high glass transition temperature (Tg >400℃) could also prevent the softening failure during packaging lamination in OLED display.

In currently, the leading companies in PI materials mainly included DuPont from the United States, Ube Industries from Japan, Kaneka Chemicals, Mitsui Chemicals and SKC KOLON from South Korea. Table 1 showed the comparison of the key performance parameters of the main products from these companies. For example, the main products of PI from Dupont was the Kapton series (such as H type, HN type and VN type), which showed excellent mechanical properties with high tensile strength. For the HN type of PI, the dielectric constants of approximately 3.4 and the dielectric strength ranging from 100 to 300kV/mm. This type of PI can also be used in a widely temperature range from 200℃ to 400℃ for a long term based on its good thermal properties with a thermal decomposition temperature above 500℃. The tensile strength, dielectric constant and CTE for the HN type PI were 230~250MPa, 3.4 and 20ppm/℃, respectively. While, the main products of PI from Ube Industries was the Upilex series (such as S-type, RN-type and VT-type). The S-type of PI thin films had showed a good resistance to chemicals based on its excellent chemical stability and can be used in a temperature above 260℃ for a long term. This series of PI films also showed excellent mechanical properties with tensile strength, dielectric constant and CTE of 530MPa, 3.1 and 12ppm/℃. For the PI product of Rayitek Hi-Tech, it showed excellent mechanical properties and thermal properties with tensile strength about 180~220MPa, dielectric constant of 3.5 and CTE about 20~50ppm/℃. The long-term temperature resistance for using is ranging from 220℃ to 280℃. For the products from Times New Material Technology in China, its typical PI product had tensile strength, dielectric constant and CTE of 200MPa, 3.6 and 235ppm/℃, and the long-term temperature resistance for using is about 220℃. Finally, the main products of PI from Mitsui Chemicals had an good heat resistance with a Tg of 260℃ and the light transmittance is also greater than 88%.

Table 1. The key performance parameters of main products from leading companies for PI.

Enterprise/Brand	Long-term temperature resistance(℃)	Tensile strength (MPa)	Dielectric constant (1MHz)	CTE (ppm/℃)
DuPont(Kapton HN)	200~400	230~250	3.4	20
Ube Industries (Upilex-S)	＞260	530	3.1	12
Rayitek Hi-Tech	200~280	180~220	3.5	20~50
Times New Material Technology	220	200	3.6	35

Organic Light-Emitting Diode (OLED) Displays - Discuss which type of PI is more popular and its reasons (such as flexibility, thermal stability). Integrated Circuit (IC) Manufacturing - Explain the role of PI (such as serving as a dielectric layer, passivation film) and specify suitable PI variants. Integrated Circuit Packaging - Emphasize the functions of PI (such as stress buffering, adhesive) and the optimal PI type for this application. These supplementary contents will enhance the technical depth of the manuscript and provide readers with a clearer understanding of the versatility of PI in the field of microelectronics.

2.1.1 The synthetic of PI

PI layer was generally made of a PAA resin solution, which made up of PMDA and ODA as the main monomers and form as polymerize in polar solvent, such as DMAc or DMF. The PI layer was obtained with the PAA resin solution had the process of salivating into gel film, directional stretching, imide and post-treatment processes. In addition to resin synthesis, other processes were all carried out in a clean workshop within 10000ppm. Figure 2 showed the synthetic route architecture of the PI. The architecture of ODA and PMDA were showed as Figure 2a, the synthetic of PI was be classified into two kinds, which were PI one step method and two step method, as showed in Figure 2b and Figure 2c. For the one step method of PI's synthetic, the ODA and PMDA were dissolved in a polar solvent with the same molar mass, then the structure of polyimide was formed with a heat process of the two reactants in polar solvent. Finally, the PI film obtained with a curving process of the PAA resin solution. For the two steps method of PI's synthetic, the ODA and PMDA were dissolved in a polar solvent with the same molar mass at a room temperature. Then the PI film was formed after the imidization reaction.

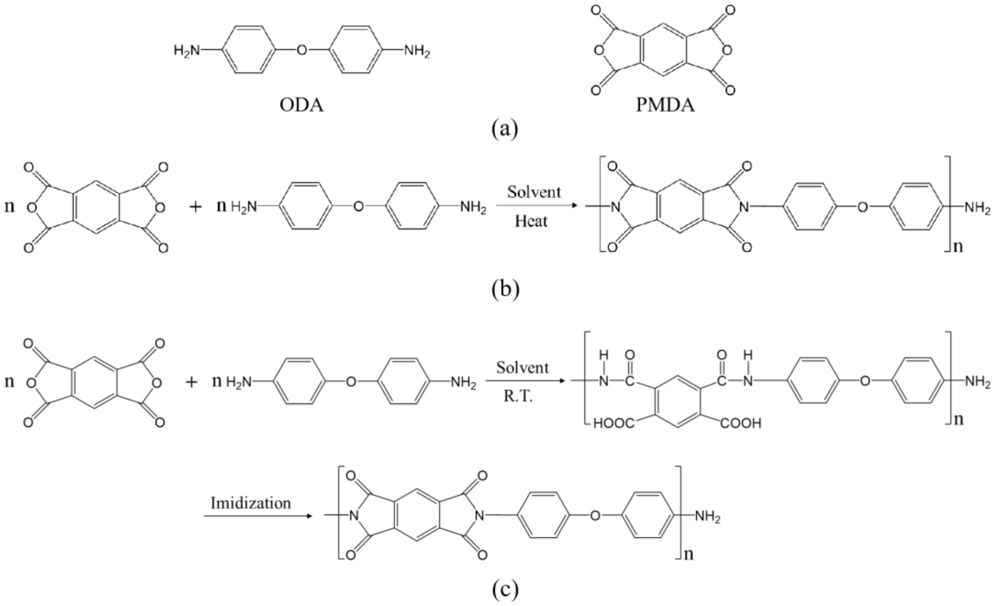

Figure 2. The synthetic route architecture of PI: (a) the architecture of ODA and PMDA, (b) the one-step synthesis method of PI, (c) two-step synthesis method of PI.

There are many countries have developed PI materials, such as American, Germany, Saudi Arabia, Japan, Chinese Taiwan, South Korea and Belgium. The company names and they developed PI products were showed in Table 2. The DuPont was the earliest enterprise to mass produce polyimide and it is also the world's largest polyimide producer in currently, with an occupying over 40% of the high-performance polyimide film market. The PI product of DuPont mainly included Kapton® and Vespel®. For the Kapton® films, DuPont had developed three type of improved polyimide film, namely HN type, FN type and VN type. The three improved PI films have accounted for 85% of the entire imine film production. The Evonik had developed the P84® fiber, which was composed only of aromatic skeleton units. Despite being an aromatic halogen-free structure without a melting point, P84® fiber is classified as a non-flammable fiber with its extreme oxygen coefficient of 38%. With excellent physicochemical properties, P84® fiber can be used in various applications from filter media for high-temperature filtration, protective clothing, sealing materials for spacecraft. The SABIC developed the EXTEM™ and further promoted the development of 5G printed circuit boards (PCBs), transparent displays and other flexible electronic applications. The UBE had successfully developed a new type of linear polyimide in the early 1980s, including the UpilexR, UpilexS, and UpilexC series films, which broke the 20 years monopoly of polyimide films made from PMDA and DDE. The Kaneka began to research polyimide films in the laboratory as early as 1980 and successfully developed a new type of homogeneous benzene PI film, which was named Apical™. In 1984, the company also established the first Apical polyimide film production line in Shiga in 1984 and began mass production in 1985. This PI product is mainly used in FPCS. The Mitsui Chemicals had developed the PI product named AURUM™ (Thermoplastic polyimide), which can be applied to precision machinery, industrial machinery components, electrical and electronic components, automotive and transportation machinery components, special wire sheaths, films and fibers, and composite material substrates. The Mitsubishi Gas Chemical was the only manufacturer in the world capable of truly industrializing the production of transparent PI films, which could meet the needs of high heat resistance and high transparency electronic products. The Mitsubishi Gas Chemical was the first company to announce the mass production of a colorless transparent polyimide film with the product named Neopulim in 2007. This PI product was mainly used in soft display related products and optical components. The Kapton® polyimide film developed by Toray has become an industry standard due to its excellent electrical performance, heat resistance, chemical resistance and clever combination of high mechanical strength based on its high performance, reliability, durability, insulation and the ability to withstand extreme temperatures, vibrations and other demanding environments. The Kapton® polyimide film adopts innovative design solutions and is widely used in various industries, such as electronic circuit materials (FPC, COF, FFC), high-temperature resistant tapes, black PI films, photovoltaics, automobiles and various industrial applications. The Taimide has over 30 years of experience in the research and development of polyimide (PI) films, also has successfully become a global leader in the production of PI films in the polyimide film industry with high technical barriers and special materials. The PI films produced are essential cutting-edge materials for various light, thin, short and small electronic products. The PI product developed by Taimide mainly included Taimide®TH, Taimide®TL, Taimide®TX, Taimide®BK, Taimide®OT and Taimide®WB. The Taimide®TH with a film thickness ranged from 12.5um to 125um. The Taimide®TL with a film thickness ranged from 12.5um to 50um and can be applied to print flexible circuit boards, protective films, enhanced plates, composite boards and flexible copper foil substrates. The Taimide®TX with a film thickness of 7.5um can be applied to tape thin high-temperature insulation, thin pressure-sensitive tapes and soft hard bonding boards. The Taimide®BK, a black polyimide film with a thickness ranging from 10um to 75um, can be applied to opaque high-temperature insulation tapes, opaque enhanced plates and composite boards. The Taimide®OT, a colorless polyimide film with a thickness ranging from 12.5um to 50um, can be applied to high-temperature resistant colorless protective films, flexible displays and flexible electronics. The Taimide®WB, a white polyimide film with a thickness ranging from 12.5um to 25um, can be applied to flexible printed circuit boards, high-temperature resistant white protective films, reinforcing films, LED light strips and barcode printing. The SKCKOLONPI is the first company in South Korea history to manufacture polyimide films, specializing in the production of cutting-edge polyimide films and paste products. The SKCKOLONPI had also developed a serious of PI products, such as LV (with a high temperature resistance), GC (black coated film), GF (laminated board), GFW (white coated film) and GL (with a low-expansion coefficient). The Torlon®PAI is the highest performing melt processability thermoplastic which was developed by SOLVAY. The typical applications of Torlon®PAI included aircraft hardware and fasteners, automotive transmission and powertrain components, as well as oil and gas exploration and recovery equipment. The excellent electrical insulation performance of this material makes it a common choice for semiconductor manufacturing and testing, as well as electrical and electronic components.

Table 2. Global leading companies and products of PI.

Country	No.	Company name	PI product
America	1	DuPont	Kapton®, Vespel®
Germany	2	Evonik	P84® fiber
Saudi Arabia	3	SABIC	EXTEM™
Japan	4	UBE	UpilexR, UpilexS, UpilexC
	5	Kaneka	Apical™
	6	Mitsui Chemicals	AURUM™
	7	Mitsubishi Gas Chemical	Neopulim
	8	Toray	Kapton®
Chinese Taiwan	9	Taimide	Taimide®TH, Taimide®TX
South Korea	10	SKCKOLONPI	LV, GC, GF, GFW, GL

Belgium	11	SOLVAY	Torlon®PAI

2.1.2 The application of PI

PI was usually regard as an insulation layer in electronics, such as OLED device and IC packaging. Based on the request of PI layer with patterning or without patterning, the usage method of PI was also classified into three methods.

2.1.2.1 The application of PI used in OLED device

For the usage of PI, if there was no patterning request for PI layer, the PAA resin solution was sprayed on a substrate directly with a spinning or slitting coating method and formed a wet organic layer which with a uniform thickness. Then a vacuum dehydration (VCD) process was taken on the wet organic layer to remove the most solvent. Finally, the PI film was formed after a curving process without another process. The formation of flexible substrate in the array structure of OLED display was usually taken this kind of usage method. As showed in Figure 3, PI was used as a cover material for foldable flexible display screens and as a substrate for high-frequency FPC (flexible printed circuit board). When PI regarded as a flexible substrate in OLED device, the PAA resin solution was coverage on the whole surface of glass substrate with a size of 370mm*470mm or 920mm*750mm, and the size of the glass substrate may be even larger than 920mm*750mm. The PI1 layer was formed on the glass substrate after a curving process with the PAA resin solution coverage on the whole surface of substrate. Then the barrier1 was deposited on the surface of PI1 as a stress buffer layer. Finally, the PI2 layer was formed on the barrier1 based on a same method with the formation of PI1. The thickness of PI1 and PI2 were usually as 6um and 6um or 8um and 8um. In the preparation of OLED devices, the yellow polyimide (YPI) with a high yellow index was usually introduced as a flexible substrate. The colorless polyimide (CPI) also was regarded as a flexible substrate in camera under panel (CUP) in organic light-emitting diode display (OLED) display which required a high transmittance (Tr%).

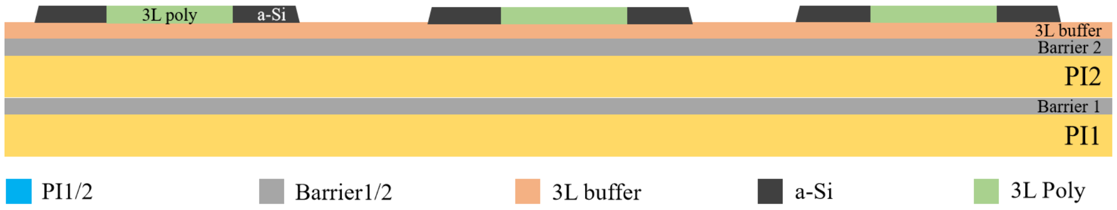

Figure 3. The architecture of PI used in the array structure of OLED device.

2.1.2.2 The application of PI used in IC packaging

With the patterning request for PI layer, there was usually two methods including transfer patterning with photoresist (PR) layer technology and laser technology for the usage of PI.[56] The process flow of the transfer patterning with PR layer technology was showed in Figure 4a. The PAA resin solution was usually spined on a substrate and the PI film was formed after a curving process. Then there was another PR layer with patterning was formed on the top of curved PI layer after the process of coating, exposure and development of PR. A wet etching or gas etching process was applied on the PI layer based on the patterned PR layer, and the patterning would be transferred from the PR layer to PI layer. Finally, the PR layer was removed from the top of patterned PI layer. This method for the usage of PI was usually used in the IC packaging. The process flow of the laser technology for the usage of PI with a patterning request was showed in Figure 4b. First, the PAA resin solution was spined on a substrate and the PI film was formed after a curving process. Then a laser process was applied on the surface of PI film, the width and depth of the opening area could be controlled by the time and intensity of laser. The laser area on the PI was defined by a CAD drawing, which was pre formed based on the process requirement. The process of plasma treatment was also necessary due to the residual of PI film in the opening area. Finally, a AOI inspection was introduced to confirm if the residual of PI still existed. This method for the usage of PI was also used in the IC packaging industry. When PI regarded as passivation layer in IC packaging, the PAA resin solution was coverage on the whole surface of silicon wafer with a size of 8 inch or 12 inch. Then the PI film with a thickness about 2um was formed on the surface of silicon wafer after a curving process. Based on the patterning request during the IC packaging process, the PI film located on the pad of IC chip was removed by taking the method as showed in Figure 4. Finally, a patterning redistribution layers (RDL) was formed on the surface of PI film based on the PVD, plating and photolithography technologies. For reducing the cost of IC packaging, the two methods of PI showed in Figure 4 were usually introduced to form passivation layer during the process of IC packaging.

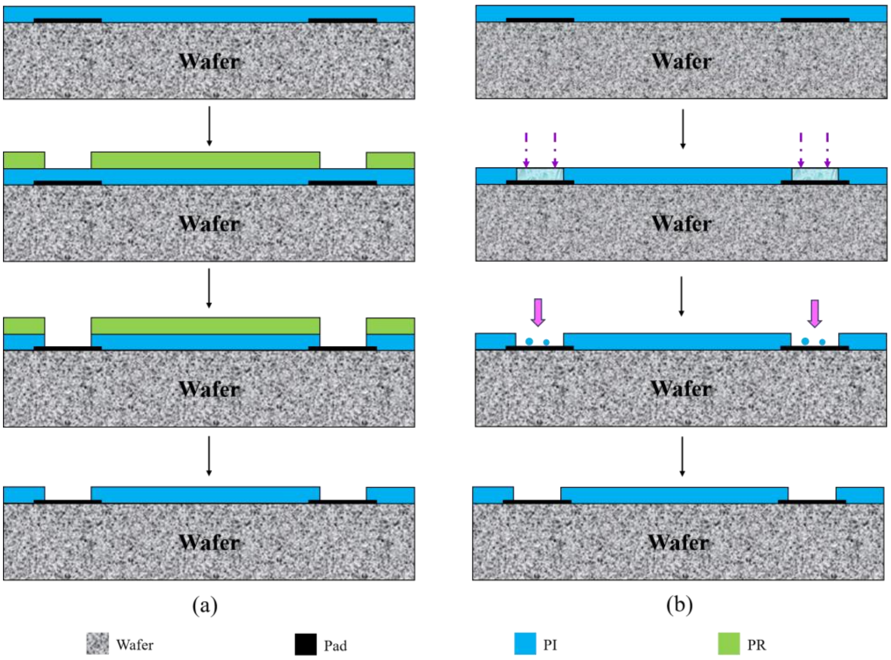

Figure 4. The process flow of PI used in IC packaging: (a) transfer patterning with PR layer, (b) forming PI patterning with laser technology.

Based on the transfer patterning with PR layer technology, there are two key process for forming patterning on PI layer.[57] Firstly, the fabrication of PI layer. As an insulating polymer material, PI film has excellent electrical insulation properties and is suitable for scenarios such as motor slot insulation and cable winding. The PI material in the form of thin film has a good flexibility and tensile resistance, which could make it easy for subsequent processing and patterning. Secondly, the patterning transfer process from PR layer to PI layer based on etching process. For the core function, the PR layer is exposed and developed through photolithography technology to form a predetermined two-dimensional or three-dimensional patterning, which is served as a mask for subsequent etching process. During the etching process, the unexposed (negative adhesive) or exposed (positive adhesive) PR areas could protect the PI substrate and achieve patterning transfer from PR layer to PI layer. For the compatibility controlling between PI and PR, the surface of PI layer needs to be modified with hydrophilicity (such as plasma treatment) to improve the uniformity and adhesion of PR coating. The high temperature resistance of PI layer is also compatible with the baking process of PR layer (usually 80~150 ℃), which could avoid the deformation or degradation of substrate. During the typical process of transfer patterning with PR technology, the thickness of PI layer was usually controlled between a few micrometers to several hundred micrometers according to demand by coating or vapor deposition methods.[58-59] While, the thickness of PR layer was usually about 1~5 microns by uniformly coated on the surface of PI layer with spin coating or spray coating methods. Then UV exposure is applied to the PR layer through a mask to induce chemical changes (positive gel decomposition or negative gel cross-linking) in the exposed area. The uncured (positive adhesive) or cured (negative adhesive) PR parts will also be removed by the development process to obtain the target patterning. Finally, during the etching transfer process, the PR patterning was used as a mask and the PI film is selectively etched by introducing a dry etching (such as plasma etching) or wet etching (chemical etching solution). The residual PR layer is also removed by using a stripping solution to obtain a patterned PI structure after etching process is completed. A high-temperature annealing process was also applied on the PI patterning layer to eliminate internal stress and enhance structural stability for completing the integration of device. The potential application areas of the transfer patterning with PR layer technology is the preparation of flexible electronics, the microelectronics packaging and the fabrication of micro nano sensor array structure, and the key challenges of this technology are the etching accuracy and PR peeling residue. The chemical stability of PI materials may result in slower etching rates and etching parameters (such as plasma power and gas ratio) need to be optimized to improve patterning resolution. The hydrophobicity on the surface of PI layer may make it difficult to completely remove PR residue.

The key characteristics of laser technology for forming patterning on PI layer are mainly including non-contact processing, high-precision control and material adaptability optimization, which is suitable for high-end fields such as microelectronics and flexible circuits. For the characteristic of non contact processing and no physical damage, the laser was directly acting on the surface of PI layer through a high-energy beam for vaporizing or modifying the material with photothermal effect, and forming patterning without physical contact. The laser technology could avoid material deformation or damage causing by mechanical stress, especially suitable for ultra-thin PI substrates (such as flexible circuit substrates). For the high precision and microscale patterning capability, the minimum processing accuracy of laser technology could reach 25 microns (about a quarter of a hair diameter), which can support the production of complex microcircuits and fine markings. The technical supporting for laser technology is the adopting beam shaping technology (such as square/circular light spots), which was used to optimize laser energy distribution and reduce energy unevenness of Gaussian light sources for improving edge sharpness of patterning on PI layer. For the process compatibility and efficiency of laser technology, the high reflection or difficult to process materials (such as metalized PI) was applied by multi laser composite technology, which could improve melting efficiency and stability with combining different wavelength lasers (such as red blue composite lasers). The scanning strategy derived from large format ultra high speed photopolymerization technology can achieve efficient large-area pattern processing with a high speed processing. For the application scenarios and technical challenges of patterning on PI layer based on laser technology, the core application included flexible electronics, anti counterfeiting label and biomedical devices, such as the fine line etching of flexible circuit boards (FPCs), the surface functionalization patterning of microfluidic chips or implantable devices and so on.

2.2 The introduction of PSPI

PSPI had two main applications of photoresist and electronic packaging. Compared to traditional photoresists, PSPI had no requirement on the application of light blocking agents and could significantly reduce processing steps. Meanwhile, PSPI also played an important role as electronic packaging adhesive, and PSPI was also used as a packaging material for buffer coatings, passivation layers and radiation shielding materials, interlayer insulation materials, chip packaging materials. PSPI were also widely used in the microelectronics industry, including packaging of integrated circuits and multi-chip packaging components. In currently, there are many companies have developed PSPI materials, such as Toray Industries, Inc., Fujifilm Electronic Materials, HD Microsystems, Kumho Petrochemical, Asahi Kasei Corporation, Eternal Materials, JSR Corporation and Merck. The global leading companies and market share in PSPI was listed in Table 3, the three biggest companies of PSPI in market share were Toray Industries, Inc., Fujifilm Electronic Materials and HD Microsystems, the values of their market share were 78%, 5.7% and 4.8% respectively. A few Chinese companies have also carried out PSPI related business, which included Jilin Optical and Electronic Materials Co., Ltd., Jiangsu

Sunera Technology Co., Ltd. and Hubei Dinglong Co., Ltd.

Table 3. Global leading companies and market share of PSPI.

No.	Company name	Market share
1	Toray Industries, Inc.	78%
2	Fujifilm Electronic Materials	5.7%
3	HD Microsystems	4.8%
4	Kumho Petrochemical	-
5	Asahi Kasei Corporation	-
6	Eternal Materials	-
7	JSR Corporation	-
8	Merck	-

The leading companies in PSPI materials mainly included DuPont from the United States, Toray from Japan, Bomi Technology and Baiyi Space-Time form China. Table 4 showed the key performance parameters of PSPI form those comparison. By applying in wafer-level packaging technology, the main products of PSPI from Dupont was the HD-4100 series, which could reach a resolution below 2um, reaching heat resistance above 400℃ and dielectric constant about 2.9~3.1.

The main PSPI product from Toray can also get a resolution below 3um, with heat resistance of 350℃ and dielectric constant about 3.0, which was widely used during the fabrication of flexible OLED substrate. By using in Huawei HiSilicon packaging, the PSPI product from Bomi Technology (China) could get the resolution about 2~5um, with a heat resistance of 400℃ and dielectric constant about 3.3~3.5. While, the PSPI product from Baiyi Space-Time could get a resolution about 5~10um, with a heat resistance of 300℃ and dielectric constant about 3.3~3.5, applying in the preparation of display panel.

Table 4. The key performance parameters of main products from leading companies for PSPI.

Company	Resolution (μm)	Heat resistance (℃)	Dielectric constant	Key application areas
DuPont (HD-4100 series)	≤2	＞400	2.9~3.1	Wafer-level packaging
Toray	≤3	350	3.0	Flexible OLED

(Photoneece)				substrate
Bomi Technology (China)	2~5	350	3.3~3.5	Huawei HiSilicon packaging
Baiyi Space-Time (China)	5~10	300	3.5	Display panel

2.2.1 The synthetic of PSPI

Traditional positive photoresist is mainly composed of three parts: film-forming agent (linear phenolic resin), photosensitive agent and solvent, which have good photosensitivity. In the molecular design of positive PSPI, it is expected to become soluble in the exposed area, which can be washed away during the development process. Meanwhile, the un-exposed area can also form a patterning during the development process. For reaching this purpose, some functional groups such as carboxyl groups which can be dissolved in dilute alkaline solutions were usually introduced into PI. Some PI dissolution inhibitors that can be decomposed when exposed to light, such as diazonaquinone sulfonate compounds were also added into PI for the preparation of PSPI.

PSPI photoresist can be classified into positive and negative photoresist based on the imaging mechanism of the photoresist sample. PSPI photoresist can also be classified into G-line/I-line/mixed line photoresist based on the exposure wavelength. Different types of PSPI photoresists have significant differences in resin selection, and are often subdivided into various types such as negative ester type PSPI, negative ion type of PSPI, positive diazonaphthoquinone type of PSPI, chemical amplification type of PSPI and so on, as showed in Figure 5. For the negative ester type PSPI, the photosensitive group was connected to the polyimide prepolymer with ester bonds, as showed in Figure 5a. For the negative ion type of PSPI, the PAA resin was obtained by reacting with organic amine compounds to form salts, as showed in Figure 5b. For positive diazonaphthoquinone (DNQ) type of PSPI, the ortho azide naphthoquinone group was introduced with side groups or directly added to impart photosensitivity, as showed in Figure 5c. For the chemical amplification type of PSPI, which was usually composed of photo induced acid generator (PAG, such as PTMA) and matrix resin (PAA), as showed in Figure 5d. Under the UV irradiation, the PAG can decompose into super strong acid, then catalyzing the decomposition or crosslinking reaction of matrix resin. Due to its recyclability, it has high efficiency and therefore has a chemical amplification effect.

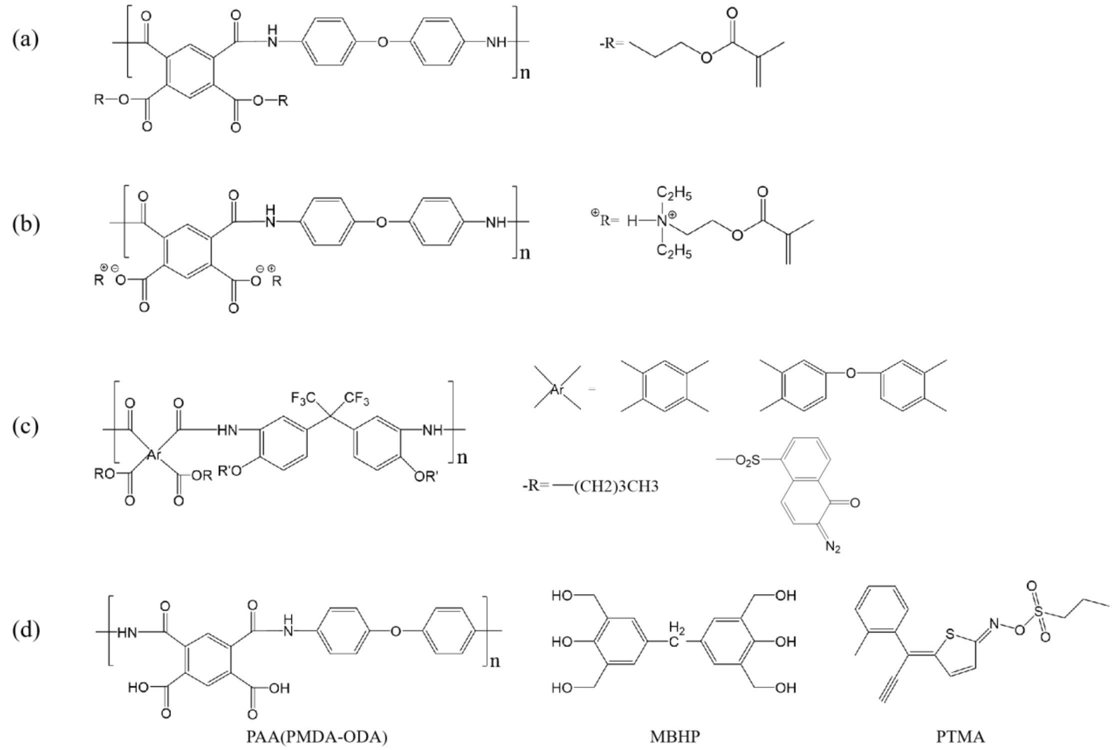

Figure 5. The classification of the PSPI: (a) the negative ester type of PSPI, (b) the negative ion type of PSPI, (c) the positive diazonaquinone type of PSPI, (d) the chemical amplification type of PSPI.

2.2.2 The application of PSPI

PSPI film was usually regard as an insulation layer in electronics, such as OLED device, IC fabrication and IC packaging. Based on the patterning request of PSPI layer, the usage of PSPI was usually introduced for forming passivation layer based on the technology of photolithography.

2.2.2.1 The application of PSPI used in OLED device

During the manufacturing of OLED device, PSPI was widely used as PLN and PDL due to its photosensitive performance, thermal stability and patterning accuracy.[60-61] The application of PSPI not only simplified the process flow, but also directly affected the luminous efficiency, resolution and reliability of OLED display device. Based on its excellent film-forming performance, PSPI could form a uniform thin film through spin coating or spray coating by after a curing process, the surface roughness (Ra) of PSPI layer could reach the value below 0.5nm, which can effectively eliminate the step differences existed in the bottom ITO electrode or TFT array structure and provide a flat substrate for subsequent organic light-emitting layer evaporation. During the high-temperature (about 200-300°C) environment of OLED packaging process, PSPI can still maintain structural stability for resisting acid and alkali corrosion, avoiding chemical reactions with subsequent organic materials.[62] For improving the luminescence uniformity and device lifespan of OLED device, PLN layer formed by PSPI can also reduce the uneven thickness of organic luminescent materials causing by the unevenness of the bottom layer and avoid brightness differences in the display screen. The dense molecular structure of PLN layer formed by PSPI can also block the penetration of external water vapor and ions to reduce the dark state current of OLED devices and extend their service life.

The material characteristics of high-precision patterning and mechanical support made it possible for PSPI using as PDL layer in the array structure of OLED display device. Without requiring additional photoresist, PSPI can directly form micrometer level patterns (line width accuracy of 1-3um) based on UV exposure, which could meet the strict requirements of pixel spacing for high-resolution (such as 4K/8K) OLED display device.[63] After exposure crosslinking, the unexposed area of negative PSPI dissolves during development process and formed pixel wells perpendicular to the sidewall, which can ensure the precise filling of organic materials during evaporation and avoiding adjacent pixel crosstalk. By using as PDL layer, PSPI layer could divide OLED panels into independent red, green, and blue (RGB) sub pixels to prevent mixing of different colored luminescent materials and ensure color purity. During the vapor deposition process of fine metal mask (FMM) technology, the mechanical strength of PSPI can support the bonding accuracy between the mask and the substrate to reduce pixel offset causing by mask deformation.

With the development of technology, PSPI was usually used as PLN, PDL and pixel supporting (PS) layer in the foldable flexible OLED device. The PDL and PS layer were usually formed with a technology named half tone mask and the architecture was showed in Figure 6. The half tone mask was made up of three parts, the fully transparent zone, the semipermeable zone and the impermeable zone. During the exposure process, the light can through the fully transparent zone on the mask completely without any loss and reach the surface of PSPI film, and the PSPI film located at the fully transparent zone was removed fully and formed the opening area after the develop process. While, only part of light can through the semipermeable zone on the mask and reach the surface of PSPI film during the process of exposure, the PSPI film located at the semipermeable zone was also removed part thickness and formed the PDL layer after the develop process. Finally, there was no light can through the impermeable zone and reach the surface of PSPI film, the PSPI film located at the impermeable zone remained the fully thickness and formed the PS layer.

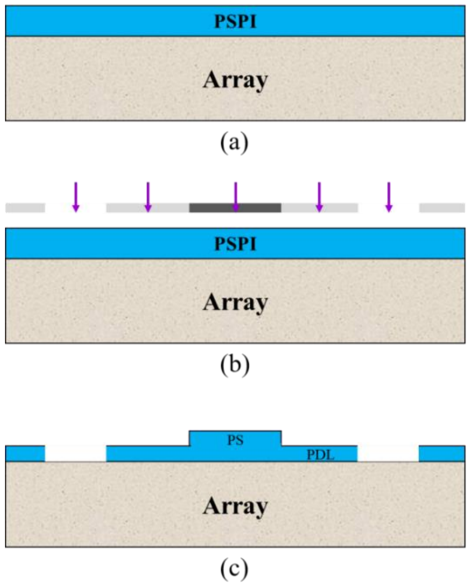

Figure 6. The architecture of PSPI application process flow: (a) PSPI coating, (b) PSPI soft bake, (c) PSPI exposure, (d) PSPI develop, (e) PSPI hard bake.

During the preparation of OLED display devices, PSPI was also used to forming the PDL layer and PS based on half-tone mask technology. The principle of half-tone mask was adjusting the exposure dose through the semi transparent area, allowing partial development of the photoresist and forming a thickness gradient slope structure to solve the step coverage problem of the PDL/PS layer.[64] The key advantage of half-tone mask was eliminating the flowing of organic material in the climbing area. For example, in the segment difference area (climbing area) of the shading layer (such as metal wiring), the traditional processes of forming PDL usually caused uneven coverage due to the flow of PLN material, which could lead to etching and wire breakage in following process.[65] While, the half tone technology could ensure the uniform coverage of PDL layer through gradient slope (controllable inclination angle above 85°) and avoid the exposing of metal traces. For the process simplification and cost reduction, the traditional processes require multiple photomasks to prepare PDL openings and PS structures separately and the half-tone mask technology is integrated into a single exposure, which could reduce the use of photomasks (such as reducing from 2 to 1 in LTPS processes). The companies such as Samsung Display and TCL China Star Optoelectronic Technology Co, Ltd. (CSOT) have all applied the half-tone mask technology in the process of flexible OLEDs device, which could significantly reduce the process time (such as PDL/PS synchronous graphing) and increasing yield over 20%. In summary, the half-tone mask technology has become the core solution for the preparation of PDL/PS layers in OLEDs device through gradient exposure, process integration and material adaptation, which was especially suitable for the thin layer and high-precision requirements of flexible screens. In the future, the half-tone mask technology need to get a breakthrough in nanoscale critical diameter control and mask cost optimization to support the development of 8K ultra high definition displays.

As showed in Figure 7, the PSPI was used to form PLN layer, PDL layer and PS layer in the preparation of OLED device. The PLN layer was covered on the source drain layer and used to reduce the undulating drop caused by the patterning source drain layer. The number of PLN layer was usually more than one layer, which was decided by the technological requirements of OLED device. The patterning anode of the electroluminescence (EL) part was formed on the surface of PLN layer. Then the PDL layer was covered on the PLN layer and anode layer, which was used to defined the pixel deposited area. The opening area in the PDL layer was used to deposit the luminescent functional layer during the electroluminescence (EL) manufacturing process with fine metal mask (FMM) technology. The PS layer was formed based on the technology of half tone mask technology and was used to as supporting part to prevent the anode from being damaged during the EL manufacturing process.

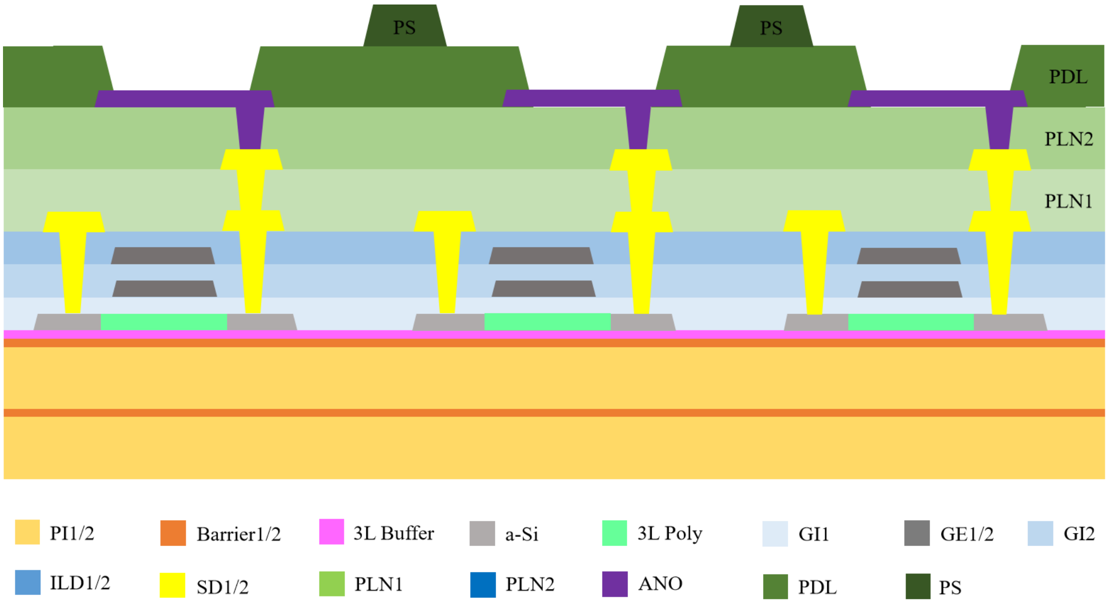

Figure 7. The architecture of PSPI used in the array structure of OLED device.

2.2.2.2 The application of PSPI used in IC fabrication

As a polymer that combines photosensitive properties and high-performance material properties, PSPI is widely used in dielectric layers and passivation films in chip manufacturing.[66] Its core characteristics and functions are reflected in three dimensions including material properties, process optimization and functional implementation. For the core characteristics and functions of PSPI as a dielectric layer, the high insulation and structural stability of PSPI were its key material characteristics. Base on the excellent dielectric properties, such as a typical dielectric constant of 3.0-3.5, a dielectric strength of 200-300kV/mm, a volume resistivity of 10^{16}-10^{18}Ω·cm and a surface resistivity of 10^{13}-106^{1}Ω·cm, PSPI could effectively isolate electrical crosstalk between different layers of the chip. When used as dielectric layers and passivation layer in manufacturing of chip, PSPI can simplify the patterning process and reduce costs obviously. Traditional non photosensitive PI relies on photoresist to complete patterning, which includes multiple steps such as coating, curing, photoresist coating, exposure, development and etching process. While, the photosensitive groups (such as epoxy groups and double bonds) contained in PSPI structure can be directly crosslinked or decomposed through radiation such as ultraviolet light, eliminating the need for additional photoresist and etching steps, shortening the process cycle and saving material costs. The protection function of PSPI was isolating environmental erosion and improving chip reliability when using as a passivation film. The passivation film in IC structure needs to protect the surface of the chip from water vapor, impurities and chemical corrosion.[67] PSPI can form a stable protective layer in high temperature and high humidity environments to reduce leakage current and increase breakdown voltage based on its dense molecular structure (main chain containing imide rings) and high temperature resistance (high Tg). For example, PSPI was used as a surface passivation layer in CPU and GPU flip chip packaging to ensure the long-term stability of precision circuits.

The application of PSPI in the semiconductor and microelectronics industry is mainly used as passivation layer and particle shielding film. For the passivation layer, the PSPI was usually used to form the protecting layer of the chip to prevent the IC from being damaged during the using process.[68] The architecture of PSPI used as a protecting layer in logic IC was showed in Figure 8. The PAA resin solution was sprayed on a substrate directly with a spinning or slitting coating method and formed a wet organic layer which with a uniform thickness. Then a soft process was carried out to remove the most solvents of wet organic layer. The exposure and develop process were carried out to form the request patterning with a mask. Finally, the curving process was used to confirm the PSPI film sturdy. For the particle shielding film, the radiation resistance performance of IC became more important based on the increasing of integrated circuit density and chip size. The high purity polyimide film is an effective radiation and particle resistant shielding material. Forming a 50~100um radiation shielding layer on the passivation film of the component casing can prevent memory errors caused by the release of trace amounts of uranium and peony. The excellent mechanical properties of polyimide can prevent chips from breaking during subsequent packaging processes. The structure of particle shielding film usually included two types, which were oxide/nitride/PSPI layer and fully PSPI layer.

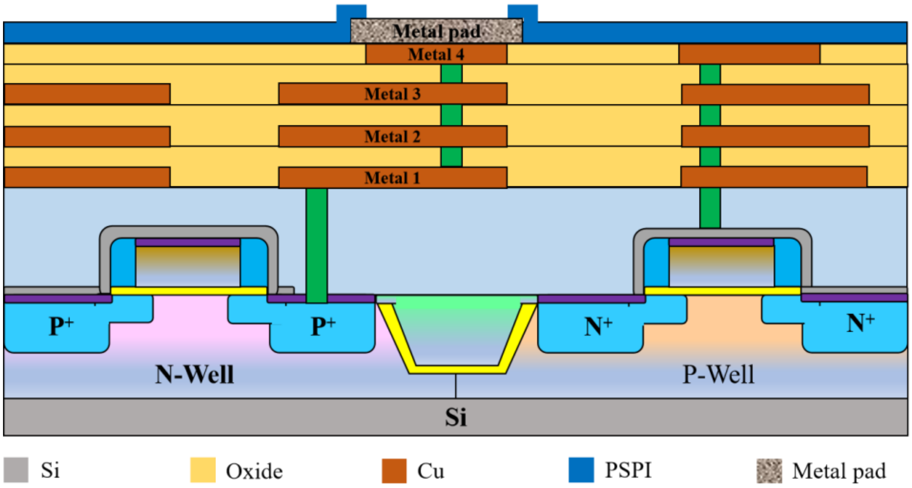

Figure 8. The architecture of PSPI used in the fabrication of logic IC.

2.2.2.3 The application of PSPI used in IC packaging

In the manufacturing of IC packaging, PSPI has played a key role in improving packaging reliability and process efficiency by using as a stress buffer layer and adhesive based on its unique material properties. For its mechanical performance advantages, a high elastic modulus (usually 2-5GPa) and low CTE (20-50ppm/°C) of PSPI could enable it to effectively absorb thermal stress between the chip and substrate for preventing warping or cracking caused by temperature cycling. The imide ring in its molecular structure endows the PSPI with high toughness for providing cushioning protection in the event of chip drop or mechanical vibration, which was especially suitable for mobile device chip packaging.[69] For the application scenarios and technological value, PSPI was used as core layer during the advanced IC packaging. For example, PSPI was served as a stress buffer layer for the rewiring layer (RDL) to isolate the thermal expansion difference between the silicon chip and the organic substrate for ensuring the stability of high-density interconnect structure in chip on wafer on substrate (CoWoS) and fan out wafer level packaging (FOWLP) technologies. When using as stress buffer layer, PSPI could also improve the lifespan of chips in high temperature and high humidity environments by reducing solder joint fatigue caused by thermal stress and the risk of packaging failure also reduced significantly.[70]

When using as an adhesive in IC packaging, the polar groups (such as carbonyl and amino groups) in PSPI molecules can form chemical bonds with metals (such as copper pillars and bumps) and silicon substrates for providing stable interfacial adhesion. During the integration of multi layer structure in 2.5D/3D packaging, PSPI was used for bonding chips, interposers and substrates to achieve mechanical fixation and electrical insulation integration of heterogeneous materials. Meanwhile, PSPI can directly form adhesive area patterning through exposure and development process without the additional photoresist steps and simplifying multi-layer stacking process. Some modified PSPI material can be cured below 200℃ to avoid high-temperature damage to thermal sensitive components (such as MEMS sensors). Finally, PSPI can also used as supporting multi-layer wiring and mechanical protection. In advanced IC packaging, such as WLCSP and fan out packaging, PSPI is used as a dielectric layer to construct a rewiring layer structure for supporting micro connections such as copper pillars and bumps and protecting internal circuits from physical damage. The high strength and toughness mechanical properties (such as strong impact resistance) could adapt to stress changes during chip packaging process.

The application of PSPI used in the IC packaging is mainly used as passivation (PA) layer during the process of IC packaging. For the passivation layer, the PSPI was usually used to form the insulation layer between re-distribution layers (RDL) to block the electrical signals between the metal circuit layers of the chip effectively, resulting no short circuits in the circuit and increasing the stability and reliability of electronic devices. Besides, the protecting layer formed by PSPI can also prevent water and oxygen from damaging the IC during the using process, which can increase the operation life of electronic devices. As showed in Figure 9a, the number of passivation layers in the IC bumping packaging was usually more than two, some electronic devices even needed three or four passivation layers. The passivation layers and RDL layers were interleaving and overlapping with each other on the surface of chips. Apart from the Cupper bump on the top layer of chip, each RDL layer was fully covered by the passivation layer to guarantee the electrical signals of chip. As showed in Figure 9b, the PSPI was also used as passivation layer in IC fan in wafer level packaging (FIWLP**).** The number of passivation layers in the IC FIWLP was usually less than two. The PA1 covered on the surface of chip with opening area corresponding to the pad of chip, and the patterning RDL1 also formed on the surfaces of PA1 and connected with pad of chip through the opening area in PA1. The PA2 also covered on the surface of PA1 and RDL1 with opening area, and the patterning RDL2 located on the surfaces of PA2 and connected with RDL1 through the opening area in PA2. It should be noted that the size of PA1 and PA2 were all same with the size of chip in the IC FIWLP package. As showed in Figure 9c, the PSPI was also used as passivation layer in IC fan out wafer level packaging (FOWLP). The number of passivation layers in the IC FOWLP was usually two. The PA1 covered on the surface of chip with opening area corresponding to the pad of chip, and the patterning RDL1 also formed on the surfaces of PA1 and connected with pad of chip through the opening area in PA1. The PA2 also covered on the surface of PA1 and RDL1 with opening area, and the patterning RDL2 located on the surfaces of PA2 and connected with RDL1 through the opening area in PA2. The size of PA1 and PA2 were all larger than the size of chip in the IC FOWLP package, which can provide wider area to distribute the RDL2 for meeting the increasing number of I/O density on chips.

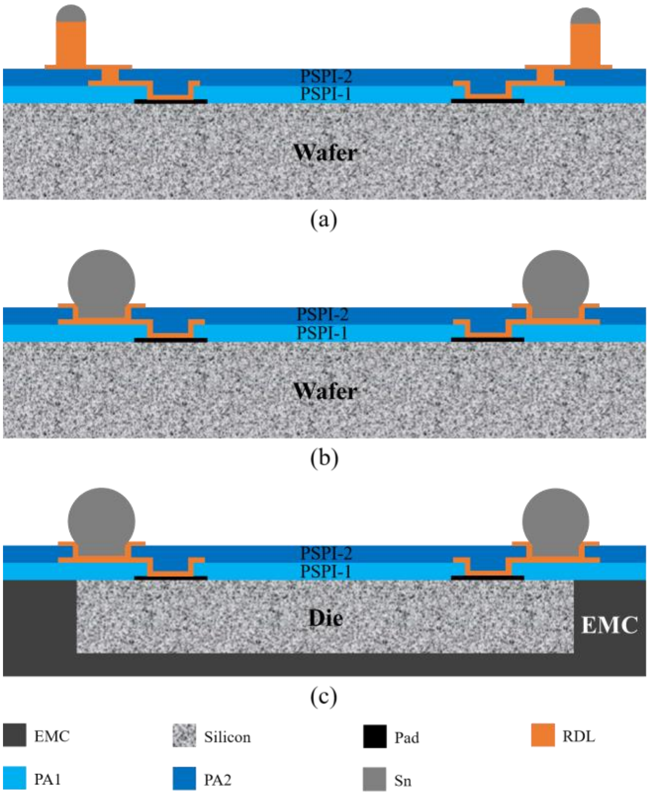

Figure 9. The architecture of PSPI used as PA layer in IC packaging: (a) in bumping packaging, (b) in FIWLP packaging, (c) in FOWLP packaging.

2.3 The comparative between PI and PSPI

Based on the applicable scenarios in microelectronics field, the comparative analysis between PI and PSPI was focusing on the characteristics and process comparison of material, the application scenario adaptability, the industry trends and challenges. For the characteristics and process comparison of material, the core advantage of PI was the stability in extreme environments, such as the high-power chips and aerospace electronics had long-term resistance to high temperatures (>300℃). The excellent mechanical strength of tensile strength (>100MPa) and coefficient of thermal expansion (as low as 20-50 ppm/°C) could buffer the chip packaging stress effectively. The insulation performance of PI had a dielectric strength of 200-300kV/mm and volume resistivity of 10^{16}-10^{18}Ω·cm. The process limitations of PI was the requirement of photoresist-assisted patterning, which included seven steps of coating, soft bake, exposure, development, hard bake, etching and stripping. Meanwhile, the core advantage of PSPI was the function of integrated lithography, the patterning layer is formed directly through coating, exposure, development and curing processes. The high-frequency adaptability of PSPI with dielectric constant (Dk) of 2.5-3.5 and low dielectric loss (Df) can ensure the signal integrity of 5G/AI chips. The flexible adaptation of PSPI with a bending radius of 50μm also make it suitable for the preparation of flexible OLED substrates. While, the thermal stability of PSPI is slightly lower than that of PI (curing temperature <250°C) and the mechanical strength of PSPI also reduced about 10~15%.

For the application scenario adaptability, the PI and PSPI were mainly applied in high temperature device packaging, high-density interconnect, flexible electronics, cost-sensitive packaging and environmentally friendly manufacturing, which were listed in Table 5. For the high temperature device packaging, such as power module and aerospace electronics, PI was usually selected for maintaining long-term stability at high temperature (>300°C) to prevent thermal failure. For the high-density interconnect, such as RDL/TSV/Fan-Out packaging, PSPI was usually chose as passivation layer for achieving ultra micro-via (<30μm) and lines (≤2μm) with lithography technology, which could also simplify the process of multi-layer stacking technology. For the flexible electronics, such as OLED display and wearable devices, PSPI was usually used as planarization layer and pixel definition layer for its low stress deformation (CTE of 2-5ppm/°C), and bending resistance cycles (>10^6 times). For the cost-sensitive packaging, such as traditional node IC packaging, PI was the best material choice for the low material cost. For the environmentally friendly manufacturing, PSPI was usually used for the replacement of organic solvents to water-based developer solution, which could also reduce the liquid of etching waste.

Table 5. The application scenario adaptability of PI and PSPI.

Scenario	Material choice	Key rationale
High-temperature device packaging	PI	Maintain long-term stability at high temperature (>300°C) to prevent thermal failure
High-density interconnect	PSPI	Achieves ultra micro-via (<30μm) and lines (≤2μm) with lithography, simplifying multi-layer stacking process
Flexible Electronics	PSPI	Low stress deformation (CTE of 2-5 ppm/°C), bending resistance sistance cycles (>10^6 times)
Cost-sensitive packaging	PI	Low material cost (but the overall cost is affected by multiple processes)
Environmentally friendly manufacturing	PSPI	Water-based developer replaces organic solvents, reducing etching waste liquid

For the industry trends and challenges of PSPI, the demand for advanced IC packaging is driving a compound annual growth rate of 24.5% and the market size is expected to exceed 12 billion RMB in 2029) by the driving forces of PSPI growth. The positive-tone PSPI (p-PSPI) is gradually to replace negative-tone products due to its higher resolution and lower defect rate. For the localization of PSPI, the import dependency is over 80% (dominated by Japan's Toray and Asahi Kasei). Meanwhile, the domestic enterprises such as Dinglong and Bomi Technology have also accelerated breakthroughs in mass production of

PSPI. The process threshold of PSPI is relatively high, such as it is required for a plasma treatment to enhance adhesion with the metal layer.

3. Conclusion

In conclusion, the PI and PSPI were widely used in OLED device, IC fabrication and IC packaging. The author introduced the synthetic, usage and application of PI and PSPI. For the patterning of PI layer, the method of transferring the patterning from the PR layer to PI layer with a wet etching or gas etching process was widely applied in IC packaging. Besides, another technology which was introducing laser technology based on a CAD drawing and plasma treatment for forming the patterning in the PI layer was used in IC packaging. Meanwhile, the PI layer without patterning was also regarded as flexible substrate during the preparation of OLED device. The PSPI was usually used as PLN/PDL/PS layer in the fabrication of OLED device and PA layer in IC fabrication and IC packing.

Based on the comprehensive analysis of industry trends and technological advancements, the future of PI material used in microelectronics will be driven by a few key technical developments, which included the innovations of ultra-low dielectric and nanocomposite materials in IC fabrications, the flexible and heterogeneous integration in IC packaging, the enhancement of fold-able OLED displays and the sustainability and multi-functionality in interdisciplinary trends. The PI films with dielectric constants below 2.5 are critical for reducing the resistance and capacitance delay (RC delay) and crosstalk in advanced nodes IC fabrications. The radiation-resistant PI which was composited with nanoscale fillers (such as boron carbide) could enhance the shielding of α-particle and thermal stability (>400℃) for aerospace and quantum computing chips. For advanced IC packaging, the ultra-thin PI films (⩽5um) could interconnect the high-density interconnects in 2.5D/3D packaging and the PI with low CTE (<10ppm/K) can minimize the thermo-mechanical stress during bonding process in Chip-on-Flex (COF) substrates. During the manufacturing of OLED device, the colorless PI (CPI) films with high transmittance (>90%) and low haze (<0.1%) are very essential for fold-able OLED devices. The encapsulation layer of hybrid PI/SiN_X barriers in flexible active-matrix organic light-emitting diode (AMOLED) could also suppress the permeability of H_2O/O_2 by replacing the rigid glass. For the sustainability and multi-functionality of PI in interdisciplinary trends, PI films embedded with nano-sensors (such ad strain and temperature) can could enable monitoring health with real-time in IC and displays based on multi-functional integration technology.

Based on comprehensive analysis of industry trends and technological advancements, the future technical evolution of PSPI in microelectronics which spanned semiconductor fabrication, advanced packaging and OLED manufacturing will be defined by the stress engineering and heterogeneous integration in advanced packaging, the fold-able displays and pixel definition in OLED manufacturing, the enabling sub-2nm nodes chip fabrication, the dynamics and challenges of market. For the sidewall angle optimization, the PSPI films with high sidewall angles (>75°) could reduce thermo-mechanical stress about 45% in flip-chip packaging and mitigate the chip-package interaction failures obviously, which can be achieved with precise control of coating, baking and development parameters. The ultra-thin PSPI films (≤5um) could enable the fine-pitch interconnects (<2μm) for chiplet based on 2.5D/3D integration by replacing multi-step etching processes. For the foldable displays and pixel definition during OLED manufacturing, the

intrinsic black PSPI based on novel formulations incorporating anthraquinone derivatives can achieve high optical density (>0.89) and low dielectric constant (<3.6) at 1000 kHz, which could eliminate the need for carbon black additives and enhance the insulation of polarizer-less OLED pixel definition layer. The encapsulation layer of hybrid PSPI/SiN_X barriers in flexible AMOLED could also suppress the permeability of H_2O/O_2 without rigid glass covering. During the chip fabrication, the ultra low-k photosensitive dielectrics (such as fluorinated PSPI) can reduce dielectric constants to 2.3~2.7, which was critical for the minimization of RC delay. The chemically amplified PSPI derivatives could offer a superior etch resistance over conventional chemIcally amplified resists (CARs), which made it possible for PSPI as a candidate for next-gen EUV lithography. For the dynamics and challenges of market, the global PSPI market is projected to reach $3.7 billion by 2032 by driving a compound annual growth rate of 22.23%. The market share of PSPI in China is expanding rapidly with an explosive growth rate.

Acknowledgments

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