Chapter 13
Application of Cold Plasma in Food Packaging

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Abstract In order to improve the performance of food packaging and the level of food safety and quality, a variety of technologies have been applied to the modification of food packaging. By comparison, cold plasma modification technology has the potential to become a new type of food packaging material modification technology due to its low cost, safety, and pollution-free characteristics, to replace traditional physical and chemical modification methods, reducing energy consumption and environmental pollution. This chapter focuses on the influence of plasma treatment of polymer packaging materials on their functional groups, properties, morphology, and biological activity. The plasma-enhanced chemical vapor deposition (PECVD) further improves the barrier properties and antibacterial activity of polymers. The surface of food packaging was treated with cold plasma directly to prepare sterile packaging materials. The process parameters and modification principles of plasma were discussed, and the multiple effects of plasma modification on polymer materials were evaluated, which provided a theoretical basis for the application of plasma in food packaging.

Keywords Cold plasma · Food packaging · Polymer · Modification · Sterilization

13.1 Introduction

Food packaging is an important part of food commercialization and plays a dominant role in the process of food industrialization. Packaging has a protective effect to protect food from physical, chemical, and biological pollution in the outside world; it can also ensure food quality and extend the shelf life of products. In general, in the process of food supply, packaging plays a role in extending the shelf life of food, reducing food pollution, and ensuring food safety. Packaging materials keep a

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balance between the environment and the product and maintain the food quality or sensory performance through the barrier properties of packaging materials (Suppakul et al. 2003). Although the food industry has been developing, foodborne diseases still occur and increasingly attract the attention of consumers. The development of modified packaging and antibacterial packaging by different physicochemical treatments or the addition of various active substances to food packaging materials to improve specific functions or impart new characteristics will be of great significance.

Due to its low price, easy to process, and good processing performance, the proportion of polymer materials in food packaging materials has gradually increased. However, the chemical inertness and low surface energy of polymer materials have limited their application in the food packaging industry to some extent (Ozdemir et al. 1999). Therefore, it is necessary to further improve the performance of polymer materials to meet the market demand and replace the expensive multilayer system composed of different polymers, which means that the surface modification of polymer packaging materials plays a crucial role in its application and development. Surface modification of polymers can be achieved through chemical and physical methods (Lee 2010). The conventional chemical modification method mainly refers to the wet chemical method of strong acid and alkali applied in industry, but the waste generated during the modification process will cause pollution to the environment. Emerging physical modification methods mainly refer to flame, irradiation, laser, ultraviolet, and cold plasma treatment. Cold plasma treatment is considered to be the safest and most versatile surface modification technology. Plasma generated from various devices has led to different surface reactions that form new chemical functional groups and functional surfaces (Chu et al. 2002; Karam et al. 2013).

Plasma is mainly divided into two types: balanced plasma (thermal plasma) and non-equilibrium plasma (non-thermal plasma), the latter is more conducive to the modification of the polymer surface because it will not cause thermal damage to the material (Surowsky et al. 2014). Since cold plasma is now used for direct sterilization of food, compared to other modification technologies, plasma modification is safer and does not cause pollution to the environment. For plasma generation devices, dielectric barrier discharge (DBD), microwave plasma, and plasma jets are more applied to the modification of polymer surfaces (as shown in Table 13.1). In addition to the generation device, the specific chemical properties of the plasma are also related to the working gas type, voltage, time, and other parameters. The active substances generated from cold plasma will induce a reaction on the surface of the polymer and change the surface properties of the polymer material, such as roughness, chemical bond, contact angle, functional properties, antibacterial activity, adhesion, and biodegradation efficiency. Therefore, cold plasma treatment can expand the application range of polymer packaging materials, improve packaging performance, and further extend the shelf life of food. In general, the effects of cold plasma on polymer packaging materials are mainly divided into the following aspects:(1) surface modification of materials to improve the barrier properties; (2) material surface functionalization; (3) deposition of specific materials on the

Table 13.1 Effects of plasma on the surface modification of different polymers

Material	Plasma source	Gas	Treatment condition	Findings	Reference
Poly lactic acid films	DBD	Air	70–80 kV, 0.5–3.5 min	Roughness↑, thermal stability↑	Pankaj et al. (2014a, b)
Defatted soybean meal-based edible film (DSM film)	Microwave plasma	O_2, dry air, He, Ar	2.45 GHz, 400–900 W, 15 min	Flexibility↑, elongation↑, roughness↑, ink adhesion↑, contact angle↑, biodegradability↑	Oh et al. (2016)
Polylactic acid (PLA) films	Microwave plasma	O_2	2.45 GHz, 50–1000 W, 40 min	Roughness↑, ink adhesion↑, contact angle↑, biodegradability↑	Song et al. (2016)
Poly(ethylene terephthalate) (PET)	DBD	O_2	40 MHz, 18 W, 1–10 min	Roughness↑, contact angle↓, adhesion↑	Cruz et al. (2010)
Biorientated polypropylene films (BOPP)	DBD	N_2, NH_3, CO_2	5.6 kHz, 20 kV, 200 mA, 0.5 min	Amino and carboxyl groups densities↑	Vartiainen et al. (2005)
Fish protein films	Alternating current (AC) glow discharge	Dry air	60 Hz, 4.4 kV, 2–5 min	Opacity↑, roughness↑, water vapor permeability↑	Romani et al. (2019)
Poly(ethyleneoxide) (PEO) nanofibers containing Beta-cyclodextrin and tea tree oil	Plasma jet	Air	300 W, 0.5–5 min	Antimicrobial activity↑	Cui et al. (2018)
Phlorotannin (PT)/*Momordica charantia* polysaccharide (MCP) nanofiber membranes	Plasma	N_2	350 W, 30 s	Antimicrobial activity↑, antioxidant ability↑	Cui et al. (2020)

"↑" and "↓" represent the enhancement and decrease of the material properties, respectively

single thin film surface; (4) sterilization of material surface. This chapter will discuss the above aspects in detail.

13.2 Food Packaging

With the further development of the food processing industry, food quality, and safety have received more and more attention from the public. In order to protect the food quality and extend the shelf life of food, it is of great significance to develop new packaging materials. Traditional food packaging materials include metals, ceramics, glass, and paper. Although these materials are still in use, due to the light weight, low cost, easy processing, and formability of polymer materials, plastics become the best choice for food packaging (Duncan 2011). However, the inherent properties of a single material limit the application scope of packaging materials. Therefore, with the integration of cross-disciplines, new types of food packaging materials are developing rapidly. Compared with traditional food packaging, new packaging materials have the following characteristics: break away from the restriction of a single material, and optimize packaging performance through the combination of materials; packaging materials are more ecologically green and environmentally friendly; design and control from the molecular scale and target to improve the characteristics of packaging materials, such as bacteriostasis and degradability. Compared with the existing modification technology, the emergence of plasma modification technology effectively reduces the processing time and optimizes the operating conditions, thereby reducing environmental pollution and reducing costs. Some chemical and physical changes can occur at the plasma–polymer interface to improve surface properties.

13.3 Effects of Cold Plasma Treatment on the Surface Modification of Polymers

13.3.1 Superficial Modification

The covalent bond on the polymer surface is broken after plasma treatment, and this further reacts with the reactive species in the plasma to form new functional groups (Bogaerts et al. 2002). When plasma generation devices are similar and act on the same polymer materials, the modified polymer materials obtained will be different, due to the influence of other process parameters in the treatment process. In general, when O_2 or air is used as the working gas, oxygen-containing functional groups such as C–O, –OH, C=O are generated on the surface of the polymer. These substances undergo further rearrangement and cause chain breakage, leading to the formation of carboxyl groups at the end of the chain (Theapsak et al. 2012). Cruz et al. (2010) also confirmed through X-ray photoelectron spectroscopy (XPS) that the ratio of total O atoms to C atoms in Poly(ethylene terephthalate) (PET) increased, indicating that after plasma treatment, oxygen was effectively bound to the PET surface. When N_2 is used as the working gas, C–N, C≡N, and amide bonds are generated on the polymer surface. Likewise, when He or Ar is used as the working gas, the reactive species from plasma destroy the C–C and C–H bonds on the surface of the polymer material, causing it to generate free radicals on the surface, which further react with oxygen or nitrogen atoms in the gas phase and form new functional groups (Song et al. 2016).

13.3.1.1 Surface Morphology

The surface morphology of polymers is affected by plasma treatment. Compared with the control group, the polymer films after plasma modification became rougher, and the sharpness of the edges was decreased, and this was attributed to the plasma etching effect. A series of chemical reactions initiated by the reactive species in the plasma results in the breaking of polymer chemical bonds, chain scission, degradation, and the physical removal of some low-molecular weight fragments of the polymer (Mirabedini et al. 2007; Pankaj et al. 2014a, b). The etching effect of plasma on polymer surface is closely related to the working gas, plasma treatment time, and the roughness of polymer film itself. When the working gas of plasma is different, the etching rate of PET showed the following trend: $O_2 > H_2 > N_2 > Ar > NH_3$. However, change in the surface roughness of PET demonstrated a different trend as $NH_3 > N_2 > H_2 > Ar > O_2$. The results showed that the roughness of polymer film was significantly related to the type of gas, but not to the etching rate of gas (Inagaki et al. 2004). At the same time, the roughness of the treated membrane will still increase significantly during storage (Song et al. 2016). In addition to working gas, Mirabedini et al. (2007) pointed out that the roughness of biaxial-oriented polypropylene (BOPP) film increased with the increase in O_2-plasma or Ar-plasma processing time. Nodular structure is formed on the surface during the treatment, and the nodular size increases with the increase in treatment time. Upon increasing the treatment time to 180 s, the surface of the BOPP film was almost completely etched, as observed in Fig. 13.1. Song et al. (2016) used polylactic acid films with a flat and uniform surface as the experimental film. After O_2-plasma treatment, the plasma-treated film became relatively rough compared with the untreated group, but still relatively average, without noticeable bulging. In general, different types of plasma treatment increased the roughness of the polymer film irrespective of working gas and treatment duration.

13.3.1.2 Contact Angle

Contact angle is a variable that determines the wettability of the polymer surface, the hydrophilicity/hydrophobicity of the surface, by measuring the tendency of the liquid to spread on the polymer. When the surface of the polymer material is wettable, it exhibits hydrophilicity and a small contact angle. Cruz et al. (2010) found that the contact angle of PET film decreased with an increase in plasma treatment time. On extending the treatment time beyond 2.5 min, the contact angle did not change significantly. Judging from the variation trend of contact angle, the

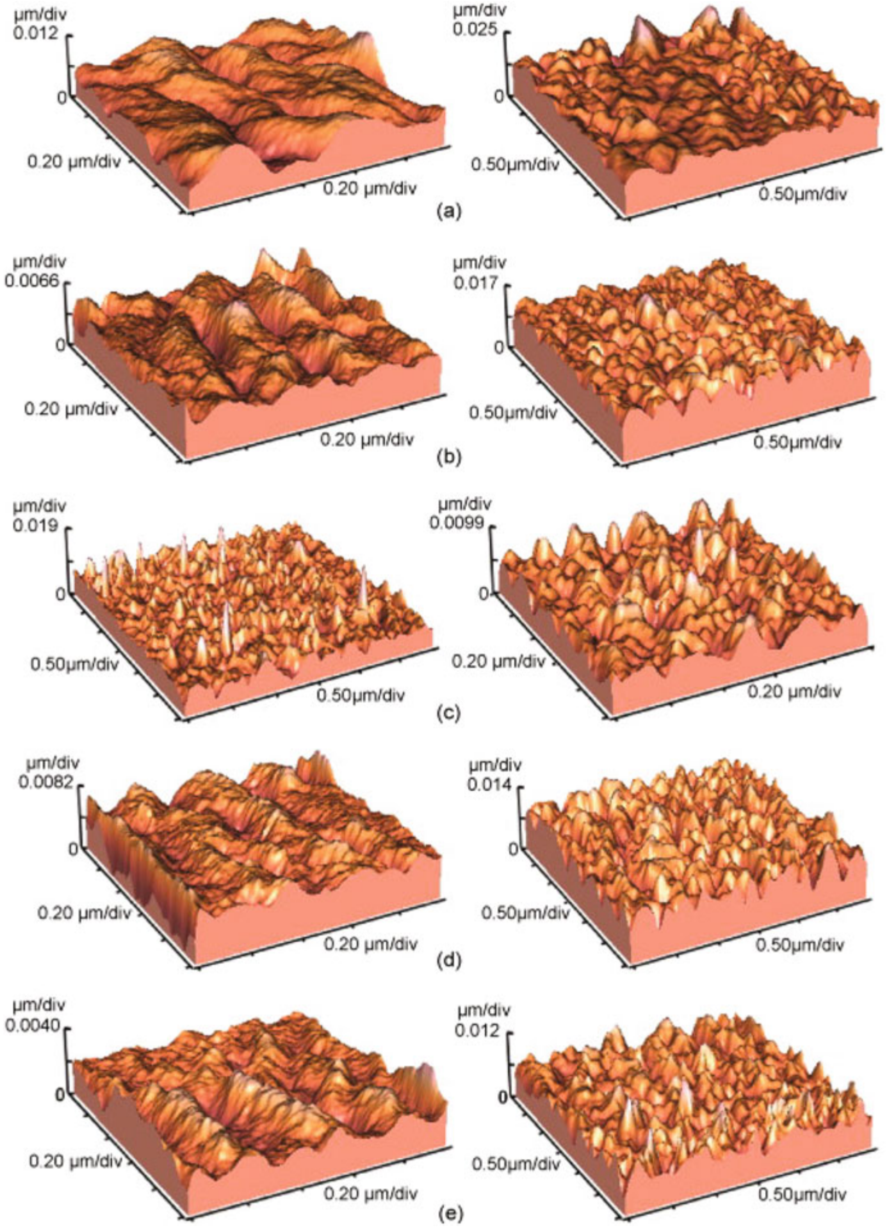

Fig. 13.1 AFM images of BOPP film; (**a**) untreated, (**b**) O_2 plasma treated for 30 s, (**c**) O_2 plasma treated for 180 s, (**d**) Ar-plasma treated at for 30 s, and (**e**) Ar-plasma treated for 180 s. (With permission from Mirabedini et al. (2007))

oxygen element in the plasma permeated the PET surface in the early stage of the treatment (0–2.5 min), which promoted the increase of surface polarity. At the later stage of treatment (2.5–10 min), the oxygen element infiltration rate was weakened; thus, the etching effect of plasma on the polymer surface manifested. Theapsak et al. (2012) also revealed through the ATR-FTIR and XPS spectra that the reduced contact angle of the PE film was attributable to the introduction of new oxygen-containing groups C–O, C=O, and –OH on the polymer surface after DBD treatment, thereby resulting in the formation of new hydrophilic groups. Paisoonsin et al. (2013) also found that the contact angle on the surface of the film initially decreased after 0–10 s and then stabilized (>10 s) following an increase in DBD plasma treatment time on the treated-PP (polypropylene) film. The reduction in the PP film contact angle after the DBD treatment was due to the presence of reactive species in the plasma, such as O, O_3, NO, NO_2, N_2O, NO^+, O_2^+, and O^+ that led to the formation of polar functional groups on the surface. Increasing the DBD treatment time beyond 10 s, the contact angle on the nano-scale oxidation layer of the PP film reached the saturation value. On the other hand, defatted soybean meal-based edible film (DSM film) and polylactic acid films showed a tendency to increase the contact angle after plasma treatment (Oh et al. 2016; Song et al. 2016). The increase in the polymer contact angle is not due to the increase of film surface hydrophobicity but due to the increase of film surface roughness. Therefore, during the evaluation of the effect of plasma on the hydrophilicity/hydrophobicity of the polymer surface, it is necessary to consider whether the plasma introduces polar groups into the surface, or only increases the surface roughness of the polymer film.

13.3.2 Surface Activation and Functionalization

Polymer surface activation and functionalization refer to the introduction of specific functional groups on the polymer surface to cause chemical changes in its structure in order to improve the adhesion, printing properties, and antibacterial properties of the polymer surface with other polymers or functional substances (Honarvar et al. 2017). After the surface of the polymer is subjected to plasma, ultraviolet photons and electrons in the plasma can break the chemical bonds in the polymer chain and introduce new functional groups to promote the formation of polar groups or cross-linked molecules on the treated surface and increase the total surface free energy. At the same time, high-energy particles in the plasma, such as free radicals, ions, neutral particles, and excited atoms or molecules, also cause etching (Pankaj et al. 2014a, b). Plasma treatment has been reported to remove loose low-molecular weight fragments on the polymer surface. This is referred to as plasma cleaning, and this led to partial bond breakage and degradation on the polymer surface, thereby increasing the roughness of the film surface to improve inert, biocompatible polymers material adhesion (Romani et al. 2019).

13.3.2.1 Adhesion

Adhesion refers to the interaction between physical and chemical molecules on the interface and the degree to which different surfaces stick together. The polymer surface after plasma treatment can change the total surface-free energy to change the adhesion. Oh et al. (2016) pointed out that after the O_2-plasma and air-plasma treatment of the DSM film, oxygen-containing functional groups or amine, and amide groups were introduced on the surface of the film, which effectively improved the adhesion of the ink. Meanwhile, plasma treatment increased surface roughness of the polymer film, which enhanced the contact area between the ink and the film surface, and then improved the adhesion of ink. At the same time, when the plasma treatment only increases the etching of the film, or only introduce free radicals on the surface, does not introduce oxygen-containing functional groups, the adhesion of the ink cannot be improved (Song et al. 2016).

13.3.2.2 Bioactive and Antimicrobial Materials

In order to improve the antibacterial activity of the packaging material and to inhibit the growth of harmful microorganisms on the surface of the packaged food, the surface of the plasma-modified packaging material can be modified through fixing antibacterial substances. After plasma treatment, new functional groups are present on the surface of the polymer, and this is improved the immobilization of other antibacterial substances. Vartiainen et al. (2005) found that after the plasma treatment of bidirectional polypropylene film (BOPP), the density of amino and carboxyl groups on the surface of the film increased. When the functional group of antibacterial enzyme glucose oxidase (GOX) was immobilized on the BOPP membrane through a covalent bond, the enzyme activity increases, and an enzyme active film was generated on the surface of the BOPP film. The BOPP film with an active enzyme membrane completely inhibited the growth of *E. coli* and significantly reduced the growth of *Bacillus subtilis*. By fixing antibacterial substances such as peptides, enzymes, polyamines, and organic acids on plasma-modified polymer films, there is great potential for the development of packaging films with antibacterial activity.

13.3.3 Barrier Properties

The barrier property of polymer materials is one of the most important properties that determine the application range of packaging materials in the food industry (Pankaj et al. 2014b). Therefore, whether plasma modification will have a significant impact on the barrier properties of polymer materials is also a key to investigate. Oh et al. (2016) stated that plasma improved the hydrophilic properties of the polymer material surface. The plasma-surface modification only recorded a film penetration depth of not more than 10 nm. The barrier properties of the polymer, such as water vapor transmittance, are determined by the thermodynamic parameters on the film surface, kinetic parameters in the film matrix, and the diffusion rate (Shogren 1997). When air, O_2, and CO_2 were used as plasma working gases, no significant effect on the water vapor transmission rate and oxygen permeability of the polymer was observed (Honarvar et al. 2017). This implied that the surface modification of plasma has no adverse effect on the barrier property of packaging materials, which is conducive to further development and application.

13.3.4 Migration Properties

An overall migration experiment of the polymer after plasma treatment is required to evaluate the total amount of non-volatile substances that the film monomer migrates into the food. Plasma acting on polymer materials has led to cross-linking of polymer, formation of new functional groups, or degradation of the polymer, and these could affect the migration of monomer in the film. At the same time, the migration characteristics of the film are also closely related to the plasma generation conditions and polymer composition. When the polymer cross-links, the tortuousness of the diffusion path of additives or other low-molecular substances is increased. This relatively prevented or reduced the migration of monomers or oligomers. Also, when polymers are degraded into decomposition products due to etching, the migration of low-molecular substances is increased. When Ar or He is used as the plasma working gas to act on the PVC film containing plasticizer, the plasma caused the cross-linking of the polymer. After 5 min of treatment, the mobility of the plasticizer was reduced to the minimum detection limit. However, when N_2 is used as the working gas, the mobility was only reduced by 4.8% (Guillard et al. 2010). After the polylactic acid film is treated with DBD, the migration test was simulated in acidic and high alcohol content foods. After the treatment, part of the polylactic acid chain was broken to form a low-molecular weight substance, thus led to the migration of a small number of lactic acid monomers, dimers, and polylactic acid oligomers into the food. However, even under extreme treatment conditions, the overall migration value is still significantly lower than the specified value of 10 mg/dm^2 (Pankaj et al. 2014a, b). Therefore, plasma treatment could affect the overall migration of the film, but it will not cause hidden dangers to food safety.

13.3.5 Biodegradable Properties

The increasing environmental problems caused by the use of plastics have aroused people’s concern about biodegradable food packaging materials. Song et al. (2016)

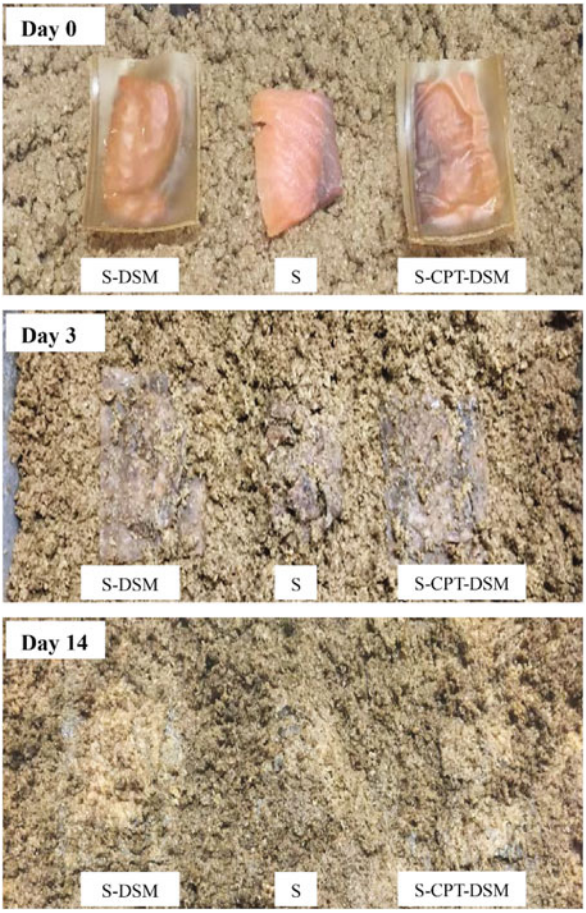

Fig. 13.2 Effects of packaging smoked salmon with the sachets made of defatted soybean meal (DSM)-based films prepared with and without the cold plasma treatment on biodegradability in compost of smoked salmon on days 0, 3, and 14 of storage at 4 °C. "S", "S-DSM", and "S-CPT-DSM" stand for the samples of smoked salmon without packaging with DSM film and those packaged using the DSM films untreated and treated by Ar-cold plasma, respectively. (With permission from Oh et al. (2016))

indicated that PLA (polylactic acid) after plasma treatment has a lower elongation at break than the untreated group. Plasma accelerates the breaking of polymer chains and promotes the photodegradation, thermal degradation, and microbial biodegradation of PLA films. The biodegradability experiment of the compost further found the degradation degree of the plasma-treated PLA bags reached 50% after day 21, and that of the untreated group was about 25% under the same conditions. Oh et al. (2016) found that the surface roughness of the DSM (defatted soybean meal) film after plasma treatment was increased, thus increased surface area. By increasing the contact area between the membrane and the biodegradability of the DSM film is promoted, as shown in Fig. 13.2. In general, plasma can enhance the biodegradability of the film to a certain extent by increasing the surface roughness and accelerating the fracture of the polymer.

13.4 Effects of Cold Plasma on the Surface Deposition of Polymers

A polymer only exhibits a single barrier property or functional property, whereas a combination of different polymers can mostly meet the various needs of food packaging, but the production cost of such multilayer polymer packaging materials is relatively high. The study of polymer barrier coatings is particularly important. The deposited layer needs to increase the functional properties of the original polymer without affecting the recyclability of the coated polymer material. Plasma-enhanced chemical vapor deposition (PECVD) is a promising layered deposition method suitable for heat-sensitive polymers (Plog et al. 2011). After the action of PECVD, a thin film of about 1 μm thick is deposited on the polymer surface, which is used to transfer specific functions (Honarvar et al. 2017). The properties of the deposited film are closely related to plasma working gas flow rate, treatment time, excitation frequency, and other process parameters (as shown in Table 13.2).

13.4.1 Antimicrobial Characteristics

Traditional polymer films such as polyolefin films are widely used because of their excellent chemical resistance, high impact resistance, and low cost. However, their inherent antibacterial activity is low, and they are susceptible to microbial contamination, which has a negative influence on food quality. Therefore, surface modification of polymer films, such as aggregation of antibacterial agents on the surface, to prepare antibacterial packaging materials, is of great practical significance (Lei et al. 2014) to extend shelf life and maintain the sensory quality of food. De Vietro et al. (2017) found that when plasma was applied directly into aerosol containing copper complex solution and deposited uniformly on the polycarbonate plate, the population of *Pseudomonas* was reduced by three orders of magnitude compared with that of the non-deposited film group. The copper coating deposited by this method can be used for food packaging preservation, such as the packaging of fresh dairy products.

13.4.2 Barrier Properties

The use of plasma-enhanced chemical vapor deposition (PECVD) to improve the barrier properties of polymer materials to enhance the barrier strength between food and the external environment, and extend the shelf life of food, has increasingly attracted the attention of researchers. One of the most common methods employed is the deposition of a colorless SiOx film on the polymer film to improve the barrier properties of the polymer material without affecting the visibility of the food. Plasma-polymerized SiOx composed of silicon, oxygen, hydrocarbon groups, and

Table 13.2 Effects of plasma on the surface deposition of different polymers

Plasma source	Treatment	Substrate material	Coating material	Findings	Reference
Pulsed microwave plasma	1500 W, O_2: 4–600 sccm, Hexamethyldisiloxane: 4 sccm	Polyethylene terephthalate (PET)	Silicon oxide	Activation energy↑	Deilmann et al. (2008a, b)
Dielectric barrier discharge (DBD)	3 min, atmospheric pressure	Polyethylene terephthalate/polypropylene (PET/PP)	Chitosan and various preservatives (sodium benzoate, potassium sorbate, calcium propionate)	Roughness↑, contact angle↓, antimicrobial activity↑	Lei et al. (2014)
Pulsed microwave plasma	7.6 Pa, O_2: hexamethyldisilazane (HMDSN) = 8:1–50:1	Polyethylene terephthalate (PET)	Nano-scale SiOx	Water vapor permeation↓	Plog et al. (2011)
Axially homogeneous plasma, Electron cyclotron resonance (ECR) plasma	1–100 Pa, 2.45 GHz, O_2: Hexamethyldisiloxane (HMDSO) = 20:1–25:1	Polypropylene (PP), Polyethylene terephthalate (PET)	SiOx	O_2 permeability↓	Joachim Schneider et al. (2007)
DBD	12.5 kV, 325 Hz	Polypropylene (PP)	Zinc oxide (ZnO)	Contact angle↓, roughness↑, antimicrobial activity↑	Paisoonsin et al. (2013)
Radio-frequency (Liu et al. 2000) discharge	Hexamethyldisiloxane (HMDSO): 1.5–3.5 sccm O_2: 50–110 sccm, 10–20 Pa, 1–50 MHz	Polycarbonate	SiOx	Thermal activation energy↑	Erlat et al. (2011)
DBD	15 kV, 350 Hz	Polyethylene (PE)	Chitosan	Roughness↑, oxygen-containing functional groups↑, antibacterial activity↑, contact angle↓	Theapsak et al. (2012)
Low-pressure plasma	27–54 Pa, 30–150 W, 13.56 MHz, Ar: 30 sccm	Organic (flat polycarbonate), inorganic (Si-c100 wafer)	Cu	Antimicrobial activity↑	De Vietro et al. (2017)

"↑" and "↓" represent the enhancement and decrease of the material properties, respectively nitrogen compounds are deposited on PET foil; this effectively reduces the water vapor transmission rate. The SiOx film deposited by O_2 and HMDSN (hexamethyldisilazane) improved the degree of cross-linking of PET foil and significantly reduced the porosity of the polymer (Plog et al. 2011). With further research on PECVD, it will be more conducive to develop high-barrier food packaging materials.

13.5 Effects of Cold Plasma on the Sterilization of Polymers

For processed foods without preservatives, sterile packaging materials are crucial to packaging. If the food packaging is not properly sterilized, it could cause microorganisms to contaminate the food from the packaging surface, thus, resulting in economic losses or health hazards to consumers. Conventional sterilization methods of packaging materials include dry heat, steam, ultraviolet light, irradiation, hydrogen peroxide, and ethylene oxide, or their combination thereof. However, according to the regulations of the US Food and Drug Administration (FDA), the concentration of residues on the packaging of chemical sterilants must be reduced to a minimum to prevent food from being spoiled or smelly due to chemical residues. It is also necessary to pay attention to whether chemical additive will chemically react with the polymer and resulting in an unknown impact on the packaged food (Deilmann et al. 2008a, b).

In contrast, the sterilization of packaging materials by plasma has become a research focus and has gradually become a substitute for chemical sterilization. Plasma sterilization is easy to operate and does not deposit chemical residues on the surface of packaging materials like chemical sterilization. Plasma is also suitable for the sterilization of heat-sensitive packaging materials (Lee et al. 2015). Plasma is employed for the sterilization of different kinds of polymers and maintains the functional properties of packaging materials (as shown in Table 13.3).

13.6 Conclusions

Polymer food packaging materials with specific barrier properties and antibacterial surfaces have increasingly attracted the attention of the food industry. This extends the shelf life of food, maintain food quality, and reduce economic losses. In this chapter, cold plasma has shown improvement in the surface wettability and surface roughness of polymer films and introduced reactive species onto polymer surfaces to enhance the functional properties and biological activity of the polymer films. The surface modification of the polymer is closely related to the plasma working gas, processing time, and other process parameters. After the plasma treatment, the surface of the polymer film was modified, and surface sterilization was achieved, thus ensuring sterile packaging materials. Therefore, as a modification technology of

Table 13.3 Effects of plasma on the surface sterilization of different polymers

Polymer	Microorganism	Plasma	Result	Reference
Polyethylene terephthalate (PET) foil	*B. subtilis*	Microwave plasma	4.4 log reduction after 30 s exposure	Schneider et al. (2005)
Glass, polyethylene (PE), polypropylene, nylon, paper foil	*Escherichia coli* O157: H7, *Staphylococcus aureus*, *E. coli* O157: H7, *S. aureus*, and *S. typhimurium*	Glow discharge	4.0 log reduction after 5 min exposure	Lee et al. (2015)
Glass slides, polyethylene (PE), polypropylene (PP), nylon, paper foil, parchment paper	*Escherichia coli* O157: H7, *Salmonella typhimurium*, *Staphylococcus aureus*	DBD	≥3.5 log reduction after 5 min exposure	Puligundla et al. (2016)
Polyethylene terephthalate (PET) bottles	*Bacillus atrophaeus*, *Aspergillus niger*	Microwave plasma	≥4.0 log reduction after 5 s exposure	Deilmann et al. (2008a, b)
Polyethylene terephthalate (PET), polystyrene, compound of PET, polyvinylidene chloride and polyethylene	*Bacillus atrophaeus* DSM 2277	DBD	5.0 log reduction after 5 s exposure	Muranyi et al. (2010)

food packaging materials, cold plasma modification technology will have a good application prospect that can satisfy food safety regulations.

References

Bogaerts A, Neyts E, Gijbels R et al (2002) Gas discharge plasmas and their applications. Spectrochim Acta B Atomic Spectrosc 57(4):609–658

Chu PK, Chen JY, Wang LP et al (2002) Plasma-surface modification of biomaterials. Mater Sci Eng R Rep 36(5):143–206

Cruz SA, Zanin M, Nascente PAP et al (2010) Superficial modification in recycled PET by plasma etching for food packaging. J Appl Polym Sci 115(5):2728–2733

Cui H, Bai M, Lin L (2018) Plasma-treated poly(ethylene oxide) nanofibers containing tea tree oil/ beta-cyclodextrin inclusion complex for antibacterial packaging. Carbohydr Polym 179:360–369

Cui H, Yang X, Abdel-Samie MA et al (2020) Cold plasma treated phlorotannin/Momordica charantia polysaccharide nanofiber for active food packaging. Carbohydr Polym 239:116214

De Vietro N, Conte A, Incoronato AL et al (2017) Aerosol-assisted low pressure plasma deposition of antimicrobial hybrid organic-inorganic Cu-composite thin films for food packaging applications. Innov Food Sci Emerg Technol 41:130–134

Deilmann M, Grabowski M, Theiß S et al (2008a) Permeation mechanisms of pulsed microwave plasma deposited silicon oxide films for food packaging applications. J Phys D Appl Phys 41 (13):135207

Deilmann M, Halfmann H, Bibinov N et al (2008b) Low-pressure microwave plasma sterilization of polyethylene terephthalate bottles. J Food Prot 71(10):2119–2123

Duncan TV (2011) Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. J Colloid Interface Sci 363(1):1–24

Erlat AG, Wang BC, Spontak RJ et al (2011) Morphology and gas barrier properties of thin SiOxcoatings on polycarbonate: correlations with plasma-enhanced chemical vapor deposition conditions. J Mater Res 15(3):704–717

Guillard V, Mauricio-Iglesias M, Gontard N (2010) Effect of novel food processing methods on packaging: structure, composition, and migration properties. Crit Rev Food Sci Nutr 50 (10):969–988

Honarvar Z, Farhoodi M, Khani MR et al (2017) Application of cold plasma to develop carboxymethyl cellulose-coated polypropylene films containing essential oil. Carbohydr Polym 176:1–10

Inagaki N, Narushim K, Tuchida N et al (2004) Surface characterization of plasma-modified poly (ethylene terephthalate) film surfaces. J Polym Sci B Polym Phys 42(20):3727–3740

Karam L, Jama C, Dhulster P et al (2013) Study of surface interactions between peptides, materials and bacteria for setting up antimicrobial surfaces and active food packaging. J Mater Environ Sci 4(5):798–821

Lee KT (2010) Quality and safety aspects of meat products as affected by various physical manipulations of packaging materials. Meat Sci 86(1):138–150

Lee T, Puligundla P, Mok C (2015) Inactivation of foodborne pathogens on the surfaces of different packaging materials using low-pressure air plasma. Food Control 51:149–155

Lei J, Yang L, Zhan Y et al (2014) Plasma treated polyethylene terephthalate/polypropylene films assembled with chitosan and various preservatives for antimicrobial food packaging. Colloids Surf B Biointerfaces 114:60–66

Liu G, Xiong YL, Butterfield DA (2000) Chemical, physical, and gel-forming properties of oxidized myofibrils and whey- and soy-protein isolates. J Food Sci 65(5):811–818

Mirabedini SM, Arabi H, Salem A et al (2007) Effect of low-pressure O_2 and Ar plasma treatments on the wettability and morphology of biaxial-oriented polypropylene (BOPP) film. Prog Org Coat 60(2):105–111

Muranyi P, Wunderlich J, Langowski HC (2010) Modification of bacterial structures by a low-temperature gas plasma and influence on packaging material. J Appl Microbiol 109 (6):1875–1885

Oh YA, Roh SH, Min SC (2016) Cold plasma treatments for improvement of the applicability of defatted soybean meal-based edible film in food packaging. Food Hydrocoll 58:150–159

Ozdemir M, Yurteri CU, Sadikoglu H (1999) Physical polymer surface modification methods and applications in food packaging polymers. Crit Rev Food Technol 39(5):457–477

Paisoonsin S, Pornsunthorntawee O, Rujiravanit R (2013) Preparation and characterization of ZnO-deposited DBD plasma-treated PP packaging film with antibacterial activities. Appl Surf Sci 273:824–835

Pankaj SK, Bueno-Ferrer C, Misra NN et al (2014a) Applications of cold plasma technology in food packaging. Trends Food Sci Technol 35(1):5–17

Pankaj SK, Bueno-Ferrer C, Misra NN et al (2014b) Characterization of polylactic acid films for food packaging as affected by dielectric barrier discharge atmospheric plasma. Innov Food Sci Emerg Technol 21:107–113

Plog S, Schneider J, Walker M et al (2011) Investigations of plasma polymerized SiOx barrier films for polymer food packaging. Surf Coat Technol 205:165–170

Puligundla P, Lee T, Mok C (2016) Inactivation effect of dielectric barrier discharge plasma against foodborne pathogens on the surfaces of different packaging materials. Innov Food Sci Emerg Technol 36:221–227

Romani VP, Olsen B, Pinto Collares M et al (2019) Improvement of fish protein films properties for food packaging through glow discharge plasma application. Food Hydrocoll 87:970–976

Schneider J, Baumgärtner KM, Feichtinger J et al (2005) Investigation of the practicability of low-pressure microwave plasmas in the sterilisation of food packaging materials at industrial level. Surf Coat Technol 200(1–4):962–966

Schneider J, Kiesler D, Leins M et al (2007) Development of plasma polymerised SiOx barriers on polymer films for food packaging applications. Plasma Process Polym 4(1):155–159

Shogren R (1997) Water vapor permeability of biodegradable polymers. J Environ Polym Degrad 5 (2):91–95

Song AY, Oh YA, Roh SH et al (2016) Cold oxygen plasma treatments for the improvement of the physicochemical and biodegradable properties of polylactic acid films for food packaging. J Food Sci 81(1):86–96

Suppakul P, Miltz J, Sonneveld K et al (2003) Active packaging technologies with an emphasis on antimicrobial packaging and its applications. J Food Sci 68(2):408–420

Surowsky B, Schlüter O, Knorr D (2014) Interactions of non-thermal atmospheric pressure plasma with solid and liquid food systems: a review. Food Eng Rev 7(2):82–108

Theapsak S, Watthanaphanit A, Rujiravanit R (2012) Preparation of chitosan-coated polyethylene packaging films by DBD plasma treatment. ACS Appl Mater Interfaces 4(5):2474–2482

Vartiainen J, Rättö M, Paulussen S (2005) Antimicrobial activity of glucose oxidase-immobilized plasma-activated polypropylene films. Packag Technol Sci 18(5):243–251