Antimicrobial Biomedical Materials: Engineering

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Abstract
The development of new antimicrobial treatments is an area of continuing research. This entry takes a bird's eye view on advances and focuses, in particular, on trends toward solvent-free chemistry by plasma-assisted coating deposition methods. General principles of antimicrobial and antifouling coatings are highlighted distinguishing between surface functionalization, chemical grafting, and coating deposition. The available technologies are mirrored against contemporary needs in demanding branches of industry in terms of costs, production speed, effectiveness, safety, and durability. The study shows large potential for new textile products and applications by plasma-assisted coating deposition, if process complexity, speed, coating flexibility, and precise control of leaching compounds can be achieved.

INTRODUCTION

While antimicrobial and antifouling surfaces have been searched for since early Phoenicians, the persistent research is illustrative for the complexity of this topic.[1] Industrial demands for materials with antibacterial coatings are intensively growing during last decades. One of the most promising areas of antibacterial materials applications is hospital use and health care. As biomedical devices and materials remain an essential part of the human health care, infections associated with such medical devices are responsible for at least 1.5–7.2% postoperational complications depending on the type of operational procedure.[2,3] The earliest and essential event in pathogenesis of a biomaterial-related infection is surface attachment of extracellular polysaccharides produced by microorganisms.[4] This roots the formation of a biofilm in which bacteria are sheltered from antibiotics and host body's innate defense system and eventually results in infections.[5,6] This poses significant health risk for patients and increased health-care costs through prolonged treatments. Moreover, due to the widespread use of biocides, prevalent antibacterial resistance has developed[7,8] often requiring new type of antibacterial materials. A promising strategy to overcome biofilm formation is the fabrication of materials with proper antimicrobial surfaces and controllable antibacterial effect, such as micropatterned surfaces,[9,10] surfaces with exposed chemical groups,[11,12] and surfaces with coatings incorporating antibiotics via novel physical and/or chemical methods.[13–15] The world leading strategy is considered to be the deposition of a thin layer of antibacterial coatings on top of materials such as nonwoven, fabrics, and plastics (bandages, material of catheters, wound textile, medical masks, etc.). Doing so, only the materials' surface will change while keeping the bulk properties unaffected. Many methods have been reported on the development of such antimicrobial surfaces. In general, two main strategies can be distinguished:[6]

1. "passive" nonfouling strategy
2. "active" antibacterial strategy

The former one is used to prevent attachment of bacteria on material surfaces by grafted polymer coatings or by designed micro-/nanopatterns.[16,17] On the other hand, the latter one aims to kill microorganisms on the material surface and in the surrounding biological environment by elution of antibacterial compounds from the materials.[12,18–21] A variety of promising methods focusing on one or combining both strategies have been purposed.[22] Conventional "wet" chemistry methods are available and are used on lab scale to produce desirable antibacterial materials. However, a number of drawbacks remain including high costs, the use of hazardous chemicals in large volumes, very low energy efficiency, and usually very specific to the substrate nature. All of which prevent the widespread implementation of these chemical methods in

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large-scale production of antibacterial surfaces, especially in biomedical sector where outstanding quality is one of the key requirements.

New developments in plasma-based methods for engineering of antibacterial materials is considered as a suitable and versatile approach transferable between a large range of different materials at a low temperature without any need of specific substrate or any chemical solvents. The plasma-assisted approach allows for very specific surface modifications of the materials by grafting chemical functionalities or by depositing nanometer thick coatings with high antibacterial efficiency. Among different antibacterial agents applied in plasma-based methods, nanoparticles of metals and oxides in size range of 5–200 nm have found to be very effective against bacteria and microorganisms. Metal compounds like silver (Ag and salts) or copper (Cu and salts), zinc (Zn), and some others are well known for intrinsic antimicrobial properties, and the release of metal ions is believed to be the main reason for their antibacterial activity.[19] Solvated Ag^{+}, Cu^{2+}, and others ions are highly active by binding to membrane proteins and inducing structural changes in the bacterial cell wall and DNA leading to distortion of the cell metabolism and eventually cell death.[23] Among them, Ag is the most investigated one. Due to their large surface-to-volume ratio and small size, silver nanoparticles (AgNPs) have raised as a new generation of antibacterials with diverse medical applications.[24] Unfortunately, the potential cytotoxicity and genotoxicity of nanoparticles obstruct practical applications in human body.[25–27] Considering the above concerns, it is important to fabricate new class of antibacterial surfaces with precise release of antibacterial constituents while confining the nanoparticle load firmly to the materials. In this way, the release of nanoparticles to the microenvironment is prevented. These novel materials combine the benefits of antibacterial properties and suppress the potential hazardous influence of the nanoparticles on human bodies.

This entry is focusing on low-temperature plasma at reduced or atmospheric pressure for manufacturing surfaces with high antibacterial activity for biomedical applications. Two strategies of production are considered: grafting and plasma deposition of thin films.

PLASMA GRAFTING AND DEPOSITION FOR ANTIMICROBIAL MATERIALS

Plasma processes can be applied at various levels to prevent biofilm formation and thus microorganisms attaching to the surface of, for example, medical tools. Plasma-assisted surface functionalization can result in anti-adhesive surfaces, while plasma grafting creates suitable grounds for subsequent (or simultaneous) attachment of antimicrobial compounds. In such methods, a monolayer of functional chemical groups is targeted. However, plasmas may also produce thin, confluent coatings. Also in this case, the prevention of biomolecule adhesion or controlled release of biocides is aimed at.[28] In addition, plasma treatment is evolving from "lab to fab" and, when applied properly, damage to the material surface is absent, even for sensitive substrates such as textiles.[29,30] Plasma treatments on textiles have been reported beneficial for a range of textile properties such as (among others) dye ability, wettability, and antimicrobial treatments.[31]

Plasma Grafting of Antibacterial Components

Anchoring or grafting antibacterial agents on the surface of substrates using wet chemical solution reactions have been discussed to enhance the efficiency of incorporation for long time. In general, a chemical pretreatment of the substrates is applied in order to introduce chemical groups such as amine groups[32,33] or sulfonated groups.[34] However, the low concentration of antibacterial agents (e.g., for AgNPs typically less than 2%) and weak bonds of the immobilization strongly affect the antibacterial efficiency of the biomedical substrates in chemical grafting. Additionally, wet methods are substrate specific, not applicable to plastics (or difficult to implement), not environmental friendly, and have to be adapted to treat textile materials like nonwoven and fabrics.

In order to counteract biofilm formation, initial attachment of proteins and polysaccharides can be prevented by creating super hydrophobic or super hydrophilic surfaces.[35–37] Although this may sound contradictory, both types of surfaces act in different manner to prevent microbial attachment. Using, for example, fluorinated carbons such as C_3F_8 and C_2F_6, the free surface energy is dramatically reduced to a level at which the biomolecules no longer stick to the surface.[38] Super hydrophilic surfaces strongly repel long-chain hydrocarbons, regularly found on organic molecules. Both have demonstrated feasibility with plasma grafting.[28]

Plasma has been widely used as a pretreatment step to activate or modify material surfaces, improving grafting efficiency or incorporating antibacterial components onto surfaces. Due to their natural antibacterial/antifungal properties, chitosan and its derivatives have been widely used in biomedical materials. Chang et al. used plasma pretreatment to promote grafting of chitosan on polyester fabrics to obtain antibacterial activity.[39] In their work, fabrics were pretreated by argon/oxygen (Ar/O_2) dielectric barrier discharge (DBD) plasma for surface activation, then exposed to atmosphere for further oxidization, and finally immersed in chitosan solvents for chitosan grafting. It was found that the modified fabrics not only exhibited strong antibacterial activity against *Bacillus subtilis* and *Staphylococcus aureus* but also improved biocompatibility with fibroblasts cells. Grafting of chitosan onto the surface of woven poly(ethylene terephthalate) (PET) materials and polyethylene (PE) films with air DBD and corona plasma pretreatments was reported.[40–42] Fig. 1 presents AFM

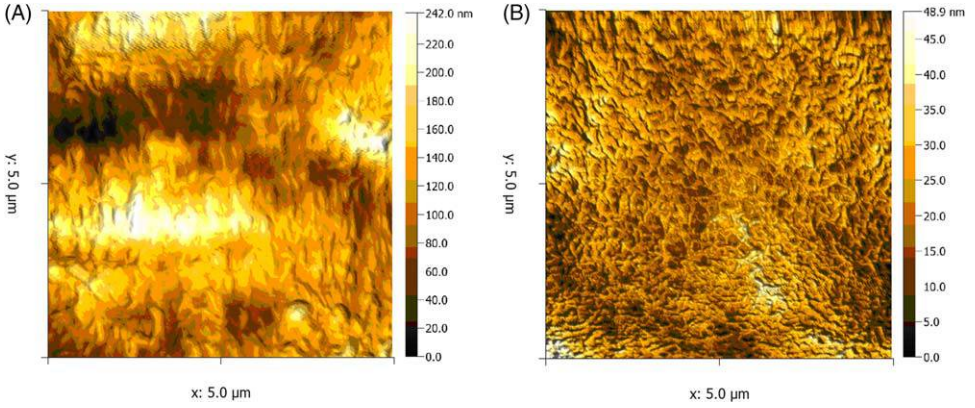

Fig. 1 AFM 2-D images of PE surface: (A) before plasma treatment and without chitosan deposition and (B) after plasma treatment and chitosan deposition.
Source: From Stoleru, Tsekov, et al.[42] ©2015 Wiley Periodicals Inc.

images of untreated and treated PE surfaces under different conditions. After plasma pretreatment, chitosan was successfully deposited on the PE surface (Fig. 1). The results further confirm the importance of plasma surface pretreatment. Similar to chitosan, having a dense loading of ammonia (NH_3) groups, quaternary NH_3 compounds (QACs) have been immobilized on surfaces via plasma deposition as well.[43–45] QACs are supposed to interact with the bacterial cell wall creating voids and thus depleting the bacterial cell.[46]

Many other natural compounds, like nisin peptides, thymol, and herbal extracts, have been grafted onto plasma-treated polymer surfaces to obtain antibacterial materials.[47–50] Three types of plasma pretreatment, namely nitrogen (N_2) plasma modification, Ar/O_2 plasma modification, and plasma-induced grafting of acrylic acid (AA), were used to incorporate nisin peptides onto the surface of low-density PE films.[47] It was found that nisin adsorption onto the surface was affected by many factors: type of surface, hydrophobic and hydrophilic interactions, surface charge, and surface topography. The antibacterial activity of nisin-functionalized films was dominated by distribution and amount of nisin on the surfaces. In general, samples with hydrophilic feature, low electrostatic surface charge, and/or granular structures showed stronger absorption capability of nisin and exhibited stronger antibacterial activities. One has to keep in mind that general antibacterial efficiency of surfaces should be considered as the combined effect of many factors instead of any single one. Duday et al. used plasma-polymerized organosilicon coatings as a reactive layer for the immobilization of nisin onto steel surfaces.[48] In addition to effective bacterial reduction, the organosilicon-based surfaces were also very stable under several cleaning conditions.

There has been growing interest in using metals as antimicrobial agents. In most cases, metal components like Ag, Cu, and zinc in form of ions, nanoparticles, microparticles, etc. are adopted because of their pronounced oligodynamic and biocidal activity. Ag-loaded cotton/polyester fabrics with antimicrobial activity were prepared by Kostic et al. by a two-step process: the raw fabrics were exposed to air DBD plasma for surface activation and then immersed into an aqueous silver nitrate ($AgNO_3$) solution for Ag sorption.[51] It was demonstrated that both treatment time and aging time strongly affected Ag^+ sorption of the fabrics. Maximum Ag sorption was found 7 days after plasma treatment of the fabrics. Antimicrobial activity of the Ag-loaded fabrics was determined after one or two washing cycles with laundry detergent. Despite of a slight decrease after the first washing cycle, antimicrobial activity of the Ag-loaded fabrics was stable afterward. This method was intended to be used in preparation of specific textiles like rubber footwear lining with antimicrobial activity and improved comfort. In addition, a similar method was used to prepare antimicrobial viscose fabrics with incorporation of Ag^+ or Cu^{2+} using $AgNO_3$ solution and copper sulfate ($CuSO_4$) solution, respectively.[52] It is interesting to note that water sorption of DBD-treated samples exhibited no change after 6 months. Sorption of Ag^+ increased up to 100% after 7 days of aging, whereas that of Cu^{2+} ions decreased with any further aging.

Due to large surface-to-volume ratio and small size, many metal or metal-based nanoparticles, such as AgNPs, Cu nanoparticles, gold nanoparticles, and zinc oxide nanoparticles, have emerged as a new generation of antibacterial agent for diverse applications.[53–56] Vu et al. incorporated AgNP onto the surfaces of polyamide 6.6 (PA) fabrics by a two-step process: raw fabrics were pretreated by an air DBD plasma for surface activation and then immersed into Ag particles dispersions for AgNPs incorporation.[53] It was confirmed that plasma pretreatment could remarkably increase dispersed AgNPs content on the fabrics surface.[57] Dispersions with three sizes of AgNPs (10, 20, and 50 nm) were prepared to study the effect of nanoparticles size on their adsorption in plasma pretreated PA fabrics. It was found that AgNPs in small size exhibited high adsorption in the fiber surfaces. In addition, AgNPs were also incorporated onto cotton textiles with help of tetrafluoromethane plasma pretreatment.[56] Plasma treatment preserved the color and mechanical properties of cotton textiles and stimulated adhesion of AgNPs on the fabric surface due to plasma etching effect. Taheri et al. developed a sophisticated method to obtain AgNP-based antibacterial

coatings, in which AgNPs were capped with mercaptosuccinic acid in solvent processes, and then grafted onto an allylamine plasma-polymerized surface.[58,59] It was shown that films exhibited no toxicity to primary fibroblast cells and no significant effect on innate immune cell function.

Comparative study of the effect of different plasma pretreatments, air DBD plasma pretreatment, and air diffuse coplanar surface barrier discharge (DCSBD) plasma pretreatment on incorporation of gold nanoparticles (AuNPs) to polypropylene (PP) nonwoven materials was carried out by Radic et al.[54] It was found that DCSBD plasma treatment introduced more hydrophilic functional groups, whereas DBD plasma treatment exhibited more pronounced morphology change of the surface. Compared to grafting of oxygenated functionalities, increase of roughness and "porosity" of the surface caused by stronger plasma etching was the main reason for a large impregnation of AuNPs on the samples.

Plasma Deposition of Antibacterial Films

In addition to plasma grafting where functional groups are produced on the substrate surface, plasma coating targets the formation of a confluent thin film covering the entire object. The active compound with respect to antimicrobial performance can be embedded in the film or be a conformal part of the film itself. The latter being exemplified by plasma sputtering of nano thin metal or metal oxide films in case of reactive sputtering. Here, the metal (or its oxide) itself will form the antimicrobial barrier.[60] In contrast to the coating material being antimicrobial, the surface structure may also exhibit interesting cell–surface interactions.[61]

Plasma sputtering in engineering of antibacterial coatings

One of most promising technologies for deposition of antibacterial coating on industrial scale is the plasma-assisted sputtering. Since energetic ions used generated in the plasma zone during sputtering (up to 50 eV), deposition of organic antibacterial films by this method is difficult and most of research has been focused on production of inorganic nanocomposites and combination of nanoparticles with organosilicon matrix. Deposition and antibacterial properties of Ag nanocomposite thin films based on an organosilicon matrix have been well studied by associating plasma polymerization and simultaneous Ag sputtering in a single-step process.[62–67] In the proposed method (Fig. 2A), an Ag radio-frequency (RF)-power electrode was subjected to Ar plasma as the source of AgNPs. The balance between Ag sputtering and plasma polymerization was monitored through a pulsed hexamethyldisiloxane (HMDSO) mass flow rate.[64] The Ag contents obtained under different plasma process conditions ranged between 0 and 32.5 atm.%. The film properties, such as Ag content, nanoparticle size, and matrix composition, were controlled

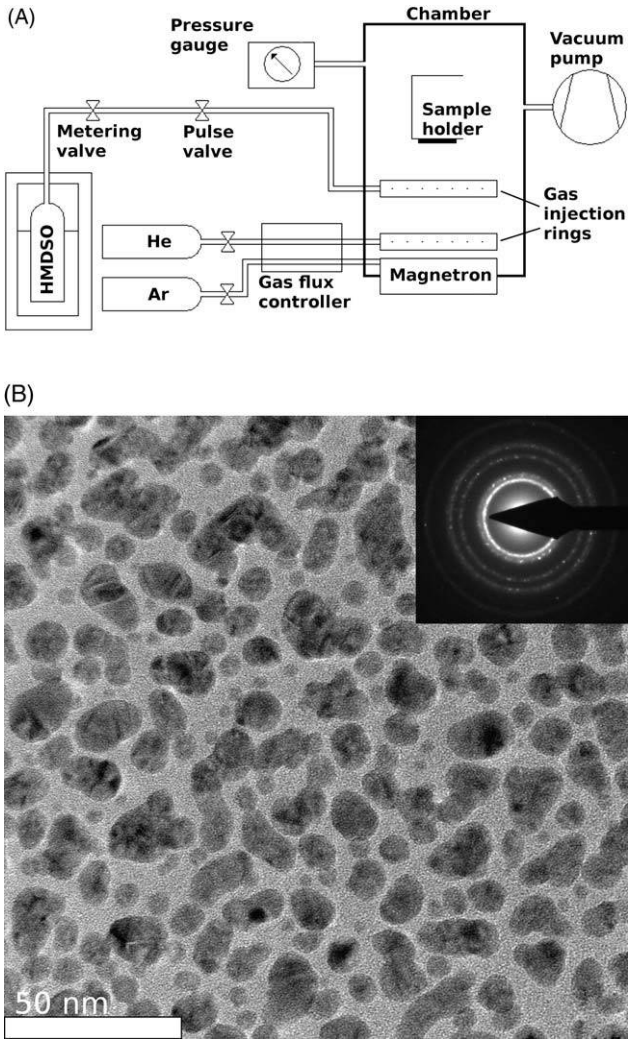

Fig. 2 Experimental setup for simultaneous plasma polymerization and Ag sputtering (A) and TEM image of nanocomposite materials high Ag volume fraction deposited on Cu grid. (B) Insertion on TEM image is a view of diffraction patterns.
Source: From Peter, Wegner, et al.[68] ©2011 Elsevier.

through processing parameters. Under certain operating conditions, Ag particles were homogeneously distributed inside the bulk matrix and presented as different volume fragments (see Fig. 2B).[62,65,68] Depending on the Ag concentration at the surface, the aging of the nanocomposite coatings in saline solution exhibited two different aging mechanisms: for the coating with low Ag content (7.5 atm.%), the amount of Ag decreased at the surface but the coating thickness did no change, whereas for the coating with high Ag content (20.3 atm.%), matrix erosion was observed with reducing Ag content.[67] The potential of anti-adhesive films was evaluated *in vitro* for the model yeast *Saccharomyces cerevisiae* by performing shear-flow-induced detachment experiments, under well-controlled hydrodynamic and physico-chemical conditions. The maximal effect was achieved for the organosilicon matrix alone. When AgNPs were incorporated, yeast detachment was

lower, probably due to the strong affinity of embedded Ag for biological components of the cell wall surface. The presence of methyl groups in the matrix network could also promote enhanced hydrophobic yeast/coating interactions. An antimicrobial action of Ag (conjugated effect of nanoparticles and chemisorbed Ag^+ and complexes released through nanoparticle oxidation) at the immediate vicinity of the coating surface occurred, depending on the Ag content.

Besides using organosilicon, hydrocarbons were also used as the matrix for the incorporation of AgNPs to obtain nanocomposite coatings by simultaneously Ag sputtering and plasma polymerization with carbon dioxide (CO_2)/ethylene (C_2H_4) or NH_3/C_2H_4 as gaseous monomers.[69–72] It was found that the Ag content, the AgNPs morphology, and Ag particles distribution in the matrix were dominated by parameters like power input into the plasma system, the gas ratio, and coating thickness.[69] Increasing CO_2/C_2H_4 ratios results in an increase of Ag content but with smaller particles size. On the other hand, a high power input results in increase of the incorporated Ag as well as in the size of the particles. The release kinetics of Ag from those coatings in deionized water was influenced by Ag content as well as by morphology and distribution of AgNPs. In general, the nanocomposite coatings released most bound Ag within the first day of immersion in water yielding an antibacterial burst. Moreover, the type of monomer mixture gas, CO_2/C_2H_4 and NH_3/C_2H_4, also led to different chemical properties and Ag release kinetic property of the nanocomposite coatings.[70] A high antibacterial effectiveness was achieved by tuning the polymer–Ag nanocomposite properties.

Other metals like Cu and platinum (Pt) were also used as sputtering electrode for the deposition of nanocomposite coatings.[73,74] Daniel et al. reported the synthesis of an antibacterial nanocomposite of Cu-containing organosilicon thin film on stainless steel using the mixed plasma-enhanced chemical vapor deposition-sputtering deposition technique.[73] It was found that the antimicrobial activity depended on the content of incorporated Cu in the nanocomposite coatings.

Direct plasma deposition of antibacterial coatings

Plasma deposition of organic coatings is characterized by a polymerization process initiated in the discharge. Therefore, gaseous, vaporized, or atomized precursor molecules are injected in the discharge zone. Polymerization is initiated by radicals from the discharge, and the coating is deposited on the surface of the substrate.[75] This technology has been deployed successfully for depositing nonadhesive coatings for antimicrobial purposes. Brush-like PEG hydrophilic surfaces and fluorocarbon-based hydrophobic treatments have been developed.[28] In addition to inherently bioactive coatings, plasma also allows for the deposition of a very thin matrix in which a bioactive component is trapped. In this case, it is clear that some mobility of the antimicrobial product is required to be active at the surface. Such coatings can be deposited via simultaneous addition of both precursor and antimicrobial to the discharge. Such slow release coatings have been used for antifouling purposes using, for example, poly(butyl)methacrylate, diethylene glycol dimethyl ether, or poly(ethylene)oxide as matrix and antibiotics, Ag, or triclosan as bioactive compound. To gain better control over release kinetics and better entrapment of the active molecules, additional post plasma coatings can be added.[28]

Since the chemical structure of organic antibacterial agents can be strongly affected by plasma, other plasma deposition methods for antibacterial coating deposition were applied through the production of thin films containing certain type of nanoparticles.[76] Stability of nanoparticles during plasma deposition is a key to success. Most of plasma-assisted methods of direct deposition are developed through the use of atmospheric pressure plasma sources whereas low-pressure plasma sources are mostly used for sputtering described in previous section. Beier et al. deposited antibacterial and abrasive-wear-resistant AgNP-contained nanocomposite coatings using an atmospheric pressure plasma jet process.[77] These films were deposited onto glass surface using an ambient air plasma jet system with HMDSO as the organosilicon precursor and spraying an optimized $AgNO_3$ solution into the plasma jet for the *in situ* formation of AgNPs in plasma. It was shown that, instead of silver oxide, mainly pure AgNPs were created inside the plasma. They also confirmed the incorporation of different Ag particles with size up to 100 nm. Washing tests indicated a burst removal of surface-bound particles at the first few washing cycles followed by a diffusion process of Ag^+, which contributed to long-term antibacterial activity even after repeated washing.

Deng et al. developed a novel, dry, one-step process using atmospheric pressure plasma jet for the deposition of nanocomposite thin films with high concentration of AgNPs.[78] An atmospheric pressure DC plasma jet, which consists of a pin-to-mesh electrode in a quartz tube, was used as the plasma source. AgNPs were provided by a feeding module and introduced into the process by the passing N_2. It was shown that control of morphology of AgNPs in the films could be achieved by varying the feeding rate of AgNPs. Ag content in the films was controlled from few percent to more than 30%. When AgNPs were introduced, they were oxidized by atomic O formed in the plasma and concurrently tetramethyldisiloxane fragments recombined on their surface which results into the film growth directly on AgNPs. Surface coating of AgNPs had a number of imperfections (cracks, pores, and open places), hence the release of Ag^+ was possible from the films by controlling the process through changing the deposition parameters. Two parameters were expected to

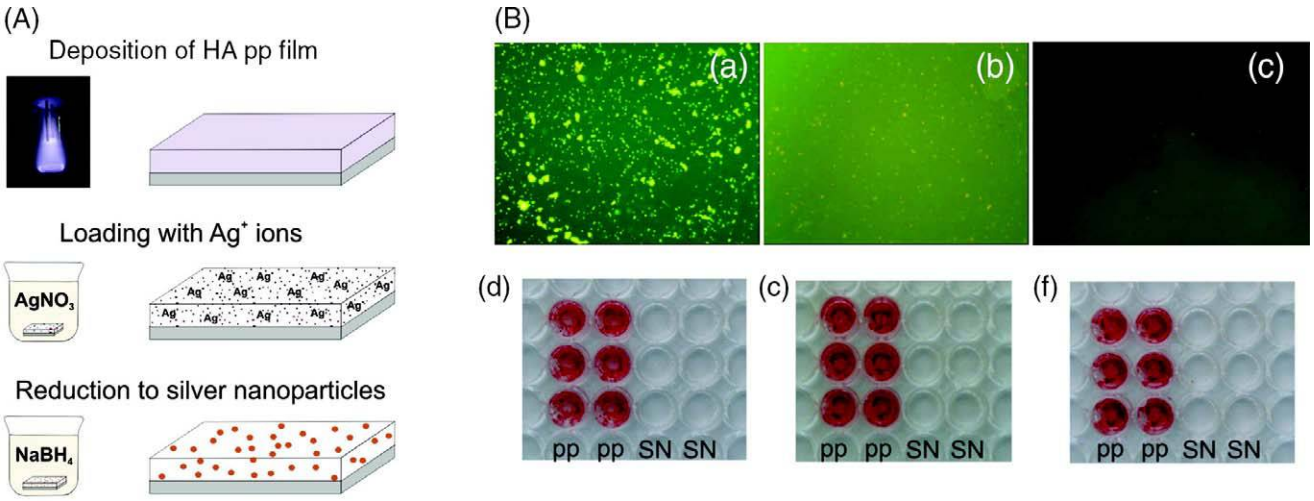

Fig. 3 (A) The experimental steps for the fabrication of AgNPs within amine plasma polymer films and structural scheme of nanocomposite film, (B) *Staphylococcus epidermidis* adhesion and colonization after 4 hours on (a) HApp only (no Ag), (b) HA film loaded with AgNPs, and (c) HA film loaded with AgNPs and covered with an additional layer 6 nm thick of HApp. Biofilm formation after 24 hours on samples loaded with AgNPs covered with an additional layer of HApp of (d) 6 nm, (e) 12 nm, and (f) 18 nm thickness.
Source: From Armentano, Arciola, et al.[79] ©2014 ACS Publications.

significantly affect the imperfections in the coatings of AgNPs: the total gas flow and the plasma discharge power. Antibacterial assays of films performed by macrodilution using *Escherichia coli* and *S. aureus* strains have demonstrated high antibacterial activity of deposited coatings.

Another type of nanocomposite coatings based on a multilayer concept, mostly with three layers as a sandwich structure, has been reported by many groups. In such approach, antibiotic nanoparticles are enclosed between two polymer layers. Vasilev et al. developed a tunable antibacterial triple-layer coating based on amine plasma polymer films loaded with AgNPs.[79] The experimental strategy for the generation of AgNPs within n-heptylamine plasma polymer (HApp) films employed is shown in Fig. 3A. Firstly, a 100-nm thick HApp film was deposited on substrates, which was placed into $AgNO_3$ solution in order to load with Ag^+. Reduction of Ag^+ to metallic Ag was subsequently achieved by immersion of samples in a solution of sodium borohydride. Finally another thin layer of HA polymers was deposited on the top of the film loaded with AgNPs (Fig. 3A). The amount of loaded AgNPs was influenced by the time of immersion in $AgNO_3$ solution, the reduction time, and the thickness of the first HA polymer. The authors found that the Ag^+ diffusion kinetics could be controlled by the second HA polymer layer and was able to completely inhibit bacterial colonization (Fig. 3B).

Besides HA polymer, polymers like polytetrafluoroethylene (PTEE) and organosilicon have also been used to obtain multilayer nanocomposite coatings. Alissawi et al. deposited two layers of PTEE coatings to immobilized AgNPs, which was deposited on the top of first layer by thermal evaporation from an alumina crucible.[80] Due to the hydrophobic property of PTEE, the second layer (also known as barrier layer) on the sample exhibited an insufficient water uptake for a high Ag^+ release. Later, they used plasma-polymerized HMDSO coatings as the barrier layer for nanocomposite films.[64] The water uptake property of nanocomposite films was strongly depending on the property of HMDSO coatings and thickness. In general, a high Ag^+ release occurs for hydrophilic thin films deposited with more O_2 during plasma polymerization. On the other hand, increasing the thickness of HMDSO-based barrier layer reduced the amount and release rate of Ag^+. AgNPs can also be immobilized on many surfaces via a double layer of plasma-polymerized organosilicon films.[81] The nanocomposite films were prepared using a three-step procedure, as shown in Fig. 4A. At first, an organosilicon thin film was deposited using a plasma jet deposition system. This 70 nm layer is used as a reservoir layer for the Ag immobilization and to control the AgNPs adhesion to the surface. In the following steps, the samples with the plasma-polymerized layer on top were immersed into a suspension of AgNPs in ethanol and raised for drying. In the final step of the process, a second layer of organosilicon film was deposited using the plasma jet system. This second layer is used as a barrier to prevent the release of AgNPs. The antimicrobial properties of the samples were tested against *Pseudomonas aeruginosa*, *S. aureus*, and *Candida albicans*, as shown in Fig. 4B. Samples with a 70-nm organosilicon film having no antimicrobial activity were used as a control. For the sample without the barrier layer, AgNPs on the materials have sufficient contact with the medium. Therefore, they can provide a fast release of Ag^+ into the medium and exhibit the strongest antimicrobial activity against

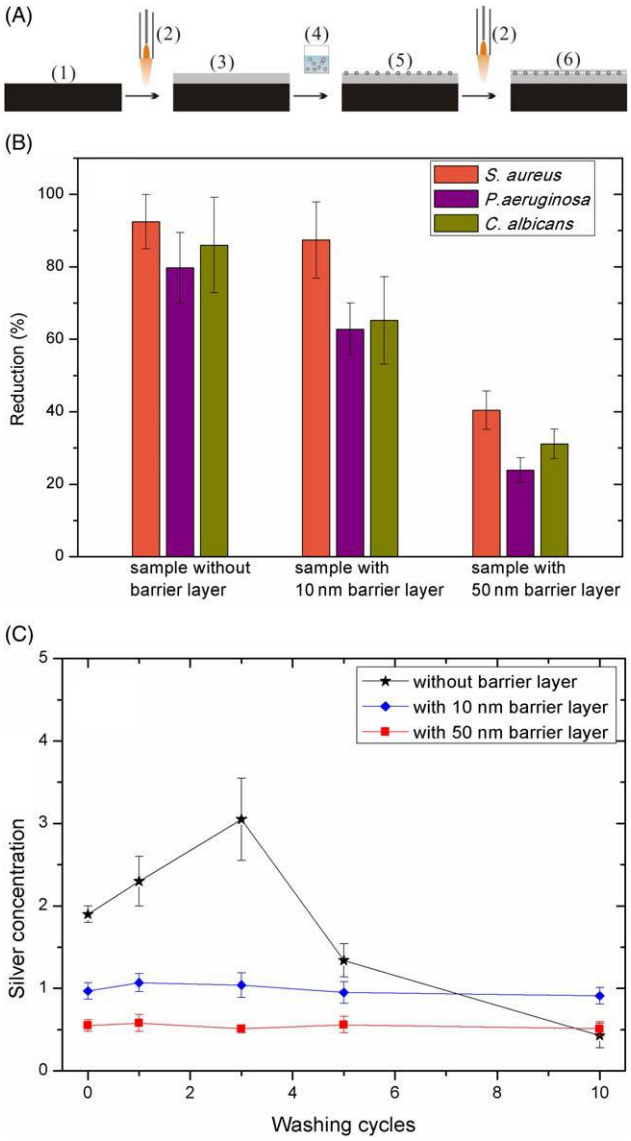

Fig. 4 (A) Immobilization on various surfaces via a double layer of plasma-polymerized organosilicon films. (B) Antimicrobial activity against three microorganisms. (C) Ag concentration of the samples after several washing cycles.
Source: From Xiaolong, Yu Nikiforov, et al.[81] ©2015 Nature.

microorganisms. When a barrier film is deposited, the direct contact between AgNPs and the medium is hampered and the release of Ag^+ from AgNPs is reduced. In this case, the Ag^+ release is only possible through small cracks and pores in the barrier layer. Moreover, the thickness of the barrier layer significantly influences the antimicrobial efficiency.[81,82]

The durability of incorporated AgNPs in the materials was evaluated through a washing test of the samples after 1, 3, 5, and 10 washing cycles for 40 minutes each in a 200 ml of deionized water. Fig. 4C shows Ag concentration on the top surface of three different samples after several washing cycles. In samples without barrier layer, Ag exhibits nonuniform kinetics of release at the first five washing cycles demonstrating high durability of the coatings with the barrier layer.

CONCLUSION

Engineering of novel materials with high antibacterial efficiency is extremely fast growing field of science and technology. Among considerable progress on lab scale, a shear number of technological boundaries remain such as substrate specificity, durability, ease of application, efficiency, broad spectrum, environmental safety, and, public concern about nanomaterials. Although a large number of demonstrated effective treatments are available, available methods suffer from complex and multistep processes, the use of toxic compounds, excessive leaching or slow but finite release, wet chemistry, or rigid matrixes. In particular for textiles, low-cost, flexible coatings and durable treatments are prerequisite for industrial implementation. Using plasma technology, energy and chemical resources can be limited, while very thin layers of well-bound coatings can be deposited. The effectiveness of plasma treatment for developing antimicrobial textiles has been proven and the challenge is to extend this technology toward industry. However, obstacles such as coating flexibility, ease of implantation in medical materials, production, and processing speed need to be tackled in order to pave the way for a new generation of antibacterial products.

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