

Description

Title of Invention: Antimicrobial Coating

Technical Field

- 5 The present invention relates to a polymer and a method of using the polymer to form a stable and durable coating that provides good contact-active antimicrobial property which is safe for human usage. The present invention also relates to an article comprising the polymer.

Background Art

- 10 Rising antimicrobial resistance is a concerning issue worldwide impacting both health and the economy. Traditional use of antimicrobial agents like antibiotics has become less sustainable pushing the need to develop more effective antimicrobial strategies. Generally, man-made surfaces do not resist microorganism growth. As such, once microbes attach onto surfaces, they would quickly colonize and form a biofilm. Biofilm formation greatly increases microbe virulence by blocking out biocides and making subsequent treatment of infection difficult. The
- 15 use of antimicrobial coating on inanimate surfaces has gained recent interest. Not only does an antimicrobial coating overcome the need for disinfectants to diffuse to the site of action, they also eliminate the conscious effort to reduce surface microbial load. More importantly, antimicrobial coatings could possibly eliminate the problem at the source by preventing bacterial adhesion. Current research in this field aims at developing polymeric coating not only
- 20 with antimicrobial activities but also enhanced durability and stability, better biocompatibility, and microbes repelling (antifouling) abilities.

- Antimicrobial polymers can be classified into two broad categories: Biocide-releasing polymer and contact active polymers. Biocide-releasing polymers have very well established biocides such as antibiotics, chlorhexidine or metal ions attached to the polymers. After coating, these
- 25 biocides will leach out in a rate-limited fashion to exert the antimicrobial effects. These functionalized antimicrobial polymers work very well but are limited by inconsistent release rate, exhaustive biocides and environmental contamination. In contrast, contact active polymers kill microbes purely by physical interaction without leaching of bioactive components. Since nothing is leached, contact-active polymers are independent of release rate and are theoretically
- 30 non-exhaustive. Several contact-active polymers such as naturally derived chitosan polysaccharides and antimicrobial peptides have been researched. However, these naturally derived substances are sensitive to pH and hydrolytic enzymes in the environment.

In addition, the field of antimicrobial coatings also faces difficulties in the technology to fabricate polymer coatings. Currently grafting is done chemically using elaborate methods such

as layer-by-layer deposition that are suitable for laboratory research but not practical when the process is scaled up.

There is therefore a need to provide an antimicrobial coating that overcomes or at least ameliorates, one or more of the disadvantages described above.

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Summary

In an aspect, there is provided a polymer having a plurality of pendant groups, wherein the pendant groups comprise: a first pendant group comprising a quaternary ammonium component having the following formula: $-R^1-(CH_2)_n-[N^+(R^2)(R^3)(R^4)](X^-)$; wherein n is any integer from 1 to 18; R^1 is $C(O)O$ or $C(O)NH$; R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or R^2 and R^3 are taken together to form a ring and R^4 is H or absent; and X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and a second pendant group comprising an organosilane component, provided that there are no other pendant groups in the polymer.

In another aspect, there is provided a polymer having a plurality of pendant groups, wherein the pendant groups consists of: a first pendant group comprising a quaternary ammonium component having the following formula: $-R^1-(CH_2)_n-[N^+(R^2)(R^3)(R^4)](X^-)$ wherein n is any integer from 1 to 18; R^1 is $C(O)O$ or $C(O)NH$; R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or R^2 and R^3 are taken together to form a ring and R^4 is H or absent; and X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and a second pendant group comprising an organosilane component.

Advantageously, the polymer of the present disclosure is a more durable, stable and contact-active antimicrobial coating. In an embodiment, the polymer of the present disclosure comprises an antimicrobial quaternary ammonium compound moiety and an anchoring alkoxy silane functional group. Consisting of a permanent positive charge on the quaternary nitrogen, the polymer may attach itself via electrostatic attraction onto negatively charged microbial surfaces, such as bacteria. This attachment may impair the microbe's physiological functions by causing the microbe to lose electrical balance, destroying the cell membrane and ultimately leading to cell death. Additionally, the quaternary ammonium compound may insert its hydrophobic alkyl tail in to the cell cytoplasmic membrane where the hydrophobic interaction increases surface pressure and further disrupts cell membrane fluidity to cause cell death.

Further advantageously, the alkoxy silane functional group may be hydrolysed into reactive silanol that may cross-link with other silanol groups on substrate surfaces via condensation reactions. This may allow alkoxy silane-containing molecules to adhere covalently onto the surface via a siloxane bond. Siloxane bond cross-linking using the polymer of the present disclosure may be applied in a variety of materials including rubber, cotton or steel on top of silica-rich materials. Further advantageously, the polymer of the present disclosure is less sensitive to pH or inactivating enzymes as it is a synthetic molecule with a permanent charge.

Quaternary Ammonium Silanes (QAS), particularly dimethyloctadecyl[3-(trimethoxysilyl)propyl]ammonium chloride (DTPAC), has been extensively researched. DTPAC is a monomeric QAS that has been used in many coating applications. DTPAC coated medical devices have shown good *in-vitro* and *in-vivo* antimicrobial activities. DTPAC has the quaternary ammonium compound moiety and the alkoxy silane moiety on the same pendant group.

Unlike DTPAC, the polymer of the present disclosure has the alkoxy silane and quaternary ammonium compound moiety separated on two separate pendant groups on the polymer. The polymer is synthesized by reacting two methacrylate-containing monomers, one containing the quaternary ammonium compound moiety and the other containing the alkoxy silane moiety, by free radical polymerization. Advantageously, since the two reactive moieties are on two separate pendant groups, it gives flexibility in polymer design. That is, the amount of alkoxy silane relative to the amount of quaternary ammonium compound moiety may be easily adjusted to optimise the property of the polymer.

Advantageously, the polymer of the present disclosure may contain, for example, 10 wt% of the anchoring alkoxy silane moiety whereas the antimicrobial quaternary ammonium component (QAC) may occupy the remaining 90 wt%. Further advantageously, the polymer of the present disclosure may have better coating efficacy, stability, contact-active antimicrobial activity, cytotoxicity and physical and functional durability compared to conventional antimicrobial QAS polymers such as DTPAC.

Further advantageously, the polymer of the present disclosure may be substantially free from any other pendant groups apart from the first pendant group comprising the quaternary ammonium component and the second pendant group comprising the organosilane component. That is, the polymer may substantially consist only of the first pendant group comprising the quaternary ammonium component and the second pendant group comprising the organosilane component. By substantially only having the first pendant group and the second pendant group, the polymer may have high antimicrobial performance, as the effectiveness of each pendant group is not compromised by the presence of additional pendant groups. That is, the maximum effectiveness of the properties of the first pendant group comprising the quaternary ammonium component (antimicrobial) and the second pendant group comprising the organosilane component (anchoring) may be achieved by not having additional pendant groups present in the polymer.

More advantageously, the polymer of the present disclosure may have durable and long-lasting antimicrobial properties that are superior to conventional antimicrobial agents such as DTPAC, even without the presence of additional pendant groups which may confer additional functionality to the polymer such as hydrophobicity.

In another aspect, there is provided a method for preparing a polymer according to any one of claims 1 to 19, comprising the steps of contacting a first monomer with a second monomer in conditions suitable for polymerization, wherein a first monomer comprising a quaternary ammonium component having the following formula: $-R^1-(CH_2)_n-[N^+(R^2)(R^3)(R^4)](X^-)$ wherein

n is any integer from 1 to 18; R¹ is C(O)O or C(O)NH; R², R³ and R⁴ are each independently an optionally substituted alkyl, optionally substituted aryl, or R² and R³ are taken together to form a ring and R⁴ is H or absent; and X is selected from the group consisting of Cl, Br, I and OSO₃CH₃; and a second monomer comprising an organosilane component, provided that no other monomer is contacted with the first and second monomer in the polymer.

Advantageously, the polymer of the present disclosure may contain, for example, 90 wt% of the first monomer comprising a quaternary ammonium component, and 10 wt% of the second monomer comprising a organosilane component. Advantageously, this may allow for maximum antimicrobial efficacy by the quaternary ammonium component while maintaining sufficient anchoring of the polymer to a substrate via the organosilane component.

In another aspect, there is provided a polymer obtainable by the method as defined above.

In another aspect, there is provided an article comprising the polymer as defined above and a substrate comprising a surface.

Advantageously, the article comprising the polymer as defined above may also have all the same advantages conferred by the polymer as defined above.

In another aspect, there is provided a method for preparing the article as defined above, comprising the steps of: forming the polymer as defined above; and contacting the polymer with the surface of the substrate under conditions suitable to adhere the polymer to the surface of the substrate.

Advantageously, the use of a direct coating method using alkoxysilane may eliminate the need for elaborated coating procedures.

In an embodiment, the method may comprise the step of pre-treating the surface of the substrate prior to the contacting step, wherein the pre-treatment step comprises plasma cleaning. Advantageously, plasma cleaning may change the surface property, for example, by increasing the surface energy and roughness of the substrate, to facilitate adhesion of the polymer.

Another aspect of the invention relates to the use of the polymers according to the invention as surface coatings.

Definitions

The following words and terms used herein shall have the meaning indicated:

The term “antimicrobial” refers to material that kills microorganisms or inhibits their growth.

The term “pendant group” refers to a group that is not part of the main backbone chain of the polymer.

The term “silane” refers to a compound having four groups attached to a silicon atom. That is, the silane has a silicon-containing group.

The term “alkoxysilyl” refers to a silicon-containing group having an alkoxy group bonded directly to the silicon atom. The alkoxysilyl may be, for example, of formula —
 5 $\text{Si}(\text{OR})(\text{Rx})_2$ where R is an alkyl and each Rx is independently a hydroxyl, alkoxy, alkyl, perfluoroalkyl, aryl, aralkyl, or part of a silicone.

The term “ester equivalent” means groups such as silane amides ($\text{RNR}'\text{Si}$), silane alkanoates ($\text{RC}(\text{O})\text{OSi}$), $\text{Si}-\text{O}-\text{Si}$, $\text{SiN}(\text{R})-\text{Si}$, SiSR and $\text{RCNR}'\text{Si}$ that are thermally and/or catalytically displaceable by $\text{R}''\text{OH}$. R and R' are independently chosen and may include
 10 hydrogen, alkyl, arylalkyl, alkenyl, alkynyl, cycloalkyl, and substituted analogs such as alkoxyalkyl, aminoalkyl, and alkylaminoalkyl. R'' may be the same as R and R' except it may not be H.

The term “hydroxysilyl” refers to a silicon-containing group having a hydroxyl group bonded directly to the silicon atom. The hydroxysilyl may be, for example, of formula —
 15 $\text{Si}(\text{OH})(\text{Rx})_2$ where Rx is an alkyl, perfluoroalkyl, aryl, aralkyl, alkoxy, hydroxyl, or part of a silicone. A compound having a hydroxysilyl group is often referred to as a “silanol”. Silanols are a subset of silanes.

The term “silicone” or “siloxane” refers to a moiety that contains a silicon-oxygen-silicon linkage group. Any other suitable groups may be attached to the silicon atoms. Such a
 20 linkage may result from the reaction of a first silane (e.g., a first silicon-containing group such as a first alkoxysilyl group or hydroxysilyl group) with a second silane (e.g., a second silicon-containing group such as a second alkoxysilyl group or hydroxysilyl group). In some embodiments, the silicone is part of a “silicone network”. A silicone network results when a first silane (i.e., a first silicon-containing group) reacts with a second silane (e.g., a second
 25 silicon-containing group) plus a third silane (e.g., a third silicon-containing group such as a third alkoxysilyl group or hydroxysilyl group) or when a first silane (e.g., a first silicon-containing group) reacts with a second silane (e.g., a second silicon-containing group) plus a third silane (e.g., a third silicon-containing group) and a fourth silane (e.g., a fourth silicon-containing group such as a fourth alkoxysilyl group or hydroxysilyl group).

As used herein, the phrases “polymeric material with a plurality of pendant groups”, “polymeric material with multiple pendant groups”, or similar phrases are used interchangeably to refer to a polymeric material that has only two different types of pendant groups. The multiple pendant groups include (1) a first pendant group containing a quaternary ammonium group; and (2) a second pendant group containing an organosilane group. The polymeric material may be
 30 crosslinked through a condensation reaction of multiple organosilane groups. Furthermore, the polymeric material may be covalently coupled to a surface comprising a metal hydroxide group such as a silanol group or, preferably, a plurality of silanol groups.

As used herein the term “non-leaching” means that the antimicrobial composition does not substantially diffuse out of or away from the polymer-coated composition while in contact with

an aqueous liquid, as measured by the Antimicrobial Leaching Test Procedure described hereinbelow.

In the definitions of a number of substituents below it is stated that "the group may be a terminal group or a bridging group". This is intended to signify that the use of the term is intended to encompass the situation where the group is a linker between two other portions of the molecule as well as where it is a terminal moiety. Using the term alkyl as an example, some publications would use the term "alkylene" for a bridging group and hence in these other publications there is a distinction between the terms "alkyl" (terminal group) and "alkylene" (bridging group). In the present application no such distinction is made and most groups may be either a bridging group or a terminal group.

"Alkyl" as a group or part of a group refers to a straight or branched aliphatic hydrocarbon group, preferably a C₁-C₁₂ alkyl, more preferably a C₁-C₁₀ alkyl, most preferably C₁-C₆ unless otherwise noted. Examples of suitable straight and branched C₁-C₆ alkyl substituents include methyl, ethyl, n-propyl, 2-propyl, n-butyl, sec-butyl, t-butyl, hexyl, and the like. The group may be a terminal group or a bridging group.

"Alkyloxy" refers to an alkyl-O- group in which alkyl is as defined herein. Preferably the alkyloxy is a C₁-C₆alkyloxy. Examples include, but are not limited to, methoxy and ethoxy. The group may be a terminal group or a bridging group.

"Aryl" as a group or part of a group denotes (i) an optionally substituted monocyclic, or fused polycyclic, aromatic carbocycle (ring structure having ring atoms that are all carbon) preferably having from 5 to 12 atoms per ring. Examples of aryl groups include phenyl, naphthyl, and the like; (ii) an optionally substituted partially saturated bicyclic aromatic carbocyclic moiety in which a phenyl and a C₅₋₇ cycloalkyl or C₅₋₇ cycloalkenyl group are fused together to form a cyclic structure, such as tetrahydronaphthyl, indenyl or indanyl. The group may be a terminal group or a bridging group. Typically an aryl group is a C₆-C₁₈ aryl group.

The term "optionally substituted" as used herein means the group to which this term refers may be unsubstituted, or may be substituted with one or more groups independently selected from alkyl, alkenyl, alkynyl, cycloalkyl, cycloalkylalkyl, cycloalkenyl, cycloalkylalkenyl, heterocycloalkyl, cycloalkylheteroalkyl, cycloalkyloxy, cycloalkenyloxy, cycloamino, halo, carboxyl, haloalkyl, haloalkynyl, alkynyloxy, heteroalkyl, heteroalkyloxy, hydroxyl, hydroxyalkyl, alkoxy, alkenyloxy, nitro, amino, alkylamino, dialkylamino, alkenylamine, aminoalkyl, alkynylamino, acyl, alkyloxy, alkyloxyalkyl, alkyloxyaryl, alkyloxycarbonyl, alkyloxcycloalkyl, alkyloxyheteroaryl, alkyloxyheterocycloalkyl, acylamino, alkylsulfonyloxy, heterocyclic, heterocycloalkenyl, heterocycloalkyl, heterocycloalkylalkyl, heterocycloalkylalkenyl, heterocycloalkylheteroalkyl, heterocycloalkyloxy, heterocycloalkenyloxy, heterocycloamino, haloheterocycloalkyl, alkylsulfinyl, alkylsulfonyl, aminosulfonyl, sulfinyl, sulfinylamino, sulfonyl, sulfonylamino, aryl, heteroaryl, heteroarylalkyl, heteroarylalkenyl, heteroarylheteroalkyl, heteroarylamino, heteroaryloxy,

arylalkenyl, arylalkyl, aryloxy, arylsulfonyl, cyano, cyanate, isocyanate, $-C(O)NH(alkyl)$, and $-C(O)N(alkyl)_2$.

"Acyl" means an $R-C(=O)-$ group in which the R group may be an optionally substituted alkyl, optionally substituted cycloalkyl, optionally substituted heterocycloalkyl, optionally substituted aryl or optionally substituted heteroaryl group as defined herein. Examples of acyl include acetyl, benzoyl and amino acid derived aminoacyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the carbonyl carbon.

"Acylamino" means an $R-C(=O)-NH-$ group in which the R group may be an alkyl, cycloalkyl, heterocycloalkyl; aryl or heteroaryl group as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

"Alkenyl" as a group or part of a group denotes an aliphatic hydrocarbon group containing at least one carbon-carbon double bond and which may be straight or branched preferably having 2-12 carbon atoms, more preferably 2-10 carbon atoms, most preferably 2-6 carbon atoms, in the normal chain. The group may contain a plurality of double bonds in the normal chain and the orientation about each is independently E or Z. Exemplary alkenyl groups include, but are not limited to, ethenyl, propenyl, butenyl, pentenyl, hexenyl, heptenyl, octenyl and nonenyl. The group may be a terminal group or a bridging group.

"Alkenyloxy" refers to an $alkenyl-O-$ group in which alkenyl is as defined herein. Preferred alkenyloxy groups are C_1-C_6 alkenyloxy groups. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

"Alkylamino" includes both mono-alkylamino and dialkylamino, unless specified. "Mono-alkylamino" means a $Alkyl-NH-$ group, in which alkyl is as defined herein. "Dialkylamino" means a $(alkyl)_2N-$ group, in which each alkyl may be the same or different and are each as defined herein for alkyl. The alkyl group is preferably a C_1-C_6 alkyl group. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

"Alkylaminocarbonyl" refers to a group of the formula $(Alkyl)_x(H)_yNC(=O)-$ in which alkyl is as defined herein, x is 1 or 2, and the sum of $X+Y=2$. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the carbonyl carbon.

"Alkyloxyalkyl" refers to an $alkyloxy-alkyl-$ group in which the alkyloxy and alkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

"Alkyloxyary" refers to an alkyloxy-aryl- group in which the alkyloxy and aryl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the aryl group.

5 "Alkyloxycarbonyl" refers to an alkyl-O-C(=O)- group in which alkyl is as defined herein. The alkyl group is preferably a C₁-C₆ alkyl group. Examples include, but are not limited to, methoxycarbonyl and ethoxycarbonyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the carbonyl carbon.

10 "Alkyloxycycloalkyl" refers to an alkyloxy-cycloalkyl- group in which the alkyloxy and cycloalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the cycloalkyl group.

15 "Alkyloxyheteroaryl" refers to an alkyloxy-heteroaryl- group in which the alkyloxy and heteroaryl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the heteroaryl group.

20 "Alkyloxyheterocycloalkyl" refers to an alkyloxy-heterocycloalkyl- group in which the alkyloxy and heterocycloalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the heterocycloalkyl group.

25 "Alkylsulfinyl" means an alkyl-S(=O)- group in which alkyl is as defined herein. The alkyl group is preferably a C₁-C₆ alkyl group. Exemplary alkylsulfinyl groups include, but not limited to, methylsulfinyl and ethylsulfinyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

"Alkylsulfonyl" refers to an alkyl-S(=O)₂- group in which alkyl is as defined above. The alkyl group is preferably a C₁-C₆ alkyl group. Examples include, but not limited to methylsulfonyl and ethylsulfonyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

30 "Alkynyl" as a group or part of a group means an aliphatic hydrocarbon group containing a carbon-carbon triple bond and which may be straight or branched preferably having from 2-12 carbon atoms, more preferably 2-10 carbon atoms, more preferably 2-6 carbon atoms in the normal chain. Exemplary structures include, but are not limited to, ethynyl and propynyl. The group may be a terminal group or a bridging group.

35 "Alkynyloxy" refers to an alkynyl-O- group in which alkynyl is as defined herein. Preferred alkynyloxy groups are C₁-C₆ alkynyloxy groups. The group may be a terminal group or a

bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

5 "Amino" refers to groups of the form $\text{-NR}_a\text{R}_b$ wherein R_a and R_b are individually selected from the group including but not limited to hydrogen, optionally substituted alkyl, optionally substituted alkenyl, optionally substituted alkynyl, and optionally substituted aryl groups.

"Aminoalkyl" means an NH_2 -alkyl- group in which the alkyl group is as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

10 "Aminosulfonyl" means an $\text{NH}_2\text{-S(=O)}_2\text{-}$ group. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

15 "Arylalkenyl" means an aryl-alkenyl- group in which the aryl and alkenyl are as defined herein. Exemplary arylalkenyl groups include phenylallyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkenyl group.

20 "Arylalkyl" means an aryl-alkyl- group in which the aryl and alkyl moieties are as defined herein. Preferred arylalkyl groups contain a C_{1-5} alkyl moiety. Exemplary arylalkyl groups include benzyl, phenethyl, 1-naphthalenemethyl and 2-naphthalenemethyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

"Arylalkyloxy" refers to an aryl-alkyl-O- group in which the alkyl and aryl are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

25 "Arylamino" includes both mono-arylamino and di-arylamino unless specified. Mono-arylamino means a group of formula arylNH- , in which aryl is as defined herein. di-arylamino means a group of formula $(\text{aryl})_2\text{N-}$ where each aryl may be the same or different and are each as defined herein for aryl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

30 "Arylheteroalkyl" means an aryl-heteroalkyl- group in which the aryl and heteroalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the heteroalkyl group.

35 "Aryloxy" refers to an aryl-O- group in which the aryl is as defined herein. Preferably the aryloxy is a $\text{C}_6\text{-C}_{18}$ aryloxy, more preferably a $\text{C}_6\text{-C}_{10}$ aryloxy. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

"Arylsulfonyl" means an aryl-S(=O)₂- group in which the aryl group is as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

5 A "bond" is a linkage between atoms in a compound or molecule. The bond may be a single bond, a double bond, or a triple bond.

"Cycloalkenyl" means a non-aromatic monocyclic or multicyclic ring system containing at least one carbon-carbon double bond and preferably having from 5-10 carbon atoms per ring. Exemplary monocyclic cycloalkenyl rings include cyclopentenyl, cyclohexenyl or cycloheptenyl. The cycloalkenyl group may be substituted by one or more substituent groups.
10 A cycloalkenyl group typically is a C₃-C₁₂ alkenyl group. The group may be a terminal group or a bridging group.

"Cycloalkyl" refers to a saturated monocyclic or fused or spiro polycyclic, carbocycle preferably containing from 3 to 9 carbons per ring, such as cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl and the like, unless otherwise specified. It includes monocyclic systems such as
15 cyclopropyl and cyclohexyl, bicyclic systems such as decalin, and polycyclic systems such as adamantane. A cycloalkyl group typically is a C₃-C₁₂ alkyl group. The group may be a terminal group or a bridging group.

"Cycloalkylalkyl" means a cycloalkyl-alkyl- group in which the cycloalkyl and alkyl moieties are as defined herein. Exemplary monocycloalkylalkyl groups include cyclopropylmethyl, cyclopentylmethyl, cyclohexylmethyl and cycloheptylmethyl. The group may be a terminal
20 group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

"Cycloalkylalkenyl" means a cycloalkyl-alkenyl- group in which the cycloalkyl and alkenyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the
25 group is a terminal group it is bonded to the remainder of the molecule through the alkenyl group.

"Cycloalkylheteroalkyl" means a cycloalkyl-heteroalkyl- group in which the cycloalkyl and heteroalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the
30 heteroalkyl group.

"Cycloalkyloxy" refers to a cycloalkyl-O- group in which cycloalkyl is as defined herein. Preferably the cycloalkyloxy is a C₁-C₆cycloalkyloxy. Examples include, but are not limited to, cyclopropanoxy and cyclobutanoxo. The group may be a terminal group or a bridging group. If
35 the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

"Cycloalkenyloxy" refers to a cycloalkenyl-O- group in which the cycloalkenyl is as defined herein. Preferably the cycloalkenyloxy is a C₁-C₆cycloalkenyloxy. The group may be a

terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

5 "Cycloamino" refers to a saturated monocyclic, bicyclic, or polycyclic ring containing at least one nitrogen in at least one ring. Each ring is preferably from 3 to 10 membered, more preferably 4 to 7 membered. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

10 "Haloalkyl" refers to an alkyl group as defined herein in which one or more of the hydrogen atoms has been replaced with a halogen atom selected from the group consisting of fluorine, chlorine, bromine and iodine. A haloalkyl group typically has the formula $C_nH_{(2n+1-m)}X_m$ wherein each X is independently selected from the group consisting of F, Cl, Br and I. In groups of this type n is typically from 1 to 10, more preferably from 1 to 6, most preferably 1 to 3. m is typically 1 to 6, more preferably 1 to 3. Examples of haloalkyl include fluoromethyl, difluoromethyl and trifluoromethyl.

15 "Haloalkenyl" refers to an alkenyl group as defined herein in which one or more of the hydrogen atoms has been replaced with a halogen atom independently selected from the group consisting of F, Cl, Br and I.

20 "Haloalkynyl" refers to an alkynyl group as defined herein in which one or more of the hydrogen atoms has been replaced with a halogen atom independently selected from the group consisting of F, Cl, Br and I.

"Halogen" may be used interchangeably with "Halo" and represents chlorine, fluorine, bromine or iodine.

25 "Heteroalkyl" refers to a straight- or branched-chain alkyl group preferably having from 2 to 12 carbons, more preferably 2 to 6 carbons in the chain, one or more of which has been replaced by a heteroatom selected from S, O, P and N. Exemplary heteroalkyls include alkyl ethers, secondary and tertiary alkyl amines, amides, alkyl sulfides, and the like. Examples of heteroalkyl also include hydroxyC₁-C₆alkyl, C₁-C₆alkyloxyC₁-C₆alkyl, aminoC₁-C₆alkyl, C₁-C₆alkylaminoC₁-C₆alkyl, and di(C₁-C₆alkyl)aminoC₁-C₆alkyl. The group may be a terminal group or a bridging group.

30 "Heteroalkyloxy" refers to an heteroalkyl-O- group in which heteroalkyl is as defined herein. Preferably the heteroalkyloxy is a C₁-C₆heteroalkyloxy. The group may be a terminal group or a bridging group.

35 "Heteroaryl" either alone or part of a group refers to groups containing an aromatic ring (preferably a 5 or 6 membered aromatic ring) having one or more heteroatoms as ring atoms in the aromatic ring with the remainder of the ring atoms being carbon atoms. Suitable heteroatoms include nitrogen, oxygen and sulphur. Examples of heteroaryl include thiophene, benzothiophene, benzofuran, benzimidazole, benzoxazole, benzothiazole, benzisothiazole,

naphtho[2,3-b]thiophene, furan, isoindolizine, xantholene, phenoxatine, pyrrole, imidazole, pyrazole, pyridine, pyrazine, pyrimidine, pyridazine, tetrazole, indole, isoindole, 1H-indazole, purine, quinoline, isoquinoline, phthalazine, naphthyridine, quinoxaline, cinnoline, carbazole, phenanthridine, acridine, phenazine, thiazole, isothiazole, phenothiazine, oxazole, isooxazole, furazane, phenoxazine, 2-, 3- or 4- pyridyl, 2-, 3-, 4-, 5-, or 8- quinolyl, 1-, 3-, 4-, or 5- isoquinolyl, 1-, 2-, or 3- indolyl, and 2-, or 3-thienyl. A heteroaryl group is typically a C₁-C₁₈ heteroaryl group. A heteroaryl group may comprise 3 to 8 ring atoms. A heteroaryl group may comprise 1 to 3 heteroatoms independently selected from the group consisting of N, O and S. The group may be a terminal group or a bridging group.

10 "Heteroarylalkyl" means a heteroaryl-alkyl group in which the heteroaryl and alkyl moieties are as defined herein. Preferred heteroarylalkyl groups contain a lower alkyl moiety. Exemplary heteroarylalkyl groups include pyridylmethyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

15 "Heteroarylalkenyl" means a heteroaryl-alkenyl- group in which the heteroaryl and alkenyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkenyl group.

20 "Heteroarylheteroalkyl" means a heteroaryl-heteroalkyl- group in which the heteroaryl and heteroalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the heteroalkyl group.

25 "Heteroarylamino" refers to groups containing an aromatic ring (preferably 5 or 6 membered aromatic ring) having at least one nitrogen and at least another heteroatom as ring atoms in the aromatic ring, preferably from 1 to 3 heteroatoms in at least one ring. Suitable heteroatoms include nitrogen, oxygen and sulphur. Arylamino and aryl is as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

30 "Heteroaryloxy" refers to a heteroaryl-O- group in which the heteroaryl is as defined herein. Preferably the heteroaryloxy is a C₁-C₁₈heteroaryloxy. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

35 "Heterocyclic" refers to saturated, partially unsaturated or fully unsaturated monocyclic, bicyclic or polycyclic ring system containing at least one heteroatom selected from the group consisting of nitrogen, sulfur and oxygen as a ring atom. Examples of heterocyclic moieties include heterocycloalkyl, heterocycloalkenyl and heteroaryl.

"Heterocycloalkenyl" refers to a heterocycloalkyl as defined herein but containing at least one double bond. A heterocycloalkenyl group typically is a C₂-C₁₂ heterocycloalkenyl group. The group may be a terminal group or a bridging group.

5 "Heterocycloalkyl" refers to a saturated monocyclic, bicyclic, or polycyclic ring containing at least one heteroatom selected from nitrogen, sulfur, oxygen, preferably from 1 to 3 heteroatoms in at least one ring. Each ring is preferably from 3 to 10 membered, more preferably 4 to 7 membered. Examples of suitable heterocycloalkyl substituents include pyrrolidyl, tetrahydrofuryl, tetrahydrothiofuranyl, piperidyl, piperazyl, tetrahydropyranyl, morpholino, 1,3-diazapane, 1,4-diazapane, 1,4-oxazepane, and 1,4-oxathiapane. A heterocycloalkyl group
10 typically is a C₂-C₁₂ heterocycloalkyl group. A heterocycloalkyl group may comprise 3 to 8 ring atoms. A heterocycloalkyl group may comprise 1 to 3 heteroatoms independently selected from the group consisting of N, O and S. The group may be a terminal group or a bridging group.

"Heterocycloalkylalkyl" refers to a heterocycloalkyl-alkyl- group in which the heterocycloalkyl and alkyl moieties are as defined herein. Exemplary heterocycloalkylalkyl groups include (2-tetrahydrofuryl)methyl, (2-tetrahydrothiofuranyl) methyl. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkyl group.

"Heterocycloalkylalkenyl" refers to a heterocycloalkyl-alkenyl- group in which the heterocycloalkyl and alkenyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the alkenyl group.

"Heterocycloalkylheteroalkyl" means a heterocycloalkyl-heteroalkyl- group in which the heterocycloalkyl and heteroalkyl moieties are as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the heteroalkyl group.

"Heterocycloalkyloxy" refers to a heterocycloalkyl-O- group in which the heterocycloalkyl is as defined herein. Preferably the heterocycloalkyloxy is a C₁-C₆ heterocycloalkyloxy. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

30 "Heterocycloalkenyloxy" refers to a heterocycloalkenyl-O- group in which heterocycloalkenyl is as defined herein. Preferably the Heterocycloalkenyloxy is a C₁-C₆ Heterocycloalkenyloxy. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the oxygen atom.

35 "Heterocycloamino" refers to a saturated monocyclic, bicyclic, or polycyclic ring containing at least one nitrogen and at least another heteroatom selected from nitrogen, sulfur, oxygen, preferably from 1 to 3 heteroatoms in at least one ring. Each ring is preferably from 3 to 10 membered, more preferably 4 to 7 membered. The group may be a terminal group or a bridging

group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

"Hydroxyalkyl" refers to an alkyl group as defined herein in which one or more of the hydrogen atoms has been replaced with an OH group. A hydroxyalkyl group typically has the formula $C_nH_{(2n+1-x)}(OH)_x$. In groups of this type n is typically from 1 to 10, more preferably from 1 to 6, most preferably from 1 to 3. x is typically from 1 to 6, more preferably from 1 to 4.

"Lower alkyl" as a group means unless otherwise specified, an aliphatic hydrocarbon group which may be straight or branched having 1 to 6 carbon atoms in the chain, more preferably 1 to 4 carbons such as methyl, ethyl, propyl (n-propyl or isopropyl) or butyl (n-butyl, isobutyl or tertiary-butyl). The group may be a terminal group or a bridging group.

"Sulfinyl" means an R-S(=O)- group in which the R group may be OH, alkyl, cycloalkyl, heterocycloalkyl; aryl or heteroaryl group as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

"Sulfinylamino" means an R-S(=O)-NH- group in which the R group may be OH, alkyl, cycloalkyl, heterocycloalkyl; aryl or heteroaryl group as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

"Sulfonyl" means an R-S(=O)₂- group in which the R group may be OH, alkyl, cycloalkyl, heterocycloalkyl; aryl or heteroaryl group as defined herein. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the sulfur atom.

"Sulfonylamino" means an R-S(=O)₂-NH- group. The group may be a terminal group or a bridging group. If the group is a terminal group it is bonded to the remainder of the molecule through the nitrogen atom.

Some of the compounds of the disclosed embodiments may exist as single stereoisomers, racemates, and/or mixtures of enantiomers and /or diastereomers. All such single stereoisomers, racemates and mixtures thereof, are intended to be within the scope of the subject matter described and claimed.

Further, it is possible that compounds of the invention may contain more than one asymmetric carbon atom. In those compounds, the use of a solid line to depict bonds to asymmetric carbon atoms is meant to indicate that all possible stereoisomers are meant to be included. The use of a solid line to depict bonds to one or more asymmetric carbon atoms in a compound of the invention and the use of a solid or dotted wedge to depict bonds to other asymmetric carbon atoms in the same compound is meant to indicate that a mixture of diastereomers is present.

The word "substantially" does not exclude "completely" e.g. a composition which is "substantially free" from Y may be completely free from Y. Where necessary, the word "substantially" may be omitted from the definition of the invention.

5 Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

As used herein, the term "about", in the context of concentrations of components of the formulations, typically means +/- 5% of the stated value, more typically +/- 4% of the stated value, more typically +/- 3% of the stated value, more typically, +/- 2% of the stated
10 value, even more typically +/- 1% of the stated value, and even more typically +/- 0.5% of the stated value.

Throughout this disclosure, certain embodiments may be disclosed in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed
15 ranges. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example,
20 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Certain embodiments may also be described broadly and generically herein. Each of the narrower species and subgeneric groupings falling within the generic disclosure also form part of the disclosure. This includes the generic description of the embodiments with a proviso or negative limitation removing any subject matter from the genus, regardless of
25 whether or not the excised material is specifically recited herein.

Detailed Disclosure of Optional Embodiments

Exemplary, non-limiting embodiments of a polymer matrix will now be disclosed.

30 Polymeric materials are provided that may contain a plurality of different pendant groups. Methods of making the polymeric material and compositions that contain the polymeric material are also provided. Additionally, articles with coatings that contain the polymeric material are provided. The polymeric material in the coatings is often crosslinked. The coatings may be antimicrobial, nonleachable, durably antimicrobial, durably adherent, water insoluble, abrasion resistant, or any combination thereof.

35 The present disclosure is generally directed to articles comprising an antimicrobial coating and methods of making said articles comprising an antimicrobial coating.

The present disclosure provides antimicrobial polymers. The antimicrobial polymers are formed by reacting, in suitable aqueous or organic solvent, monomers that comprise a chemical group that serves one or more functional purposes in the polymer.

In some embodiments, the antimicrobial polymers may be coated (e.g., as a film or layer) onto a substrate as described herein. The polymers have antimicrobial activity that may kill or inhibit microorganisms that come into contact with the polymer. The antimicrobial activity may be tested using a standardized antimicrobial resistance test such as, for example, JIS-Z 2801 (Japanese Industrial Standards; Japanese Standards Association; Tokyo, Japan). In some embodiments, the polymers further may have abrasion-resistant properties. The abrasion-resistant property of the polymer, when coated on a relatively hard surface, may be tested using the ASTM test method D 7027.26676.

Polymers of the present disclosure include pendant groups with antimicrobial activity. The groups with antimicrobial activity may be selected for properties that are desirable in the articles on which the polymer is coated. For example, the antimicrobial group may be selected because it provides a polymer having substantial optical clarity (i.e. high optical transmission throughout a narrow or broad spectrum of wavelengths, low haze) or a low coefficient of friction. These properties easily may be measured by a person of ordinary skill in the art, for example, by methods disclosed herein.

A polymer may have a plurality of pendant groups, wherein the pendant groups comprise: a first pendant group comprising a quaternary ammonium component having the following formula: $-R^1-(CH_2)_n-[N^+(R^2)(R^3)(R^4)](X^-)$, wherein n is any integer from 1 to 18; R^1 is $C(O)O$ or $C(O)NH$; R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or R^2 and R^3 are taken together to form a ring and R^4 is H or absent; and X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and a second pendant group comprising an organosilane component, provided that there are no other pendant groups in the polymer.

A polymer may have a plurality of pendant groups, wherein the pendant groups consists of: a first pendant group comprising a quaternary ammonium component having the following formula: $-R^1-(CH_2)_n-[N^+(R^2)(R^3)(R^4)](X^-)$ wherein n is any integer from 1 to 18; R^1 is $C(O)O$ or $C(O)NH$; R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or R^2 and R^3 are taken together to form a ring and R^4 is H or absent; and X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and a second pendant group comprising an organosilane component.

n may be any integer from 1 to 18, 1 to 2, 1 to 3, 1 to 4, 1 to 5, 1 to 6, 1 to 8, 1 to 10, 1 to 12, 1 to 14, 1 to 16, 2 to 3, 2 to 4, 2 to 5, 2 to 6, 2 to 8, 2 to 10, 2 to 12, 2 to 14, 2 to 16, 2 to 18, 3 to 4, 3 to 5, 3 to 6, 3 to 8, 3 to 10, 3 to 12, 3 to 14, 3 to 16, 3 to 18, 4 to 5, 4 to 6, 4 to 8, 4 to 10, 4 to 12, 4 to 14, 4 to 16, 4 to 18, 5 to 6, 5 to 8, 5 to 10, 5 to 12, 5 to 14, 5 to 16, 5 to 18, 6 to 8, 6 to 10, 6 to 12, 6 to 14, 6 to 16, 6 to 18, 8 to 10, 8 to 12, 8 to 14, 8 to 16, 8 to 18, 10 to 12, 10 to 14, 10 to 16, 10 to 18, 12 to 14, 12 to 16, 12 to 18, 14 to 16, 14 to 18 or 16 to 18. n may be any integer selected from 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 or 18. n may be 2, n may be 12 or 16, preferably if R^2 and R^3 taken together form a ring.

R¹ may be C(O)O or C(O)NH. R¹ may be C(O)O.

R², R³ and R⁴ may each independently be optionally substituted alkyl, optionally substituted aryl or R² and R³ may be taken together to form a ring and R⁴ is H or absent.

5 R² and R³ may each independently be H, optionally substituted C1 alkyl, optionally substituted C2 alkyl, optionally substituted C3 alkyl, optionally substituted C4 alkyl, optionally substituted C5 alkyl, optionally substituted C6 alkyl.

R² and R³ may each independently be an optionally substituted C1 to C2 alkyl, optionally substituted C1 to C4 alkyl, optionally substituted C1 to C6 alkyl, optionally substituted C2 to C4 alkyl, optionally substituted C2 to C6 alkyl, or optionally substituted C4 to C6 alkyl.

10 R² and R³ may each independently be an optionally substituted aryl. The optionally substituted aryl may be an optionally substituted C₆-C₁₈ aryl, optionally substituted C₆-C₁₀ aryl, optionally substituted C₆-C₁₂ aryl, optionally substituted C₆-C₁₄ aryl, optionally substituted C₆-C₁₆ aryl, substituted C₈-C₁₀ aryl, optionally substituted C₈-C₁₂ aryl, optionally substituted C₈-C₁₄ aryl, optionally substituted C₈-C₁₆ aryl, optionally substituted C₈-C₁₈ aryl, optionally substituted C₁₀-
15 C₁₂ aryl, optionally substituted C₁₀-C₁₄ aryl, optionally substituted C₁₀-C₁₆ aryl, optionally substituted C₁₀-C₁₈ aryl, optionally substituted C₁₂-C₁₄ aryl, optionally substituted C₁₂-C₁₆ aryl, optionally substituted C₁₂-C₁₈ aryl, optionally substituted C₁₄-C₁₆ aryl, optionally substituted C₁₄-C₁₈ aryl or optionally substituted C₁₄-C₁₈ aryl. The optionally substituted aryl may be an optionally substituted C₆, C₇, C₈, C₉, C₁₀, C₁₁, C₁₂, C₁₃, C₁₄, C₁₅, C₁₆, C₁₇ or C₁₈ aryl.

20 R² and R³ may each independently be H, methyl, ethyl, n-propyl, 2-propyl, n-butyl, sec-butyl, t-butyl, n-propyl or n-hexyl. R² and R³ may independently be methyl.

The quaternary ammonium component may have the following formula: -C(O)O-(CH₂)₂-[N⁺(CH₃)₂(R⁴)](X⁻).

25 R⁴ may be an optionally substituted alkyl. R⁴ may be an optionally substituted C14 alkyl, optionally substituted C15 alkyl, optionally substituted C16 alkyl, optionally substituted C17 alkyl, optionally substituted C18 alkyl, optionally substituted C19 alkyl, optionally substituted C20 alkyl, optionally substituted C21 alkyl, optionally substituted C22 alkyl, optionally substituted C22 alkyl, optionally substituted C23 alkyl or optionally substituted C24 alkyl.

30 R⁴ may be an optionally substituted aryl. The optionally substituted aryl may be an optionally substituted C₆-C₁₈ aryl, optionally substituted C₆-C₁₀ aryl, optionally substituted C₆-C₁₂ aryl, optionally substituted C₆-C₁₄ aryl, optionally substituted C₆-C₁₆ aryl, substituted C₈-C₁₀ aryl, optionally substituted C₈-C₁₂ aryl, optionally substituted C₈-C₁₄ aryl, optionally substituted C₈-C₁₆ aryl, optionally substituted C₈-C₁₈ aryl, optionally substituted C₁₀-C₁₂ aryl, optionally substituted C₁₀-C₁₄ aryl, optionally substituted C₁₀-C₁₆ aryl, optionally substituted C₁₀-C₁₈ aryl, optionally substituted C₁₂-C₁₄ aryl, optionally substituted C₁₂-C₁₆ aryl, optionally substituted C₁₂-C₁₈ aryl, optionally substituted C₁₄-C₁₆ aryl, optionally substituted C₁₄-C₁₈ aryl or optionally substituted C₁₄-C₁₈ aryl. The optionally substituted aryl may be an optionally substituted C₆, C₇, C₈, C₉, C₁₀, C₁₁, C₁₂, C₁₃, C₁₄, C₁₅, C₁₆, C₁₇ or C₁₈ aryl.
35

R³ may be an optionally substituted C14 to C16 alkyl, optionally substituted C14 to C18 alkyl, optionally substituted C14 to C20 alkyl, optionally substituted C14 to C18 alkyl, optionally substituted C14 to C20 alkyl, optionally substituted C14 to C22 alkyl, optionally substituted C14 to C24 alkyl, optionally substituted C16 to C18 alkyl, optionally substituted C16 to C20 alkyl, optionally substituted C16 to C22 alkyl, optionally substituted C16 to C24 alkyl, optionally substituted C18 to C20 alkyl, optionally substituted C18 to C22 alkyl, optionally substituted C18 to C24 alkyl, optionally substituted C20 to C22 alkyl, optionally substituted C20 to C24 alkyl, or optionally substituted C22 to C24 alkyl.

R⁴ may be -C₁₄H₂₉, -C₁₅H₃₁, -C₁₆H₃₃, -C₁₇H₃₅, -C₁₈H₃₇, -C₁₉H₃₉, -C₂₀H₄₁, -C₂₁H₄₃, -C₂₂H₄₅, -C₂₃H₄₇ or -C₂₄H₄₉. R⁴ may be -C₁₆H₃₃.

R² and R³ may be taken together to form a ring, and then R⁴ may be H or absent. The ring may be an optionally substituted heterocyclic ring. The heterocyclic ring may be saturated or unsaturated. The heterocyclic ring may be a heterocycloalkyl ring or a heteroaryl ring having 5 to 10 ring atoms and in each case having one to three heteroatoms selected from N, O or S.

When the ring is a heterocycloalkyl ring, R⁴ may be H. When the ring is a heteroaryl ring, R⁴ may be absent.

The heterocycloalkyl ring may be selected from the group consisting of aziridine, diaziridine, azetidine, diazetidine, pyrrolidine, imidazolidine, pyrazolidine, piperidine, piperazine, morpholine and thiomorpholine.

The heteroaryl ring may be selected from the group consisting of azirine, diazirine, azete, diazete, pyrrole, imidazole, pyrazole, triazole, tetrazole, pyridine, diazine, oxazine, thiazine, triazine, tetrazine and pentazine.

The heterocyclic ring may be a pyridine.

The total number of carbon atoms present in R², R³ and R⁴ combined, may be greater than 12, greater than 14, greater than 16, greater than 18, or greater than 20.

The total number of carbon atoms present in R², R³ and R⁴ combined, may be less than 30, less than 28, less than 26, less than 24, or less than 22.

The total number of carbon atoms present in R², R³ and R⁴ combined, may be in the range of 12 to 14, 12 to 16, 12 to 18, 12 to 20, 12 to 22, 12 to 24, 12 to 26, 12 to 28, 12 to 30, 14 to 16, 14 to 18, 14 to 20, 14 to 22, 14 to 24, 14 to 26, 14 to 28, 14 to 30, 16 to 18, 16 to 20, 16 to 22, 16 to 24, 16 to 26, 16 to 28, 16 to 30, 18 to 20, 18 to 22, 18 to 24, 18 to 26, 18 to 28, 18 to 30, 20 to 22, 20 to 24, 20 to 26, 20 to 28, 20 to 30, 22 to 24, 22 to 26, 22 to 28, 22 to 30, 24 to 26, 24 to 28, 24 to 30, 26 to 28, 26 to 30 or 28 to 30.

The quaternary ammonium component may have the following formula: -C(O)O-(CH₂)₂-N⁺(CH₃)₂(C₁₆H₃₃)(X⁻).

The quaternary ammonium component may have the following formula: $-\text{C}(\text{O})\text{O}-(\text{CH}_2)_2-\text{N}^+(\text{CH}_3)_2(\text{C}_{16}\text{H}_{33})(\text{Br}^-)$.

5 The first quaternary ammonium pendant groups are coupled (e.g., covalently coupled) to the polymer such that, the bactericidal activity of the antimicrobial coupled to the polymer is insoluble in water (i.e., the antimicrobial is non-leaching when the polymer is contacted with an aqueous composition). Suitable antimicrobial quaternary ammonium compounds may have at least one C_1 - C_{24} linear or branched chain alkyl or alkenyl group. Quaternary amine groups in compositions of the present disclosure may include quaternary amine groups that are pendant groups in the polymer, as well as free quaternary amine groups, as described herein.

10 The quaternary ammonium component may have the following formula: $-\text{COO}-(\text{CH}_2)_2-\text{N}^+(\text{CH}_3)_2-\text{R}^4$.

The quaternary ammonium component may have the following formula: $-\text{COO}-(\text{CH}_2)_2-\text{N}^+(\text{CH}_3)_2-\text{C}_{16}\text{H}_{33}$.

15 Nonlimiting examples of suitable antimicrobial quaternary ammonium components on the polymer may include hexadecyldimethylethylamine, octadecyldimethylethylamine, hexadecyldimethylpropylamine, hexadecyldimethylamine hydrochloride, lauryldimethylamine hydrobromide, and octadecyldimethylpropylamine.

The second pendant group may comprise an organosilane component.

20 The organosilane pendant group may include a silicon-containing group. This pendant group may crosslink the antimicrobial polymeric material, bond the antimicrobial polymeric material to a substrate, or it may confer the ability of the polymer to perform any combination of the foregoing bonding configurations. A nonlimiting example of a suitable organosilane pendant group is the propyl trimethoxysilane group found in methacryloylpropyl trimethoxysilane.

The organosilane component may be organosilane or an organic silane ester.

25 The organosilane component may have the following formula: $-\text{R}^5-(\text{CH}_2)_m-\text{Si}(-\text{O}-\text{R}^6)_3$, wherein m is any integer from 1 to 6; R^5 is $\text{C}(\text{O})\text{O}$ or $\text{C}(\text{O})\text{NH}$; and R^6 is selected from the group consisting of H, an optionally substituted alkyl and a silane ester.

30 m may be any integer from 1 to 6, 1 to 2, 1 to 3, 1 to 4, 1 to 5, 2 to 3, 2 to 4, 2 to 5, 2 to 6, 3 to 4, 3 to 5, 3 to 6, 4 to 5, 4 to 6 or 5 to 6. m may be any integer selected from 1, 2, 3, 4, 5 or 6. m may be 3.

R^5 may be $\text{C}(\text{O})\text{O}$ or $\text{C}(\text{O})\text{NH}$. R^5 may be $\text{C}(\text{O})\text{O}$.

R^6 may be H or optionally substituted alkyl. R^6 may be H, or optionally substituted C1 to C5 alkyl. R^6 may be H or optionally substituted C1 alkyl, optionally substituted C2 alkyl, optionally substituted C3 alkyl, optionally substituted C4 alkyl, or optionally substituted C5 alkyl.

R⁶ may be an optionally substituted C1 to C2 alkyl, optionally substituted C1 to C3 alkyl, optionally substituted C1 to C4 alkyl, optionally substituted C1 to C5 alkyl, optionally substituted C2 to C3 alkyl, optionally substituted C2 to C4 alkyl, optionally substituted C2 to C5 alkyl, optionally substituted C3 to C4 alkyl, optionally substituted C3 to C5 alkyl or optionally substituted C4 to C5 alkyl.

R⁶ may be H, methyl, ethyl, n-propyl, 2-propyl, n-butyl, sec-butyl, t-butyl or n-propyl.

R⁶ may be methyl. The organosilane component may have the following formula: -C(O)O-(CH₂)₃-Si(-O-CH₃)₃.

R⁴ may be H. The organosilane component may have the following formula: -COO-(CH₂)₃-Si(-O-H)₃.

R⁴ may be an organic silane ester. The organosilane component may have the following formula: --C(O)O-(CH₂)₃-Si(-O-Si-R⁷)₃, wherein R⁷ is be an optionally substituted alkyl.

R⁷ may be H or optionally substituted alkyl. R⁷ may be an optionally substituted C1 alkyl, optionally substituted C2 alkyl, optionally substituted C3 alkyl, optionally substituted C4 alkyl, optionally substituted C5 alkyl, or optionally substituted C6 alkyl.

R⁷ may be an optionally substituted C1 to C2 alkyl, optionally substituted C1 to C4 alkyl, optionally substituted C1 to C6 alkyl, optionally substituted C2 to C4 alkyl, optionally substituted C2 to C6 alkyl, or optionally substituted C4 to C6 alkyl.

R⁷ may be H, methyl, ethyl, n-propyl, 2-propyl, n-butyl, sec-butyl, t-butyl, n-propyl or n-hexyl.

R⁷ may be methyl. The organosilane component has the following formula: -C(O)O-(CH₂)₃-Si(-O-Si-CH₃)₃.

The ratio of the organosilane component to the quaternary ammonium component may be in the range of about 1:2 to about 1:5, about 1:2 to about 1:3, about 1:2 to about 1:4, about 1:3 to about 1:4, about 1:3 to about 1:5 or about 1:4 to about 1:5. The ratio of the organosilane component to the quaternary ammonium component may be about 1:3.6.

No other pendant groups may be present in the polymer. The polymer may comprise only of the first pendant group comprising a quaternary ammonium component having the following formula: -R¹-(CH₂)_n-[N⁺(R²)(R³)(R⁴)](X⁻), wherein n is any integer from 1 to 18; R¹ is C(O)O or C(O)NH; R², R³ and R⁴ are each independently an optionally substituted alkyl, optionally substituted aryl, or any two of R², R³ and R⁴ are taken together to form a ring; and X is selected from the group consisting of Cl, Br, I and OSO₃CH₃; and the second pendant group comprising an organosilane component.

The only pendant groups that may be present in the polymer may be the first pendant group comprising a quaternary ammonium component having the following formula: -R¹-(CH₂)_n-[N⁺(R²)(R³)(R⁴)](X⁻), wherein n is any integer from 1 to 18; R¹ is C(O)O or C(O)NH; R², R³ and

R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or any two of R^2 , R^3 and R^4 are taken together to form a ring; and X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and the second pendant group comprising an organosilane component.

5 A method for preparing a polymer as defined above, may comprise the steps of contacting a first monomer with a second monomer in conditions suitable for polymerization, wherein a first monomer comprising a quaternary ammonium component having the following formula: $-\text{R}^1-(\text{CH}_2)_n-[\text{N}^+(\text{R}^2)(\text{R}^3)(\text{R}^4)](\text{X}^-)$ wherein n is any integer from 1 to 18; R^1 is $\text{C}(\text{O})\text{O}$ or $\text{C}(\text{O})\text{NH}$; R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or any two of R^2 , R^3 and R^4 are taken together to form a ring; and X is selected from the group
10 consisting of Cl, Br, I and OSO_3CH_3 ; and a second monomer comprising an organosilane component, provided that no other monomer is contacted with the first and second monomer in the polymer.

The ratio of the first monomer comprising a quaternary ammonium component to the second monomer comprising an organosilane component may be in the range of about 100:1 to 4:1 by
15 weight, about 100:1 to about 75:1, about 100:1 to about 50:1, about 100:1 to about 25:1, about 100:1 to about 10:1, about 75:1 to about 50:1, about 75:1 to about 25:1, about 75:1 to about 10:1, about 50:1 to about 25:1, about 50:1 to about 10:1, about 50:1 to about 4:1, about 25:1 to about 10:1, about 25:1 to about 4:1 or about 10:1 to about 4:1.

20 The first monomer comprising the quaternary ammonium component and the second monomer comprising an organosilane component may comprise a methacrylate group.

The first monomer comprising the quaternary ammonium component may be 2-(methacryloyloxy)ethyl]dimethyl hexadecyl ammonium bromide and the second monomer comprising the organosilane component may be 3-trimethylsilylpropyl methacrylate.

The methacrylate groups may be reacted by free radical polymerization to form the polymer.

25 Polymers of the present disclosure may be formed in any suitable solvent (e.g., an organic solvent) that will solublize or make a dispersion of the resultant polymer. Suitable organic solvents may have a boiling point about 200°C . or lower and may be mixed with small portions ($<10\%$, w/w) of acidified water without substantially degrading the solvent properties. Adding the acidified water to the solvent may facilitate complete hydrolysis of silane groups which, in
30 turn may optimize the formation of $-\text{Si}-\text{O}-\text{Si}-$ bonds within the polymer and between the polymer and the substrate. This may result in improved durability of antimicrobial coating on the substrate. Preferably, the solvent flashpoint is 100°C . or lower. Nonlimiting examples of suitable organic solvents may include an alcohol (e.g., isopropyl alcohol, methanol), MEK, acetone, DMF, DMAC (dimethyl acetamide,) ethyl acetate, THF, etc. The monomers may be
35 mixed with the solvent and reacted to form an antimicrobial polymer. Suitable monomers may include derivatives of acrylate monomers, methacrylate monomers, vinyl monomers, and olefinic monomers. The monomers may comprise chemical groups that are pendant from the polymer backbone after the polymerization reaction. The pendant groups may include a first quaternary ammonium group, and a second organosilane group (e.g., trimethoxysilylpropane).

Antimicrobial polymers of the present disclosure may be synthesized by reacting, in an organic solvent, monomers comprising the pendant groups. Suitable monomers for the reaction include, for example, acrylate monomers, methacrylate monomers, acylamide and methacrylamide monomers and combinations thereof. Other suitable monomers for the reaction may include vinyl monomers and olefinic monomers.

The monomers may be combined, on a weight percent basis, in various ratios in the reaction. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise from about 20% to about 80% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 20% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 30% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 40% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 50% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 60% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise greater than 70% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the quaternary ammonium pendant group may comprise 70% to 80% of the monomers reacted to form a polymer. While it is possible that some quaternary ammonium monomers may be reacted in an uncharged state the weight % calculation is based on the quaternary ammonium form. For example, a tertiary amine acrylate may be reacted as a tertiary amine and subsequently protonated with an acid.

In some embodiments, the monomer comprising the organosilane pendant group may comprise from about 1% to about 20% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the organosilane pendant group may comprise greater than 2% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the organosilane pendant group may comprise greater than 5% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the organosilane pendant group may comprise greater than 10% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the organosilane pendant group may comprise greater than 15% of the monomers reacted to form a polymer. In some embodiments, the monomer comprising the organosilane pendant group may comprise 15% to 20% of the monomers reacted to form a polymer.

In some embodiments, the reaction mixture used to make the antimicrobial polymer comprises at least 20% monomers comprising a quaternary ammonium pendant group and at least 2% monomers comprising an organosilane pendant group.

The monomers are mixed in an organic solvent and are reacted under conditions suitable to form a polymer. For example, the reaction mixture may be purged with nitrogen to remove

other dissolved gasses. In some embodiments, the reaction mixture may be sealed, heated, and mixed (e.g., mixed at 65° C.) for a period of time sufficient to allow polymerization of, for example, at least 99.5% of the monomers. In some embodiments, an additional initiator (e.g., 2,2-Azobis(2-methylbutyronitrile) may be added to the mixture to react with any unreacted monomers from the original mixture. The extent of the reaction of monomers may be determined by, for example, a calculation of the percent solids in the mixture. The antimicrobial polymer typically comprises about 25 weight percent (wt %) of the composition in which it is made.

A polymer may be obtainable by the method as defined above.

10 An article may comprise the polymer as defined above and a substrate comprising a surface.

Antimicrobial polymers of the present disclosure may be applied as a coating to a variety of substrates. Useful substrates include, for example, articles that may comprise and/or be coated with a layer comprising non-siliceous ceramic materials (e.g., carbides, borides, nitrides), siliceous materials such as glasses and siliceous ceramic materials (e.g., silicides), metals (e.g., stainless steel, titanium, gold, silver, chromium, cobalt, tantalum as well as alloys of these metals and alloys of these metals with other metals such as, for example, cobalt-chromium alloys and titanium alloys used in orthopedic implants), and/or metal oxides. The substrate may be films, sheets, tubes, fibers, and the like formed of polymeric materials that are either thermoplastic polymers or thermoset polymers. Exemplary polymeric substrates include, but are not limited to, thermoplastic and thermoset polymers that are optionally plasticized and include polyolefins, polyethylene, polypropylene, fluoropolymers, polyamides, polyethers, epoxies, polyvinyl chloride and plasticized polyvinylchloride, polyisoprene, polyisobutylene, block copolymers such as styrene-butadiene styrene and styrene-isoprene styrene, hydrogenated versions of these available from Kraton Polymers, metallocene polyolefins, rayon polyester, polyethylene terephthalate (PET), poly(meth)acrylates, polycarbonates, polystyrenes, polystyrene copolymers such as styrene acrylonitrile copolymers, polyesters, polyethersulfone, acrylics and acrylic copolymers, polyacrylamides, and polyurethanes, silicones such as two part cured polydimethylsiloxanes, natural rubber latex, polyisoprene, nitrile rubber, and the like, as well as combinations thereof including blends thereof and laminates thereof. Suitable degradable polymer substrates include, for example, polylactic acid (PLA), polyglycolic acid (PGA), and combinations thereof.

The substrates may be used to fabricate a variety of useful articles (e.g., as a part, a portion, or the entirety of the article). The surface of the substrate may comprise one or more of a variety of surface topographies including, for example, substantially planar surfaces, contoured surfaces, microreplicated structures, and a combination of any two or more of the foregoing. The articles (e.g., medical devices) comprise a variety of surfaces that may be deliberately or incidentally contacted with microbiologically-contaminated items during routine use. Suitable articles may be found in health care environments (e.g., patient care rooms, countertops, bedrails, patient care equipment such as instruments and stethoscopes (including, for example, stethoscope diaphragms and/or tubing), and in-dwelling medical devices such as venous access catheters,

nasal gastric tubes, shunts, myringotomy tubes, intrauterine devices, urinary catheters, patient feeding tubes, ventilator tubing, endotracheal tubes, and other flat, tubular, or shaped flexible medical devices intended for contact with mammalian tissue). Other nonlimiting exemplary medical devices that may be coated with an antimicrobial composition according to the present disclosure include contact lenses, intraocular lenses, artificial corneas, wound dressings, eye bandages, materials for the sustained release of an active compound such as a drug delivery patch, moldings that may be used in surgery, such as heart valves, vascular grafts, catheters, artificial organs, orthopedic implants, encapsulated biologic implants, e.g. pancreatic islets, materials for prostheses such as bone substitutes, or moldings for diagnostics, membranes or biomedical instruments or apparatus

The polymer may be adhered to the surface of the substrate.

The article may be a medical device. The article may be a microneedle.

Microneedle-assisted transdermal delivery systems are not equivalent to conventional transdermal patches, in that they are not simply applied to the surface of the skin. Microneedles function principally by breaching the protective barrier of skin, the *stratum corneum*, and often penetrate into the viable epidermis and dermis. The *stratum corneum* may prevent the foreign materials, including microorganisms, from entering the body. As such, one of the critical issues for clinical usage of microneedle is the risk of infection because of the compromised *stratum corneum*. Microneedle treatment was found to permit the permeation of bacteria by means of various *in vitro* models, including Silescol membranes, excised porcine skin and mouse skin, even though the extent of the permeation was not greater than that enabled by hypodermic injection. In addition, microorganisms were shown to adhere to microneedles after its application. Therefore inappropriate reuse of microneedles will increase the risk of infection. Furthermore, clinical trials that demonstrated lack of infection with microneedle usage recruited healthy volunteers and prior to application of microneedle arrays, skin treatment sites were typically cleansed with alcohol wipes to reduce the skin's microbial bioburden. It is unknown what the infection potential would microneedles lead to under normal circumstances in immune-compromised patients. As such, patient safety would be enhanced by manufacturing microneedles using sterile techniques. The risk of infection associated with the use of microneedles may also be reduced by imparting microneedles with antimicrobial properties.

The microneedle may be a 3M Solid Microstructured Transdermal Systems (sMTS) microneedle array.

The article may be substantially free from anything other than the polymer as defined above and a substrate comprising a surface. The article may be substantially free from any further additives apart from the substrate to be coated by the polymer and the polymer itself.

A method for preparing the article as defined above, may comprise the steps of: forming the polymer as defined above; and contacting the polymer with the surface of the substrate under conditions suitable to adhere the polymer to the surface of the substrate.

Preferred for this invention is a reactive surface containing some small amount of water. By “reactive”, it is meant that the surface must contain some groups which will react with some of the silanols generated by hydrolysis of the silanes of this invention.

5 In any embodiment the method of making an antimicrobial coating according to the present disclosure, one or more catalyst may be used in the process. Suitable catalysts include any compound that promotes the formation of Si—O—Si bonds. Nonlimiting examples of suitable catalysts include an acid (e.g., a mineral or an organic acid), a base (e.g., an organic base), tin octoate and 1,8-Diazabicycloundecene (DBU). The acid may be sulfuric acid, hydrochloric acid, nitric acid or acetic acid.

10 Typically, the final concentration of the catalyst may be relatively low (e.g., about 0.04 weight percent). A person of ordinary skill in the art will recognize that the concentration of the catalyst should be sufficiently high enough to catalyze the cross-linking reaction, while avoiding substantial interference with the optical properties (e.g., color) of the coating, if undesirable, and/or avoiding interference with the shelf-life of the coating mixture.

15 The present disclosure provides methods for coating the antimicrobial polymer of the present disclosure onto a substrate. The composition (e.g., the reaction mixture) comprising the antimicrobial polymer in solvent (e.g., an aqueous solvent, an organic solvent) may be contacted with a substrate. The solvent may be evaporated to leave the antimicrobial polymer in the form of a coating on the substrate. In some embodiments, the substrate may be heated before and/or during the contacting step to accelerate the evaporation of the solvent. Preferably, the substrate is heated to a temperature that does not degrade the function of the polymer or a component of the substrate onto which the polymer is coated. A suitable temperature for contacting the polymer composition on a glass substrate is from room temperature to about 120° C. A person of ordinary skill in the art will recognize that higher temperatures will facilitate faster removal of organic solvent from the polymer composition.

20 In some embodiments, the antimicrobial polymer may be diluted to a final concentration of 1 wt. % to about 20 wt % in a solvent such as an organic solvent before using the diluted composition to coat the antimicrobial polymer onto a substrate. In some embodiments, the antimicrobial polymer is diluted to a final concentration of 1 wt % to about 5 wt % in the organic solvent before using the diluted composition to coat the antimicrobial polymer onto a substrate. Suitable organic solvents to dilute the polymer have a flashpoint below 150° C. and include ethers, ketones esters and alcohols, for example, isopropyl alcohol.

25 In one embodiment, the method of preparing an antimicrobial polymer-coated surface includes the step of forming a polymer. The polymer may be formed by mixing a plurality of monomers in a suitable solvent (e.g., an organic solvent such as isopropyl alcohol, for example) as disclosed herein. In some embodiments, a relatively small portion (e.g., 3%) of the solvent may comprise acidified water. Acidified water in the reaction mixture may facilitate bonding between silane groups in the composition and between silane groups in the composition and a

substrate comprising active silanes. Optionally, after forming the antimicrobial polymer, the polymer composition may be diluted, as described above, before contacting it with a substrate.

The polymer may be applied to the substrate by a variety of processes known in the art such as, for example, wiping, brushing, dip coating, curtain coating, gravure coating, kiss coating, spin coating, and spraying.

Contacting the polymer with the substrate further comprises contacting the polymer under conditions that facilitate adherence of the polymer to the surface of the substrate. A person having ordinary skill in the art will appreciate that during and after the period which solvent in which the polymer is dissolved and/or suspended evaporates, components of the polymer will begin reacting with each other and, optionally, with active silane groups on the surface of the substrate to form Si—O—Si bonds. This reaction will proceed relatively slowly at ambient temperature (circa 23° C.). Heating the substrate may facilitate the formation of cross-linking covalent bonds between the silane groups in the antimicrobial polymer composition and the silane groups, if present, on the surface of the substrate. Thus, in certain embodiments, the formation of the Si—O—Si bonds may be accelerated by the optional step of exposing the coated substrate to an elevated temperature. Without being bound by theory, other forces (e.g., hydrophobic interaction, electrostatic interaction, hydrogen bonding, adhesion) also may facilitate adherence of components of the polymer to the surface of the substrate.

In general, exposing the substrate to higher temperatures while contacting it with the polymer will require shorter times for the solvent to evaporate and for the polymer to adhere to the substrate. However, the contacting step should be performed at temperatures below which siloxane bonds dissociate. For example, in some embodiments, the contacting step may be conducted at about ambient temperature (20-25° C.) for about 10 minutes to about 24 hours. In some embodiments, the contacting step may be conducted at about 130° C. for about 30 seconds to about 3 minutes. The conditions for the contacting step may have a significant impact on the properties of the polymer coating on the substrate. For example, a polymer contacted (“cured”) at room temperature for 24 hours may be measurably more hydrophobic than a polymer cured at about 130° C. for about 3 minutes. In some embodiments, the hydrophobicity of the coating correlates with the durability of the polymer coating on the surface of the substrate.

In some embodiments, the method optionally includes pre-treatments of the surface of the substrate by priming, plasma etching, corona for interfacial adhesion of the coating to surface.

The pre-treatment may be priming. The priming may be plasma cleaning. The plasma cleaning may be done by using oxygen or argon plasma. Plasma cleaning may change the surface property of the substrate to facilitate adhesion of the polymer. Plasma cleaning may increase the surface energy and roughness of the substrate.

In some embodiments, the method optionally includes post treatments of the coating by heating or irradiations including UV, IR plasma, E-beam for further improvement of interfacial adhesion of the coating to surface of the substrate. These treatments may promote inter-polymer crosslinking, as well as promote covalent linkages between the polymer and the surface, thereby

improving the durability of the coating on the surface of the substrate. If the substrate is exposed to an elevated temperature, the method may include cooling the substrate. Typically, the substrate is cooled to room temperature.

5 It should be noted that, in any embodiment of the methods disclosed herein, pretreatment of the substrate prior to applying antimicrobial polymer compositions of the present disclosure may improve the bonding between the polymer and the substrate (e.g., siliceous material). Pretreatment of the substrate may include, for example, soaking the substrate in a volatile solvent (e.g., water, isopropyl alcohol) and/or wiping the substrate with the volatile solvent. Option-
10 ally, the solvent may further comprise a composition of a basic compound such as sodium hydroxide or potassium hydroxide, for example. In some embodiments, the solvent may be saturated with the composition of the basic compound.

In particular, pretreatments that include heating the substrate from about 30 °C to about 200 °C (preferably, about 30 °C to about 150 °C) for 20 minutes to 60 minutes may improve the bonding between the polymer and the substrate.

15 In some embodiments, pretreatment by heating the substrate shortly before the antimicrobial coating is applied results in improved bonding (e.g., as measured by the durability of the coating) between the coating and the substrate. The improved bonding may result in significantly greater durability of the polymer layer on the substrate. Without being bound by theory, it is believed that pretreatment of the substrate by heating removes excess moisture and
20 other impurities (e.g., organic residues) present on the surface of the substrate (e.g., siliceous material) and provides greater ability of the surface silane groups to react with the silanated polymers and/or compounds in the coating compositions disclosed herein.

Antimicrobial polymer coatings of the present disclosure are durable (i.e., substantially non-leachable). The following method may be used to test the release of diffusible antimicrobial
25 activity from polymer-coated articles of the present disclosure.

The non-leaching nature of the antimicrobial polymer on a surface may be demonstrated using zone of inhibition testing according to Section 12 of ASTM E2149-01 entitled "Standard Test Method for Determining the Antimicrobial Activity of Immobilized Antimicrobial Agents Under Dynamic Contact Conditions". The zone of inhibition is presented as a distance in
30 millimeters from the source of an antimicrobial agent in which the antimicrobial is effective. Preferably, the zone is ≤ 3 mm; more preferably, the zone is ≤ 1 mm; even more preferably, the zone is 0 mm.

A use of the polymer may be as a surface coating.

Brief Description of Drawings

The accompanying drawings illustrate a disclosed embodiment and serves to explain the principles of the disclosed embodiment. It is to be understood, however, that the drawings are designed for purposes of illustration only, and not as a definition of the limits of the invention.

Fig.1

[Fig. 1] is a schematic diagram of (A) PDT-10% polymer synthesis from nanomeric DMA- C_{16} and TMSPMA via free radical polymerization and subsequent coating onto substrate; and (B) direct coating of DTPAC monomer onto substrate. During the coating process, methoxysilane of both polymers were hydrolysed into reactive silanol which cross linked with silanol groups on substrate surface to form stable covalent siloxane linkage.

Fig.2

[Fig. 2] is an 1H -NMR spectra overlay of DMA- C_{16} and PDT-10%. Disappearance of 5.6 and 6.1 ppm peaks on PDT-10% spectrum, which correspond to the terminal vinyl hydrogen (Ha and Hb) on DMA- C_{16} , indicated that free radical polymerization reaction had taken place.

Fig. 3

[Fig. 3] shows surface characterization of QAS-coated surfaces. (A) ATR-FTIR absorbance spectra of free and coated PDT-10% to monitor progress of coating. (B) Representative images of water droplets on uncoated and QAS-coated glass surfaces. (C) Contact angles of uncoated and QAS-coated glass surfaces.

Fig. 4

[Fig. 4] shows a graph of the percentage retention of coated polymer after 10 and 100 cycles of physical abrasion.

Fig. 5

[Fig. 5] shows a graph of the antimicrobial activity (log reduction) of coated PDT-10% and DTPAC against *S. aureus*, *E. coli* and *C. albican*: (A) Initial Challenge; and (B) Re-Challenge after thorough rinsing and left for 1 week. *set-up with >2 log reduction (>99%) compared to control.

Fig. 6

[Fig. 6] refers to graphs showing the relative cell viability after 24 hours exposure to different PDT-10% and DTPAC concentrations on (A) HDF, (B) HaCaT keranocytes and (C) HEK 293 cells.

5 **Fig. 7**

[Fig. 7] refers to images showing the contact angles of the microneedle back surface that is (A) untreated and (B) plasma treated for 3 minutes.

Fig. 8

[Fig. 8] refers to images showing the contact angle against time after plasma treatment.

10 **Fig. 9**

[Fig. 9] shows the SEM-EDX analysis on (A) untreated microneedles and (B) microneedles coated with PDT-10%.

Fig. 10

15 [Fig. 10] shows the characterization of microneedle surface by rhodamine B coating method: (A) negative control microneedles, (B) PDT-10% coated microneedles, and (C) PDT-10% coated microneedles after 20 times of penetration test on skin.

Fig. 11

[Fig. 11] shows the FTIR characterization of PDT-10% coating on microneedles.

Fig. 12

20 [Fig. 12] shows a graph of viable bacterial counts of PDT-10% coated microneedles (MN) against *S. aureus* after 24 hours of exposure.

Fig. 13

[Fig. 13] shows a graph of relative human cell viability after 24 hours of exposure to the extraction of PDT-10% coated microneedles.

Examples

Non-limiting examples of the invention and a comparative example will be further described in greater detail by reference to specific Examples, which should not be construed as in any way limiting the scope of the invention.

5 Example 1: Materials

The monomers used for polymer synthesis were [2-(methacryloyloxy)ethyl]dimethyl hexadecyl ammonium bromide (DMA-C₁₆Br) (in-house prepared) and 3-trimethylsilylpropyl methacrylate (TMSPMA, Sigma-Aldrich, USA). 2,2'-Azobis(2-methylpropionitrile) (AIBN, DuPont, USA) was the free radical initiator in the reaction and diethyl ether (Merck, Germany) was used to precipitate the synthesized polymer. DTPAC 42% (w/w) solubilized in methanol was obtained from Sigma-Aldrich (USA). Acetic acid (Merck, Germany) was used to prepare the acidic solution for polymer hydrolysis. Phosphate-buffered saline (PBS, pH 7.4) for the dilution of polymer solutions in the assays was prepared from 10X PBS (Vivantis, Malaysia). The human cell lines were grown in Dulbecco's modified eagle medium (DMEM, Life Technologies, USA) supplemented with 10% fetal bovine serum (FBS, Life Technologies, USA) and 1% penicillin-streptomycin solution (PAN-Biotech GmbH, Germany). Adherent cells were detached from culture surfaces via trypsin prepared from 10X trypsin-EDTA (PAA Laboratories, Austria). Thiazolyl Blue tetrazolium bromide (MTT, 98%, MP Biomedicals, France) and Dimethyl sulphoxide (DMSO) (MP Biomedicals, France) were reagents for the MTT assay.

20

Example 2: Synthesis of [2-(methacryloyloxy)ethyl]dimethyl hexadecyl ammonium bromide (DMA-C₁₆Br)

DMA-C₁₆Br monomer was synthesized in accordance to literature. Briefly 124 mmol (19.5 g) DMA and 62 mmol (18.9 g) 1-bromohexadecane (Sigma-Aldrich, Singapore) were mixed in a 100 mL flask using magnetic stirrer purged with nitrogen gas for 5 minutes. Hydroquinone (100 mg) was added to prevent spontaneous radical polymerization of DMA. The reaction flask was then placed in a 50 °C water bath and stirred continuously for 12 hours. The white-gray precipitate was filtered from the reaction mixture and washed with 100 mL of cold diethyl ether three times to remove unreacted reactants. The final product was recrystallized using acetone and dried under vacuum at room temperature with 85% yield. ¹H-NMR (CDCl₃, δ ppm) characterization of newly synthesized DMA-C₁₆Br: 5.6 (H^a, 1 H), 6.1 (H^b, 1 H), 1.9 (H^c, 3 H), 4.6 (H^d, 2 H), 4.1 (H^e, 2 H), 3.5 (H^f, 6 H), 3.6 (H^g, 2 H), 1.3 (H^h, 28 H), 0.8 (Hⁱ, 3 H).

30

Example 3: Free radical polymerization of PDT-10% copolymer

PDT-10% was synthesized from DMA-C₁₆Br and TMSPMA in the presence of AIBN. A 50 mL Schlenk flask equipped with a magnetic stirrer was connected to a vacuum line, and the moisture was removed by heating under vacuum. When the flask was cooled down, dry nitrogen was filled in. Under a nitrogen atmosphere, DMA-C₁₆Br (2 g), isopropanol (10 g), and AIBN (0.05 g) were added into the flask that was tightly sealed with a rubber septum. The mixture was then heated to 90 °C and stirred constantly at 400 rpm. During the heating process, 150 mL TMSPMA (0.15 g) was injected into the flask dropwise, and the reaction was allowed to proceed for 1hr before adding another 150 mL TMSPMA. After 2 hours, a combination including DMA-C₁₆Br (1.25 g), IPA (5 g), and AIBN (0.05 g) was purged and injected into the flask, followed by adding 100 mL TMSPMA dropwise. The same composition of DMA-C₁₆Br, IPA, AIBN, and TMSPMA was refilled again after 3 hours and the whole reaction mixture was further heated for 12hours at 90 °C with stirring. Thereafter, another 0.05 g AIBN was added to achieve a high monomer conversion and the polymerization was terminated 2 hours later. Final solution was dropped into excess amount of cold diethyl ether to precipitate PDT-10%. The dissolution-precipitation cycle was repeated for two times to remove the residual monomers. The obtained viscous product was isolated and dried under vacuum. Yield was 89 %.

Example 4: Preparation of the polymer coatings

Glass slides (22 mm × 22 mm, Continental Laboratory Products, USA) were used as the substrate for coating PDT-10% and DTPAC. The glass slides were first cleansed with 10% sodium hydroxide for one hour followed by rinsing thoroughly with sterile Milli-Q water and soaking in 96% ethanol. The glass slides were air dried prior to use. Acetic acid, adjusted to pH 2.5, was added to PDT-10% solubilized in isopropanol and DTPAC solution to form a final concentration of 5 mg/mL. The mixture was heated at 50 °C for 30 minutes to enhance hydrolysis. Pre-treated glass slide was added with 100 µL of hydrolyzed polymer and dried at 130 °C, 2 hours for cross-linking reaction between the polymer and glass surface.

Example 5: Characterizations on polymers and coatings

¹H NMR was conducted on PDT-10% using Bruker Avance III 400-Mhz (Germany) NMR spectrometer. Deuterated chloroform (CDCl₃) was used as solvent, and all chemical shifts were reported in ppm. A Spectrum 100 fourier transform infrared (FT-IR) Spectrophotometer (PerkinElmer, USA) with an attenuated total reflectance (ATR) set-up was used to monitor the polymer synthesis, hydrolysis and crosslinking reactions. Infrared spectra were collected between 4000 and 650 cm⁻¹ at a resolution of 4 cm⁻¹. Water contact angle was measured with a static contact angle measurement device (Attension, BiolinScientific). The machine is equipped with a digital camera, automatic liquid dispensers, and sample stage allowing hands-free contact

angle measurement via automated placement of a drop of water. The drop shape is captured automatically and then analyzed via OneAttension software to determine the static contact angle. polymer coated substrates were subjected to physical abrasion using Taber Linear Abraser 5750 with a vertical load of 1 Kg. 10 and 100 abrasion cycles were performed with a magnitude of 1 inch. Absorbance of the characteristic peak for quaternary ammonium silane polymers was measured using ATR-FTIR before and after abrasion. Measurements were done in triplicates at 3 points on the same surface. Retention of coating expressed as:

$$\frac{\text{Absorbance after Abrasion}}{\text{Absorbance before Abrasion}} \times 100\%$$

PDT-10% was synthesized from DMA-C₁₆ and TMSPMA via free-radical polymerization (Fig. 1A). DMA-C₁₆ (102) consists of a 16-carbons long alkyl chain quaternary ammonium moiety that is responsible for antimicrobial activity while TMSPMA (104) consist of alkoxy silane moiety for surface attachment. Polymerization was possible because both monomers contained vinyl carbon in their methacrylate functional group. PDT-10 (106) is the polymerized form containing –Si-O-CH₃ methoxysilane groups (108) which is then cross-linked to form PDT-10 coat (110) containing –Si-O-Si siloxane groups (112). This was confirmed by the disappearance of 5.6 and 6.1 ppm peaks in ¹H-NMR spectrum of PDT-10% (202) when compared to DMA-C₁₆ (204) (Fig. 2). After PDT-10% was successfully synthesized, coating of a substrate with the polymer followed. During the coating process, PDT-10% polymer underwent a series of transformation at the silane anchoring moiety (methylsilane → silanol → siloxane) to facilitate cross-linking and coating onto glass substrate. DTPAC was included in the study as comparison. Fig. 1B shows direct coating of DTPAC monomer (122) onto substrate. DTPAC monomer contains –Si-O-CH₃ methoxysilane groups (124) which is cross-linked to form DTPAC coat (126) containing –Si-O-Si- siloxane groups (128).

ATR-FTIR spectroscopy was used to monitor the process of coating. Fig. 3A shows the ATR-FTIR absorbance spectra of free (302) and coated (304) PDT-10% to monitor progress of coating. Characteristic absorbance band of methoxysilane (–Si-O-CH₃) in the uncoated polymer (302) peaked at 1089 cm^{–1}. The formation of siloxane crosslink during the coating process was confirmed by the disappearance of the 1089 cm^{–1} peak after coating (304), because methoxysilane group was subjected to hydrolysis and formation of siloxane crosslink during the coating process. To further assess coating efficiency, surface hydrophobicity characteristic of both coated substrates were examined. Uncoated glass substrate (control, 310) showed good water wettability as shown by a small contact angle (26.1° ± 0.85°). However, upon coating, the contact angles for both polymer coated substrate increased drastically (PDT-10% (312): 83.6° ± 5.6°; DTPAC (314): 80.9° ± 2.4°) (Fig. 3B and C). Contact angle of both polymer coatings were not significantly different (p-value >0.05). This increase in hydrophobicity was not surprising and further suggested that coating of PDT-10% was as successful as DTPAC.

Example 6: Antimicrobial activity of polymer coatings: initial and re-challenge

Gram-positive bacteria *Staphylococcus aureus* (ATCC 6538P), Gram-negative bacteria *Escherichia coli* (ATCC 8739), and fungus *Candida albicans* (ATCC 2091) were employed for antimicrobial testing. Both bacteria were obtained from Oxoid, Singapore and the fungus from MicroBiologics, France. All bacteria cultures were maintained in nutrient broth (Acumedia, Michigan) incubated at 37 °C, while *C. albicans* culture in tryptone soya broth (Oxoid, England) at 28 °C. Stock microbial suspensions were frozen in 15% glycerol at -80 °C and thawed prior to use.

E. coli, *S. aureus* and *C. candida* were grown to their exponential phase before they were harvested and diluted with medium to give a working concentration of 9.0×10^5 colony forming unit /mL (CFU/ml). 36 µL of the microbial suspension was subsequently seeded onto polymer coated glass slides in duplicate. Uncoated glass slide was used as negative control. An 18 mm by 18 mm polypropylene cover film was overlaid to spread the seeded microbial suspension over the coated surface. The final microbial load in each set-up was 10^4 CFU/cm². All glass slides were incubated for 24 hours at 37 °C (bacteria) or 28 °C (fungus), 90% humidity. After 24 hours incubation, the glass slides were removed and soaked in 10 mL phosphate buffered saline (PBS, Vivantis, Malaysia) to recover residual microbes. Microbes were enumerated using viable plate count. Briefly, the recovered microbes were serially diluted in PBS and 100 µL of each dilution was plated on nutrient agar (bacteria) or tryptone soya agar (fungus) followed by 18 hours incubation in duplicates. The CFU were counted and the antimicrobial activity (or log reduction) is calculated as:

$$A = \log (C/S)$$

where, A: Antimicrobial activity (log reduction)

C: Average number of viable bacteria on untreated surfaces after 24 hours (Control)

S: Average number of viable bacteria on treated surfaces after 24 hours (Sample)

To test for antimicrobial durability, after one round of antimicrobial testing, the coated surfaces were rinsed thoroughly, air dried for 1 week before re-challenged with the same set of microbes. Procedures were as described in this section.

Coating durability

Physical durability of the coated polymer is crucial as it limits the lifespan of the polymer coating. It does not justify the use of a potent polymer coating if it detaches very easily from the surface. Therefore, after coating, the coated substrates were challenged with physical assault by abrasion to simulate real-life usage, and IR absorbance of characteristic peaks were compared before and after abrasion. After 10 cycles of abrasion (402), the percentage retention of coated PDT-10% was still very high at $70\% \pm 8\%$ while that of DTPAC dropped to $30\% \pm 12\%$.

When the cycles were increased to 100 cycles (404), PDT-10% retention was still at 62 % $\pm$ 10 % but DTPAC has fallen out of detection limit (Fig. 4). The reason for the drastic drop in DTPAC coating retention could be due to the non-specific linkage between DTPAC molecules. For the same concentration of polymer, DTPAC has a much higher amount of methoxysilane groups that could allow for non-specific siloxane bond formation between DTPAC molecules instead of with the glass substrate. This *in-situ* condensation could cause most of the non-specific DTPAC polymers to be removed after abrasion. In contrast, PDT-10% has less methoxysilane groups and therefore reduced probability of non-specific cross-linking. Hence, the flexibility to adjust the proportion between the quaternary ammonium component (QAC) and methoxysilane before polymerization may be beneficial in reducing non-specific cross-linking and enhance physical stability and durability of polymer coating.

Antimicrobial activities

After coating, the polymer was tested for antimicrobial properties against *S. aureus* (502), *E. coli* (504), and *C. albican* (506) representing Gram-positive, Gram-negative and unicellular fungi receptively. Antimicrobial activity of DTPAC and PDT-10% coats were compared against uncoated glass slides (Fig. 5A). The calculated log reduction in microbial load indicates antimicrobial activity of polymer coatings. From the results, PDT-10% coating showed good antimicrobial activity for all 3 organisms with >2 log reduction (>99 %). In contrast, DTPAC coating was only able to reduce *S. aureus* load by >99 % but not for *E. coli* and *C. albican*. To determine functional (antimicrobial) durability of polymer coatings, coated substrates were re-challenged with the same set of microbes after one week. Thorough rinsing and high heat treatment were performed to prevent contamination from the previous challenge. It was found that the PDT-10% coating retained its antimicrobial activity as compared to that in the initial challenge while DTPAC coating lost its antimicrobial activity (Fig. 5B). Loss of antimicrobial effect for the DTPAC coating could be due to the non-specific DTPAC polymers being washed away during preparation for the re-challenge test, similarly to the results in the physical durability test that shows drastic loss of DTPAC coating only after 10 cycles of abrasion. From these results, it can be shown that the PDT-10% polymer can form a more stable and durable coating by being able to adjust the alkoxysilane moiety to reduce non-specific cross-linking *in-situ*.

It must be noted that the antimicrobial activities of QAC monomer, the copolymer and coating are thought to be different. Changes in physiochemical properties after polymerization often lead to the loss of antimicrobial function of polymer. Although DMA-C₁₆ (the quaternary ammonium portion of PDT-10%) has antimicrobial effect in solution, it was necessary to test PDT-10% for antimicrobial activity before coating. The results showed that PDT-10% retained its antimicrobial activity albeit poorer anti-*Candida* property which may be due to a decrease in solubility due to the large steric hindrance that occurs after polymerization (data now shown). The concentration of PDT-10% polymer on the substrate surface could be postulated to provide higher contact-active antimicrobial activity than solubilized PDT-10%, as solubilized PDT-10% may have reduced activity due to dilution by the solvent. However, this would not be an issue for a large polymer such as PDT-10% in the form of a coating.

Materials' biocompatibility

Thiazolyl Blue Tetrazolium Bromide (MTT) cytotoxicity assay was used to test the cytotoxicity of the material on human dermal fibroblasts (HDF), human adult low calcium high temperature (HaCaT) keratinocytes and human embryonic kidney 293 (HEK293) cells. Each cell type was grown in *Dulbecco's Modified Eagle's medium (DMEM, Gibco, Life Technologies, USA)* supplemented with fetal bovine serum (FBS, *Gibco, Life Technologies, USA*). Cells not more than the sixth passage were used. Once they have reached 80% confluence, the cells were harvested and seeded at 10^4 cells per well in 96-well flat-bottomed microtitre plates. The cells were allowed to attach for 24 hours prior to testing. PDT-10% solubilized in dimethyl sulfoxide (DMSO, MP Biomedicals, France) and DTPAC solution were filtered through a 0.2 μm cellulose filter (Acrodisc, USA) and serially diluted two-fold with sterile water. Prior to the experiment, 180 μL of fresh culture medium was replaced to maintain the growing cells and 20 μL of polymer solution was added into each well in six-replicates. Final polymer concentration in each microwells range from 0–250 $\mu\text{g/mL}$. The microtitre plates were incubated at 37 °C, 24 hours in humidified 5% CO_2 (Binder, Germany). Following that, all the media was removed and replaced with 180 μL of fresh culture medium and 20 μL of 5 mg/mL MTT solution (MP Biomedicals, France). The plates were incubated for 4 hours, 37 °C. The medium was again removed and formazan crystals formed were dissolved in 200 μL DMSO. Absorbance of dissolved crystals was measured using Tecan Infinite M200 microplate reader (Switzerland) at 595 nm. Wells containing only DMSO were used as blank. Cell viability was expressed as:

$$(A_{595} \text{ Sample} - A_{595} \text{ DMSO}) / (A_{595} \text{ control} - A_{595} \text{ DMSO}) \times 100\%.$$

Statistical analysis was performed by one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test using IBM SPSS Statistics 19. The difference was considered to be statistically significant at p-value < 0.05.

Cytotoxicity testing is necessary to evaluate biocompatibility of PDT-10% to ensure it is safe for human's usage. A retrospective approach was employed by testing different concentrations of PDT-10% in solution instead of extracting leached materials from PDT-10% coating. This enabled us to quantify the cytotoxic concentration and the safety limits of leached polymer. PDT-10% is labelled 602 and DTPAC was included for comparison (604). Generally, as the concentration of polymer increases, cytotoxicity also increases as shown by a dropped in relative cell viability (Fig. 6). It was evident that at 62.5 $\mu\text{g/mL}$ and above, all 3 cells experienced full toxic effect of both the polymers. Although a decreasing cell viability trend was observed, PDT-10% demonstrated lesser toxic effect on all 3 cell types which was shown by a gentler and more gradual decrease in cell viability than DTPAC at concentrations between 3.91–31.3 $\mu\text{g/mL}$. Many researches have shown good biocompatibility of DTPAC *in vivo*. PDT-10% has comparable, if not less, cytotoxicity as DTPAC.

Example 7: Non-leaching antimicrobial microneedles

The copolymer PDT-10% was employed to form a durable and safe antimicrobial coating on 3M DDS solid microstructured transdermal system (sMTS). 3M MTS microneedle is stored in a sterile state, but it can be reusable by end users and exposure to open environment. Herein, the antimicrobial coating is not designed for treatment purpose, but to reduce the infection risk during microneedle application, especially microneedle reusage.

Materials

The antimicrobial compound PDT-10% was synthesized in house. For other chemicals: isopropanol was purchased from Tedia (USA), acetic acid was purchased from Merck (USA), rhodamine B was purchased from Alfa Aesar (UK). The source of materials for antimicrobial test and cell culture were the same with that used in the above example.

Preparation of PDT-10% Coated Microneedles

In a typical process, 5 mg/ml of PDT-10% coating solution was solubilized in a mixture containing 90% of isopropanol and 10% of acetic acid solution (pH 2.5) following by heating at 50 °C for 30 min. Before coating, 3M sMTS microneedle array was primed with oxygen plasma in a plasma cleaner for 3 min to render them hydrophilicity. Then, 90 µl PDT-10% coating solution was transferred to the treated microneedle array and the array was heated at 50 °C for 1 h to finish the coating of PDT-10% on the needles. The coated needles were washed under tap water for 10 seconds and repeated the washing for 5 times with 10 seconds' interval between each washing before dried again in oven. 1 mg/ml and 0.2 mg/ml of PDT-10% coating solutions were further prepared and used to coat 3M sMTS for antimicrobial and cytotoxicity test, respectively.

Characterizations of PDT-10% Coating on Microneedles

The copolymer PDT-10% has demonstrated superior durability and antimicrobial efficiency on glass substrate, and this effect was extended to antimicrobial performance for microneedles (3M sMTS). 3M sMTS is injection molded from liquid crystal polymers (LCPs) due to their excellent properties, e.g. high mechanical properties, high temperature resistance, chemical stability and good biocompatibility. However, the low surface energy of LCP polymer and the resulting poor adhesion to additional coatings make it difficult to be coated. Fortunately, low pressure and low temperature non-equilibrium plasma activation is a suitable method for pre-treating the surface of many polymers. The excited species of the plasma can modify most polymer surfaces to depth of several nanometers to achieve desired polarities while maintaining the bulk properties, regardless of their substrate pattern geometry and chemical reactivity.

Fig. 7 shows that the contact angle of sMTS microneedle back surface was reduced from around 78° to 20° after plasma treatment. This is because the plasma can activate the polymer surface by creating more oxygen-containing functional groups (such as –OH and –OOH)

on the polymer surface thus increasing the hydrophilicity of the surface. The same reactive functional groups are expected to exist on the needle surface after plasma treatment, which can then form crosslink with the silane group of PDT-10%. We further evaluated the shelf life of this effect. Fig. 8 indicates that the contact angle only increased slightly with time after plasma treatment. This ensured enough working time for the following coating work.

The plasma activated microneedles were further coated with PDT-10%. Platinum sputtering was applied to coat the samples at 10 mA for 180 s. SEM was applied to analyze the microneedle morphology change after coating followed by energy dispersive X-ray spectrometer (EDX) characterization. By using SEM, a high magnification of microneedles were shown. The analysis was performed on FE-SEM (JSM-6700F, JEOL, Japan) equipped with Oxford Instruments INCA X-ray microanalysis system. The appearance of the PDT-10% coated microneedles remained the same white colour as control and no difference was observed under stereomicroscopy observation (up to 12.25 times magnification) compared with control microneedles. It was shown in Fig. 9 that the surface of PDT-10% coated microneedles was rougher than the control microneedle. The change of surface morphology is mainly due to the PDT-10% coating. The EDX analysis showing the existence of bromine atom on the coated microneedles further confirmed the successful coating of PDT-10% on microneedles.

In order to evaluate the durability of PDT-10% coating on microneedles, the coated microneedles was applied on human dermatomed skin at a force of 20 N for 20 times, then the microneedles was checked according to rhodamine B staining.

Rhodamine B staining method was used as an indirect method to characterize the change of microneedle surface property after PDT-10% coating. The coated microneedle array was flood-stained with 90 μ l of 1 mg/ml rhodamine B solution and dried at 50 $^{\circ}$ C for 1 h, then the microneedles were observed under a stereomicroscope. To exclude the solvent influence on the microneedle surface properties, microneedle arrays that experienced plasma treatment and flood-coating of a mixture containing 90% of isopropanol and 10% of pH 2.5 acetic acid solution were used as a negative control.

Fig.10 showed that rhodamine B only accumulated at the base of the needles and did not stain on the tips of control needles. On the contrary, the whole needle body was stained with rhodamine B on PDT-10% coated microneedles (Fig. 10B), which indicated that the tips of microneedles were successfully coated with PDT-10% by the flood coating method. Even after penetrated into skin for 20 times, the PDT-10% coated microneedles were still well covered by rhodamine B stain (Fig. 10C). This indicated that the PDT-10% coating was very durable and cannot be easily removed during the multiple penetration of microneedles into skin.

ATR-FTIR was used to monitor the crosslinking reaction between the microneedle array and PDT-10% copolmer. The back side of the microneedle array with a flat surface was used for this characterization. The back side of the microneedle array was coated with PDT-10% in the same way as described above for microneedles and then subjected to ATR-FTIR examination. Infrared spectra were collected between 4000 and 650 cm^{-1} at a resolution of 4 cm^{-1} .

ATR-FTIR results demonstrated that the coating of PDT-10% on microneedles was not via physical deposition but by forming new chemical bonds (see Fig. 11). PDT-10% (1102) has a strong peak at 1089 cm^{-1} which is the characteristic stretch of the Si—O bond of methoxysilane (—Si—O—CH₃). The formation of siloxane crosslink during the coating process was confirmed by the disappearance of the 1089 cm^{-1} peak after coating (1104), because methoxysilane group was subjected to hydrolysis and formation of siloxane crosslink during the coating process. The ATR-FIR also unveiled that the PDT-10% coating can be hardly washed off as indicated by the similar profile before and after washing (1106).

Antimicrobial Assays and Cytotoxicity Assay of Polymer Coated microneedles

S. aureus was grown to their exponential phase and appropriately diluted in 0.3% agar slurry to achieve the standard inoculum size around $4\text{--}7 \times 10^6$ CFU/ml. The agar slurry was prepared in 0.85% NaCl solution and autoclaved before use. Then, 100 μl bacterial agar slurry was added on the PDT-10% coated microneedles and spread with pipette tips to ensure the good contact. Uncoated microneedles were used as controls. Bacteria recovery was carried out after incubation at $37\text{ }^{\circ}\text{C}$ in humidified condition for 24 hours. Inoculated bacteria were recovered by placing the tested microneedles into 50 ml Falcon tubes containing 10 ml of PBS with 0.5% Tween 80. The tubes were sonicated for 1 min in an ultrasonic water bath (Ultrasonic LC60H, Fisher Scientific) and then vortexed for 1 min before serially diluting the samples in the Tween 80 containing PBS. A viable count was conducted using the spread plate method after appropriate dilution. The CFUs were counted and the antimicrobial activity was expressed as log reduction number of the microorganisms after 24 hours compared with control. If no colony was found on the plate even at the lowest dilution time, then the count was taken as one for calculation.

The biocompatibility of the coated microneedles was evaluated by testing their cytotoxicity against HaCaT (1302) and HDF (1304) keratinocytes using MTT assay (Fig. 13). Microneedles coated with different concentrations of PDT-10% were extracted in 3 ml of PBS at $37\text{ }^{\circ}\text{C}$ for 24 hours. Cells were seeded at a density of 10^4 cells per well in 96-well flat-bottomed microplates (Costar, Corning) and incubated with DMEM culture medium (supplemented with 10% FBS and 1% penicillin-streptomycin solution) for 24 hours. Thereafter, the culture medium was replaced with 180 μl of fresh medium and 20 μl of microneedle extraction solution in each well. For control group, 180 μl fresh culture medium and 20 μl of PBS were added. The culture medium was removed after 24 hours of incubation. Then 20 μl fresh medium and 20 μl of sterile MTT solution (5 mg/ml in PBS) were further added. After another 4 hours of incubation at $37\text{ }^{\circ}\text{C}$, the supernatant was removed by aspiration, and resultant formazan crystals were dissolved in 150 μl of DMSO with shaking. The absorbance at 570 nm was measured using a microplate reader (Tecan, Switzerland) with 650 nm as reference wavelength. Relative cell viability was represented as the percentage of the control group.

As shown in Fig. 12, the antimicrobial efficacy of the PDT-10% coated microneedles depended on the initial concentration of the PDT-10% coating solution. When microneedles were coated with 5 mg/ml and 1 mg/ml of PDT-10%, no bacteria was recovered and log reduction of 4.1 was

obtained. When microneedles was coated with 0.2 mg/ml of PDT-10%, significant reduction of viable bacteria were recovered compared to control but the log reduction was only 1.2. This could be explained by the insufficient coating on the surface of microneedles when the concentration of the copolymer was low.

- 5 In previous report, we have demonstrated that PDT-10% antimicrobial material was non-toxic to human cell lines and indicated that they may be safe to human body. To further verify the non-leaching property of PDT-10% coating, extracted solution was harvested by immersing antimicrobial microneedles in PBS buffer at 37 °C for 24 hours. After incubated with the extraction of PDT-10% coated microneedles for 1 day, no significant
10 difference in cell viability was observed as compared to controls (see Fig. 13). It shows that PDT-10% coated microneedles is non-leaching and safe to both HaCaT keratinocytes and HDF cells.

Summary

- In summary, this study demonstrated a method for conferring antimicrobial activity
15 against *S. aureus* to microneedles using an antimicrobial copolymer coating via a simple thermal-curing process. *S. aureus* is one of the most commonly existing bacteria on skin and the test against *S. aureus* is a proof of concept of our antimicrobial microneedles. The plasma treatment method changed the surface property of the microneedles and rendered the coating possible. This plasma pretreatment method can potentially be used
20 to coat other drug molecules on microneedles as well. A recent study also indicated that plasma treatment significantly increased the surface energy and roughness of the polycarbonate and polyether ether ketone microneedles resulting in better adsorption and release of BSA. Other coating methods may be employed for this antimicrobial coating purpose. Furthermore, PDT-10% is expected to be coated on a large range of substrate as
25 other compounds. Microneedles made from other materials can also be enhanced with PDT-10% coating to harvest the antimicrobial activity to reduce the risk of infection.

Comparative Example 1: Comparison With Other Antimicrobials

- Table 1. Minimum inhibitory concentration (MIC) and minimum bactericidal
30 concentration (MBC)/minimum fungicidal concentration (MFC) against *E. coli*, *S. aureus* and *C. albicans* at an inoculum size of approximately 10⁵ CFU/mL. The unit of the MIC and MBC/MFC values is µm/mL.

Microorganisms		PMAPTAC	PMT-5%	PMT-10%	PDT-10%	DTPAC
<i>S. aureus</i>	MIC	62.5	62.5	62.5	7.8	3.9
	MBC	250	125	125	7.8	3.9
<i>E. coli</i>	MIC	62.5	125	62.5	62.5	62.5
	MBC	62.5	125	62.5	62.5	62.5
<i>C. albicans</i>	MIC	> 500	> 500	> 500	125	15.6
	MFC	> 500	> 500	> 500	>125	62.5

Table 1 shows the antimicrobial measurements taken for the following polymers:

PMAPTAC: polymer of [3-(methacryloylamino) propyl]trimethyl ammonium chloride

5 PMT-5%: polymer having monomer weight ratio of 95% MAPTAC (19.0 g) to 5% 3-trimethylsilylpropyl methacrylate (TMSPMA) (0.5 g)

PMT-10% : polymer having monomer ratio of 90% MAPTAC (18.0 g) to 10% TMSPMA (1.0 g).

10 PDT-10% (inventive polymer): polymer having monomer ratio of 90% [2-(methacryloyloxy)ethyl]dimethyl hexadecyl ammonium bromide (DMA-C₁₆Br) to 10% TMSPMA

DTPAC: dimethyloctadecyl[3-(trimethoxysilyl)propyl]ammonium chloride

15 It can be seen that PDT-10% has superior antimicrobial properties compared to the other comparative examples. Neither PMT-5% nor PMT-10% have a long alkyl chain on the quaternary ammonium moiety. It is thought that the effective bactericidal mechanism of PDT-10% may partly be due to its long alkyl tail which can penetrate and disrupt the membrane of the microbial cells..

Industrial Applicability

The polymer and article disclosed in the present application may have applications in indoor air and HVAC (Heating, ventilation, and air conditioning) systems in buses, truck refrigeration, schools, hospitals, and other buildings.

The polymer and article disclosed in the present application may have applications in the medical industry, for example in catheters, knobs & handles, sinks & basins, dressing trolley, drip stand/IV pole, bed and stair rails, toilet seats, and other medical carts in hospitals & health care systems.

The polymer and article disclosed in the present application may have applications in mold remediation, for example on building walls, ceilings, automobile seat covers and surface coatings.

The polymer and article disclosed in the present application may have applications in the building and construction industry, for example in interior and exterior wall paints.

The polymer and article disclosed in the present application may have applications in the food and beverage industry, for example in consumer packaged goods and can coatings.

The polymer and article disclosed in the present application may have applications in the textiles industry, for example in sport shoes, sweat t-shirts, wrist band, head band, socks, backpacks and caps.

The polymer and article disclosed in the present application may have other applications in cosmetics and personal care products such as tooth brushes, dental restorations, soaps, hair products, deodorants, female hygiene products, children's articles, kitchen towels (dish cloth) and agricultural products such as seed treatment.

The polymer and article disclosed in the present application may have applications as an antifouling coating that repels microorganisms.

It will be apparent that various other modifications and adaptations of the invention will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the invention and it is intended that all such modifications and adaptations come within the scope of the appended claims.

Claims

1. A polymer having a plurality of pendant groups, wherein the pendant groups comprise:

a first pendant group comprising a quaternary ammonium component having the following formula:



wherein n is any integer from 1 to 18;

R¹ is C(O)O or C(O)NH;

R², R³ and R⁴ are each independently an optionally substituted alkyl, optionally substituted aryl,

- 10 or wherein R² and R³ are taken together to form a ring and R⁴ is H or absent; and

X is selected from the group consisting of Cl, Br, I and OSO₃CH₃; and

a second pendant group comprising an organosilane component,

provided that the polymer is substantially free of any other pendant groups.

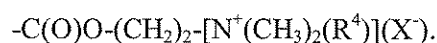
2. The polymer according to claim 1, wherein R¹ is C(O)O.

- 15 3. The polymer according to claim 1 or 2, wherein n is 2.

4. The polymer according to any one of the preceding claims, wherein R² and R³ are each independently an optionally substituted C₁ to C₆ alkyl.

5. The polymer according to claim 4, wherein R² and R³ are both methyl.

- 20 6. The polymer according to any one of the preceding claims, wherein the quaternary ammonium component has the following formula:

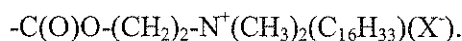


7. The polymer according to any one of the preceding claims, wherein R⁴ is an optionally substituted C₁₄ to C₂₄ alkyl.

8. The polymer according to claim 7, R⁴ is C₁₆ H₃₃.

- 25 9. The polymer according to any one of the preceding claims, wherein the total number of carbon atoms present in R², R³ and R⁴ combined, is greater than 12.

10. The polymer according to any one of the preceding claims, wherein the quaternary ammonium component has the following formula:



11. The polymer according to claim 1 or 2, wherein n is 12 or 16.
12. The polymer according to claim 11, wherein R² and R³ are taken together to form a heterocyclic ring, and R⁴ is H or absent.
13. The polymer according to claim 12, wherein the heterocyclic ring is pyridine.
14. The polymer according to any one of the preceding claims, wherein the organosilane component is organosilane or an organic silane ester.
15. The polymer according to claim 14, wherein the organosilane component has the following formula:

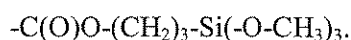


wherein m is any integer from 1 to 6;

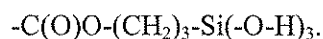
R⁵ is C(O)O or C(O)NH; and

R⁶ is selected from the group consisting of H, an optionally substituted alkyl and a silane ester.

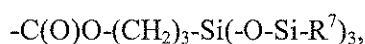
16. The polymer according to claim 15, wherein R⁵ is C(O)O.
17. The polymer according to claim 15 or 16, wherein R⁶ is an optionally substituted C₁ to C₅ alkyl.
18. The polymer according to claim 17, wherein R⁶ is methyl.
19. The polymer according to any one of claims 15 to 18, wherein the organosilane component has the following formula:



20. The polymer according to claim 15, wherein the organosilane component has the following formula:

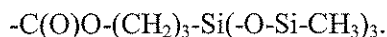


21. The polymer according to claim 15, wherein the organosilane component has the following formula:



wherein R⁷ is an optionally substituted alkyl.

22. The polymer according to claim 21, wherein the organosilane component has the following formula:



23. The polymer according to any one of the preceding claims, wherein the ratio of the organosilane component to the quaternary ammonium component is in the range of 1:2 to 1:5.
24. A polymer having a plurality of pendant groups, wherein the pendant groups consists of:

a first pendant group comprising a quaternary ammonium component having the following formula:



wherein n is any integer from 1 to 18;

R^1 is $\text{C}(\text{O})\text{O}$ or $\text{C}(\text{O})\text{NH}$;

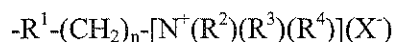
R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or any two of R^2 , R^3 and R^4 are taken together to form a ring; and

- X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and

a second pendant group comprising an organosilane component.

25. A method for preparing a polymer according to any one of claims 1 to 20, comprising the steps of contacting a first monomer with a second monomer in conditions suitable for polymerization, wherein

- a first monomer comprising a quaternary ammonium component having the following formula:



wherein n is any integer from 1 to 18;

R^1 is $\text{C}(\text{O})\text{O}$ or $\text{C}(\text{O})\text{NH}$;

- R^2 , R^3 and R^4 are each independently an optionally substituted alkyl, optionally substituted aryl, or any two of R^2 , R^3 and R^4 are taken together to form a ring; and

X is selected from the group consisting of Cl, Br, I and OSO_3CH_3 ; and

a second monomer comprising an organosilane component,

provided that no other monomer is contacted with the first and second monomer in the polymer.

26. The method according to claim 25, wherein the ratio of the first monomer comprising a quaternary ammonium component to the second monomer comprising an organosilane component is in the range of about 100:1 to 4:1 by weight.
27. The method according to claim 25 or 26, wherein the first monomer comprising the quaternary ammonium component and the second monomer comprising an organosilane component comprise a methacrylate group.
28. The method according to any one of claims 25 to 27, wherein the first monomer comprising the quaternary ammonium component is 2-(methacryloyloxy)ethyl]dimethyl hexadecyl ammonium bromide and the second monomer comprising the organosilane component is 3-trimethylsilylpropyl methacrylate.
29. A polymer obtainable by the method according to any one of claims 25 to 28.
30. An article comprising the polymer of any one of claims 1 to 24 and a substrate comprising a surface.
31. The article according to claim 30, wherein the polymer is adhered to the surface of the substrate.
32. The article according to claim 30 or 31, wherein the substrate comprises a material selected from the group consisting of non-siliceous ceramic material, siliceous material, metal, metal oxide, polymer and any mixture thereof.
33. The article according to any one of claims 30 to 32, wherein the substrate is in a form selected from the group consisting of film, sheet, tube, fiber, needle and any mixture thereof.
34. The article according to any one of claims 30 to 33, wherein the article is a medical device.
35. The article according to any one of claims 30 to 34, wherein article is a microneedle.
36. A method for preparing the article of any one of claims 30 to 35, comprising the steps of:
providing the polymer of any one of claims 1 to 24; and
contacting the polymer with the surface of the substrate under conditions suitable to adhere the polymer to the surface of the substrate.
37. The method of claim 36, wherein the polymer is solubilized in a solvent.
38. The method of claim 36 or 37, wherein the contacting step further comprises adding a catalyst.

39. The method of claim 38, wherein the catalyst is an acid.
40. The method of any of claims 38 to 39, comprising the step of pre-treating the surface of the substrate prior to the contacting step.
41. The method of claim 40, wherein the pre-treatment step comprises plasma cleaning.
- 5 42. The use of the polymer of any one of claims 1 to 24 as a surface coating.