



(12) **DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION**

(13) **A1**

(22) **Date de dépôt/Filing Date:** 2023/07/11

(41) **Mise à la disp. pub./Open to Public Insp.:** 2024/02/05

(30) **Priorité/Priority:** 2022/08/05 (US17/817,666)

(51) **Cl.Int./Int.Cl. C23C 14/06** (2006.01),
A01N 25/34 (2006.01), **A01N 59/20** (2006.01),
A01P 1/00 (2006.01), **A61L 2/20** (2006.01),
B05D 5/00 (2006.01), **C23C 14/32** (2006.01),
C23C 14/35 (2006.01)

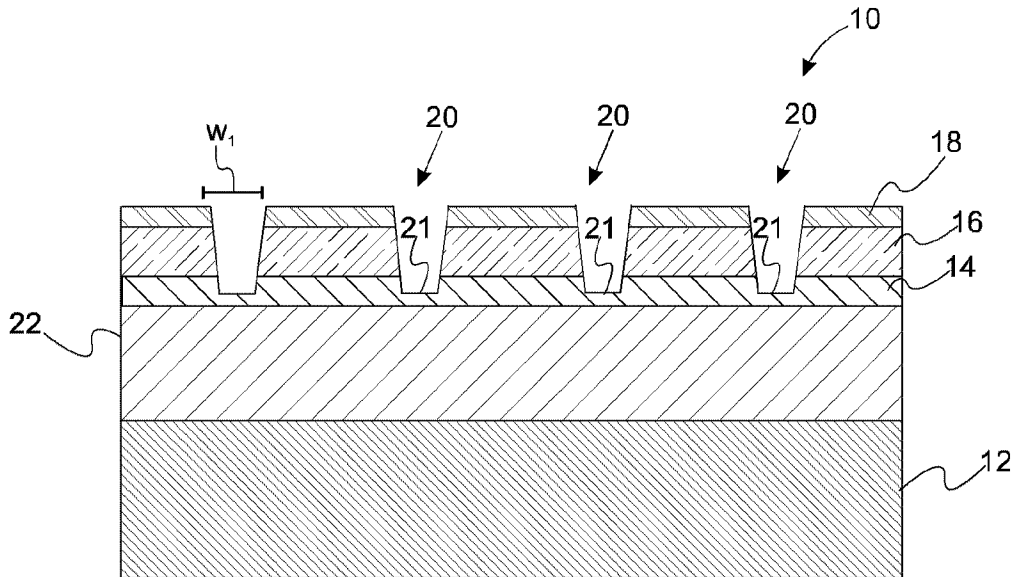
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(54) **Titre : REVETEMENT ANTI-MICROBIEN PAR DEPOT PHYSIQUE EN PHASE VAPEUR, COMME L'EVAPORATION PAR ARC CATHODIQUE**

(54) **Title: ANTI-MICROBIAL COATING PHYSICAL VAPOR DEPOSITION SUCH AS CATHODIC ARC EVAPORATION**



(57) **Abrégé/Abstract:**

A bioactive coated substrate includes a base substrate, a first interlayer disposed over the base substrate, an outermost bioactive layer disposed on the first interlayer, and a topcoat layer disposed on the outermost bioactive layer. Characteristically, a plurality of microscopic openings extending through the topcoat layer and the outermost bioactive layer expose the first interlayer and the outermost bioactive layer. A method for forming the bioactive coated substrate is also provided.

ABSTRACT

A bioactive coated substrate includes a base substrate, a first interlayer disposed over the base substrate, an outermost bioactive layer disposed on the first interlayer, and a topcoat layer disposed on the outermost bioactive layer. Characteristically, a plurality of microscopic openings extending through the topcoat layer and the outermost bioactive layer expose the first interlayer and the outermost bioactive layer. A method for forming the bioactive coated substrate is also provided.

ANTI-MICROBIAL COATING PHYSICAL VAPOR DEPOSITION SUCH AS CATHODIC ARC EVAPORATION

TECHNICAL FIELD

[0001] In at least one aspect, the present invention relates to a coating system with bioactive properties that is formed by physical vapor deposition and related methods.

BACKGROUND

[0002] Physical vapor deposition (PVD) is a technique for thin film formation or coating a substrate. PVD involves vaporization of a material that then condenses on a surface, forming a coating layer. PVD can result in the deposit of macroparticles, which are often considered a defect. The macroparticles may be loosely bound to the coated layer. Mechanical processes can be used to remove these macroparticles, but removal leaves pinholes, which are also often considered defects. For example, cathodic arc evaporation (CAE), a form of PVD, involving a high current, low voltage arc on the surface of a cathodic target produces macroparticles. Because macroparticles and pinholes are recognized as defects, great effort to eliminate or reduce the size and quantity of macroparticles is afforded.

[0003] Coatings with bioactive properties can be useful for various purposes. Bioactive refers to a material having biological effects or physiological effects on living things. For example, a bioactive material includes a material resulting in a modification in the normal biological function or a physiological mechanism of a living thing. Bioactive, as used herein, includes beneficial and detrimental effects to microorganisms or modifications to the normal functioning of a microorganism. One common bioactive material is antimicrobial substances. Antimicrobial coatings serve many purposes. Generally, antimicrobial coatings inhibit the growth or kill microbes like viral, bacterial or fungal organisms. One particularly relevant example includes preventing the spread of communicable diseases by the use of antimicrobial materials. Antimicrobial materials may also serve hygienic purposes. The desire to prevent the spread of disease and for heightened hygiene has resulted in significant efforts to develop antimicrobial materials. The use of antimicrobial materials in health care facilities and health treatments can provide significant benefits. Health facilities, such as hospitals,

present unique environments that combine high concentrations of germs and individuals with vulnerable immunities. Therefore, facilities such as hospitals greatly benefit from antimicrobial surfaces. Antimicrobial materials for medical equipment can reduce the burden of disinfecting and prevent the spread of disease. Further, affordable antimicrobial surfaces could present benefits on any surface that comes into contact with living things. For example, surfaces involved in cooking or commonly touched surfaces like doorknobs could greatly benefit from antimicrobial properties. Even primarily decorative surfaces, if affordable, could benefit from antimicrobial characteristics and assist in inhibiting the spread and growth of harmful or undesirable antimicrobial life.

[0004] But producing antimicrobial materials can be difficult and expensive. Further, antimicrobial properties may have other undesirable properties. For example, some antimicrobial materials may be too soft. Other antimicrobial materials may have poor abrasion resistance. Microban® is an antimicrobial coating that includes silver particles dispersed in an organic matrix. Antimicrobial coatings involving an organic matrix may have the aesthetic appearance of paint. In some applications, the appearance of paint may be undesirable. Some antimicrobial coatings may use nanoparticle vapor deposition to deposit nanoparticles with antimicrobial properties on the surface of a coating. For example, ABACO® from Protec, is an antimicrobial coating using nanoparticles. However, the use of nanoparticles can be complex and expensive. Further such coatings may have delicate surfaces or poor abrasion resistance. Another example of antimicrobial materials includes various metals. For example, silver is known to have antimicrobial properties. However, as stated above silver can be expensive, and its properties may not be suitable for many applications. For example, the appearance or abrasion resistance of silver may be unsuitable for certain applications.

[0005] Accordingly, there is a need for an antimicrobial coating that solves one or more of these problems or offers an alternative to current antimicrobial materials.

SUMMARY

[0006] In at least one aspect, a bioactive coated substrate is provided. The bioactive coated substrate includes a base substrate, a first bioactive layer disposed over the base substrate, and a topcoat layer disposed on the outermost bioactive layer. Characteristically, the topcoat layer defines a plurality of microscopic openings that expose the outermost bioactive layer.

[0007] In another aspect, a bioactive coated substrate is provided. The bioactive coated substrate includes two or more layers (e.g., alternating) of bioactive material and an inert material where the inert layer always on top. The bioactive coated substrate includes pits or cracks with exposure of some combination of rings and spots of bioactive material. Bioactive materials are compounds and alloys of Cu (e.g., Cu, Cu₂O, CuO, brass, bronze) while inert materials include compounds and alloys of Zr, Ti, Cr, DLC. The bioactive coated substrate can include a hydrophobic layer includes a SiO_x adhesion layer and a fluorinated polymer layer.

[0008] In another aspect, a method of forming the bioactive coated substrate set forth herein is provided. The method includes steps of providing a base substrate and then depositing an outermost bioactive layer over the substrate. The outermost bioactive layer has a plurality of macroparticles extending from a surface of the outermost bioactive layer. Otherwise, macroparticles extending from the surface are applied to the outermost bioactive layer. A topcoat layer is deposited on the outermost bioactive layer. Characteristically, the plurality macroparticles extend into the topcoat layer. At least a portion of the plurality macroparticles is removed to form a plurality of microscopic openings in the topcoat layer down to the outermost bioactive layer.

[0009] In another aspect, a bioactive coated substrate is provided. The bioactive coated substrate includes a base substrate, a first interlayer disposed over the base substrate, an outermost bioactive layer disposed on the first interlayer, and a topcoat layer disposed on the outermost bioactive layer. A plurality of microscopic openings extending through the topcoat layer and the outermost bioactive layer expose the first interlayer and the outermost bioactive layer. Characteristically, the plurality of microscopic openings originating in the first interlayer.

[0010] In still another aspect, a method for forming a bioactive coated substrate is provided. The method includes steps of providing a base substrate and depositing a first interlayer over the base substrate. The first interlayer includes a plurality of macroparticles protruding from the surface of the first interlayer. An outermost bioactive layer is deposited over the first interlayer where the plurality of macroparticles extends into the outermost bioactive layer. A topcoat layer is deposited on the outermost bioactive layer where the plurality of macroparticles extends into the topcoat layer. Finally, at least a portion of the plurality of macroparticles is removed to form a plurality of microscopic openings in the topcoat layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIGURE 1A is a cross-sectional view of a variation of a bioactive coated substrate having a plurality of microscopic openings.

[0012] FIGURE 1B is a cross-sectional view of a variation of a bioactive coated substrate having a plurality of microscopic openings.

[0013] FIGURE 1C is a cross-sectional view of a variation of a bioactive coated substrate having a plurality of microscopic openings.

[0014] FIGURE 1D is a top view of a variation of a bioactive coated substrate having a plurality of microscopic openings.

[0015] FIGURE 2A is a cross-sectional view of a variation of a bioactive coated substrate having multiple bioactive layers a plurality of microscopic openings in the topcoat layer.

[0016] FIGURE 2B is a cross-sectional view of a variation of a bioactive coated substrate having multiple bioactive layers a plurality of microscopic openings in the topcoat layer.

[0017] FIGURE 2C is a cross-sectional view of a variation of a bioactive coated substrate having multiple bioactive layers a plurality of microscopic openings in the topcoat layer.

[0018] FIGURE 3A is a cross-sectional view of a precursor-coated substrate having a single bioactive layer with a plurality of macroparticles and a topcoat layer.

[0019] FIGURE 3B is a cross-sectional view of a precursor coated substrate having multiple bioactive layers with an outermost bioactive layer having a plurality of macroparticles.

[0020] FIGURE 4 is a cross-sectional view of a bioactive coated substrate coated with a hydrophobic layer.

[0021] FIGURE 5 is a flow chart depicting a method for preparing a bioactive coated substrate.

[0022] FIGURE 6 provides Table 1 which shows the properties of bioactive coated substrates and a copper penny.

[0023] FIGURE 7 provides Table 2 which shows results for the growth of bacteria (i.e., *S. aureus*) on stainless steel, brass, a multilayer sample having a buried active layer with microscopic openings, and a sample with the bioactive layer on top.

[0024] FIGURE 8 provides top surface elemental mapping (EDS) of a bioactive coated substrate.

[0025] FIGURE 9 provides SEM cross-section images of a bioactive coated substrate.

DETAILED DESCRIPTION

[0026] Reference will now be made in detail to presently preferred compositions, embodiments and methods of the present invention, which constitute the best modes of practicing the invention presently known to the inventors. The Figures are not necessarily to scale. However, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various and alternative forms. Therefore, specific details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for any aspect of the invention and/or as a representative basis for teaching one skilled in the art to variously employ the present invention.

[0027] Except in the examples, or where otherwise expressly indicated, all numerical quantities in this description indicating amounts of material or conditions of reaction and/or use are to be understood as modified by the word “about” in describing the broadest scope of the invention. Practice within the numerical limits stated is generally preferred. Also, unless expressly stated to the contrary: percent, “parts of,” and ratio values are by weight; the description of a group or class of materials as suitable or preferred for a given purpose in connection with the invention implies that mixtures of any two or more of the members of the group or class are equally suitable or preferred; description of constituents in chemical terms refers to the constituents at the time of addition to any combination specified in the description, and does not necessarily preclude chemical interactions among the constituents of a mixture once mixed; the first definition of an acronym or other abbreviation applies to all subsequent uses herein of the same abbreviation and applies *mutatis mutandis* to normal grammatical variations of the initially defined abbreviation; and, unless expressly stated to the contrary, measurement of a property is determined by the same technique as previously or later referenced for the same property.

[0028] It must also be noted that, as used in the specification and the appended claims, the singular form “a,” “an,” and “the” comprise plural referents unless the context clearly indicates otherwise. For example, reference to a component in the singular is intended to comprise a plurality of components.

[0029] The phrase “composed of” means “including” or “comprising.” Typically, this phrase is used to denote that an object is formed from a material.

[0030] The term “comprising” is synonymous with “including,” “having,” “containing,” or “characterized by.” These terms are inclusive and open-ended and do not exclude additional, unrecited elements or method steps.

[0031] The phrase “consisting of” excludes any element, step, or ingredient not specified in the claim. When this phrase appears in a clause of the body of a claim, rather than immediately following the preamble, it limits only the element set forth in that clause; other elements are not excluded from the claim as a whole.

[0032] The phrase “consisting essentially of” limits the scope of a claim to the specified materials or steps, plus those that do not materially affect the basic and novel characteristic(s) of the claimed subject matter.

[0033] With respect to the terms “comprising,” “consisting of,” and “consisting essentially of,” where one of these three terms is used herein, the presently disclosed and claimed subject matter can include the use of either of the other two terms.

[0034] The term “substantially,” “generally,” or “about” may be used herein to describe disclosed or claimed embodiments. The term “substantially” may modify a value or relative characteristic disclosed or claimed in the present disclosure. In such instances, “substantially” may signify that the value or relative characteristic it modifies is within $\pm 0\%$, 0.1% , 0.5% , 1% , 2% , 3% , 4% , 5% or 10% of the value or relative characteristic.

[0035] It should also be appreciated that integer ranges explicitly include all intervening integers. For example, the integer range 1-10 explicitly includes 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10. Similarly, the range 1 to 100 includes 1, 2, 3, 4, . . . 97, 98, 99, 100. Similarly, when any range is called for, intervening numbers that are increments of the difference between the upper limit and the lower

limit divided by 10 can be taken as alternative upper or lower limits. For example, if the range is 1.1 to 2.1 the following numbers 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 2.0 can be selected as lower or upper limits. In the specific examples set forth herein, concentrations, temperature, and reaction conditions (e.g. pressure, flow rates, etc.) can be practiced with plus or minus 50 percent of the values indicated rounded to three significant figures. In a refinement, concentrations, temperature, and reaction conditions (e.g., pressure, flow rates, etc.) can be practiced with plus or minus 30 percent of the values indicated rounded to three significant figures of the value provided in the examples. In another refinement, concentrations, temperature, and reaction conditions (e.g., flow rates, etc.) can be practiced with plus or minus 10 percent of the values indicated rounded to three significant figures of the value provided in the examples.

[0036] In the examples set forth herein, concentrations, temperature, and reaction conditions (e.g., pressure, flow rates, etc.) can be practiced with plus or minus 50 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples. In a refinement, concentrations, temperature, and reaction conditions (e.g., pressure, flow rates, etc.) can be practiced with plus or minus 30 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples. In another refinement, concentrations, temperature, and reaction conditions (e.g., pressure, flow rates, etc.) can be practiced with plus or minus 10 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples.

[0037] For all compounds expressed as an empirical chemical formula with a plurality of letters and numeric subscripts (e.g., CH₂O), values of the subscripts can be plus or minus 50 percent of the values indicated rounded to or truncated to two significant figures. For example, if CH₂O is indicated, a compound of formula C_(0.8-1.2)H_(1.6-2.4)O_(0.8-1.2). In a refinement, values of the subscripts can be plus or minus 30 percent of the values indicated rounded to or truncated to two significant figures. In still another refinement, values of the subscripts can be plus or minus 20 percent of the values indicated rounded to or truncated to two significant figures.

[0038] The thickness of all layers described herein can have a thickness from 50 to 1500 nm unless explicitly stated to the contrary.

[0039] Abbreviations:

- [0040] “CAE” means cathodic arc evaporation.
- [0041] “EDS” means Energy-dispersive X-ray spectroscopy.
- [0042] “PVD” means physical vapor deposition.
- [0043] “SEM” means scanning electron microscopy.
- [0044] “XRF” means X-ray fluorescence.
- [0045] The term “microscopic opening” refers to an opening that has at least one spatial dimension that is less than 15 microns.
- [0046] Referring to Figures 1A, 1B, and 1C, a schematic cross-section of a substrate coated with a bioactive material is provided. Bioactive coated substrate 10 includes a base substrate 12 and a first interlayer 14 disposed over and optionally contacting the substrate. In a refinement, first interlayer 14 has a thickness from about 50 to 1500 nm. The term “base substrate” refers to the substrate before is coated to form the bioactive substrate set forth below. Outermost bioactive layer 16 is disposed over and optionally contacts first interlayer 14. As used, the term “outermost bioactive layer” refers to the bioactive layer furthest from the base substrate. In a refinement, outermost bioactive layer 16 has a thickness from about 50 to 5000 nm. In a refinement, bioactive coated substrate 10 also includes a topcoat layer 18 disposed over and optionally contacting the topcoat layer. In a refinement, topcoat layer 18 has a thickness from about 50 to 1500 nm.
- [0047] Characteristically, a plurality of microscopic openings 20 exposes outermost bioactive layer 16 to ambient. In a refinement, the plurality of holes includes an opening type selected from the group of pores, pinholes, pits, and combinations thereof. In this regard, Figure 1D provides a top view from the topcoat layer side illustrating the exposure of the underlying layers. The plurality of openings 20 is at least partially defined by topcoat layer 18. The plurality of microscopic openings 20 can be further defined by outermost bioactive layer 16 and first interlayer 14 depending on how deep the microscopic openings extend. Typically, the microscopic openings have an average width w_1 of about 100 nm to 10 microns. In this context, “width” means a distance between walls extending from the microscopic opening bottom 21 that defines each opening. In a further refinement, the topcoat layer 18 defines at least about 1 microscopic opening per square millimeter. Alternatively, the width w_1 is the minimum diameter of a circular cylinder that can enclose a microscopic opening. In some

refinements, the topcoat layer 18 defines in increasing order of preferences, at least about 1 microscopic opening per square millimeter, at least about 2 microscopic openings per square millimeter, at least about 3 microscopic openings per square millimeter, at least about 4 microscopic openings per square millimeter, or at least about 5 microscopic openings per square millimeter.

[0048] In a refinement, base layer 22 is interposed between substrate 12 and first interlayer 14. Base layer 22 optionally contacts substrate 12 and an interlayer (e.g., first interlayer 14) on opposite faces. In a refinement, the base layer is composed of a component selected from the group consisting of zirconium carbonitride, zirconium nitride, zirconium oxycarbide, zirconium oxynitride, and zirconium oxycarbonitride. Base layer 22 when present typically has a thickness from about 20 to 300 nm. It should be appreciated that the present embodiment is not limited by the particular deposition methods for depositing outermost bioactive layer 16 and topcoat layer 18. For example, these layers can be made by CVD, PVD which could be sputtering, or CAE.

[0049] Outermost bioactive layer 16 and topcoat layer 18 can be applied to any suitable substrate 12. A suitable substrate 12 can be composed of any material that exhibits thermal stability at an operational (i.e., the temperature that the bioactive coated substrate is used at) or deposition temperatures for each of the layers. In particular, substrate 12 should be thermally stable at a temperature of at least 80°C. In a refinement, the substrate 12 should be thermally stable at a temperature of at least 250°C. In some refinements, a suitable substrate 12 can be composed of any material that is electrically conductive. For example, suitable materials that the base substrate can be composed of include, but are not limited to, metals, metal alloys, and/or carbon materials. Additional examples of suitable materials that the base substrate can be composed of include, but are not limited to, stainless steel, chromium-nickel plated brass, chromium-nickel-copper plated zinc, chromium-nickel-copper plated ABS plastic and chromium-nickel-copper plated aluminum.

[0050] In some variations as depicted in Figures 1A, 1B, and 1C, the microscopic openings narrow along a direction perpendicular to the base substrate 12.

[0051] In the variation depicted in Figure 1A, the topcoat layer defines a plurality of microscopic openings that expose the first interlayer 14 and the outermost bioactive layer 16. In this regard, at least a subset of the microscopic openings extend to first interlayer 14.

[0052] In the variation depicted in Figure 1B, the topcoat layer defines a plurality of microscopic openings that only expose the outermost bioactive layer 16. In this regard, at least a subset of the microscopic openings extends to the outermost bioactive layer 16. In this refinement, first interlayer 14 is optional.

[0053] In the variation depicted in Figure 1C, the topcoat layer defines microscopic openings that expose the first interlayer 14 and the outermost bioactive layer 16. In this regard, a first subset of the microscopic openings extend to the first interlayer 14 and a second subset of the microscopic openings extend only to the outermost bioactive layer 16.

[0054] Figure 2A, 2B, and 2C provide schematic cross-sections of a bioactive coated substrate 10' having a multilayer stack 24 that includes one or more additional bioactive layers 16' alternating with one or more additional interlayers 14'. The multilayer stack 24 is interposed between the base substrate 12 and the first interlayer 14. Characteristically, additional microscopic openings extend to a microscopic opening bottom 28 such that any layer above microscopic opening bottom 28 is exposed to ambient. In particular, that first bioactive layer 16, any additional bioactive layer 16', first interlayer 14, and any additional interlayers 14' above the microscopic opening bottom, the microscopic opening bottom interlayer, and each interlayer above the microscopic opening bottom interlayer are exposed to ambient. A set forth above, topcoat layer 18 is disposed over outermost bioactive layer 16. In one refinement, the additional microscopic openings originate from an interlayer. In another refinement, the additional microscopic openings originate from a bioactive layer. In still another refinement, additional microscopic openings originate from both interlayers and bioactive layers. Typically, there can be 1 to 10 additional bioactive layers 16' and 1 to 10 interlayers 14'. It should be appreciated that microscopic openings 20 can extend to outermost bioactive layer 16 and/or to any of the additional interlayers 14' and/or to any of the additional bioactive layers 16'. In a refinement, the first interlayer 14 and additional interlayers 14' can be composed of zirconium carbonitride, zirconium nitride, zirconium oxycarbide, zirconium oxynitride, or zirconium oxycarbonitride. In another refinement, the additional interlayers 14' can also be bioactive layers but with a different thickness and/or stoichiometry than the bioactive layers, it contacts on opposite faces. In this regard, interlayers 14 can be composed of various copper alloys, as set forth below. In another refinement, the first interlayer 14 and additional interlayers 14' can be composed of a metal nitride. For example, the first interlayer 14 and additional interlayers 14' can be composed of zirconium nitride (ZrN), titanium nitride (TiN),

zirconium oxycarbides (ZrOC), zirconium oxides (ZrO₂), diamond-like-carbon (DLC) or a combination thereof.

[0055] In some variations as depicted in Figures 2A, 2B, and 2C, the microscopic openings narrow along a direction perpendicular to the base substrate 12.

[0056] In the variation depicted in Figure 2A, the topcoat layer defines a plurality of microscopic openings that expose the first interlayer 14, additional interlayers 14', the outermost bioactive layer 16, and additional bioactive layers 14'. In this regard, at least a subset of or all of the microscopic openings extend to first interlayer 14 and/or the additional interlayers 14'.

[0057] In the variation depicted in Figure 2B, the topcoat layer defines a plurality of microscopic openings that expose the first interlayer 14, additional interlayers 14', the outermost bioactive layer 16, and additional bioactive layers 14'. In this regard, at least a subset of or all the microscopic openings extends to the outermost bioactive layer 16 and additional bioactive layers 16'.

[0058] In the variation depicted in Figure 2C, the topcoat layer defines a plurality of microscopic openings that expose the first interlayer 14, additional interlayers 14', the outermost bioactive layer 16, and additional bioactive layers 14'. In this regard, a first subset of the microscopic openings extend to first interlayer 14 and additional interlayers 14' and a second subset of the microscopic openings extend to the outermost bioactive layer 16 and additional bioactive layers 16'.

[0059] In a variation, the plurality of microscopic openings 20 is formed from a plurality of macroparticles formed on a surface of or within one or more of first interlayer 14, outermost bioactive layer 16, additional interlayer 14', additional bioactive layers 16' the outermost bioactive layer 16 during deposition of that layer as set forth below. In this context, the term "macroparticles" refers to particles having at least one spatial dimension greater than 100 nm. Typically, cathodic arc deposition and CAE can form such macroparticles while sputtering tends to form smooth layers without such particles. The macroparticles extend into the topcoat layer and are subsequently removed as described below in more detail to form the microscopic openings.

[0060] Other techniques can be used to expose the bioactive layers and interlayers. For example, masking and selective etching as in photolithography can be used to expose the bioactive layers and interlayers. In another refinement, the top layer can be porous through columnar growth or, like with electroplating. In still another refinement, bioactive layers and interlayers can be exposed

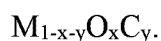
through microcracking or pitting by applying a stressed layer. In yet another refinement, the top layer could be partially removed by mechanical means like scratching or drilling. In another, bioactive layers and interlayers can be deposited with crack or pits or porosity.

[0061] In another variation, base layer 22, the first interlayer 14, and additional interlayers 14' are independently composed of zirconium or titanium, carbon, and nitrogen where zirconium is present in an amount of at least 50 mole percent with each of the carbon and nitrogen present in an amount of at least 0.02 and 0.1 mole percent, respectively. In a refinement, base layer 22 and interlayers 14 are independently composed of a compound having the following formula:



where M is zirconium or titanium and x is 0.0 to 0.3 and Y is 0.1 to 0.5. In a refinement, x is 0.0 to 0.2 and y is 0.2 to 0.3. In another refinement, x is at least in increasing order of preference 0.0, 0.02, 0.03, 0.04, 0.05, 0.07, or 0.09 and at most in increasing order of preference, 0.5, 0.4, 0.3, 0.25, 0.2, 0.15, or 0.11. Similarly, in this refinement, y is at least in increasing order of preference 0.1, 0.15, 0.2, 0.25, 0.27, or 0.29 and at most in increasing order of preference, 0.6, 0.5, 0.40, 0.35, 0.33, or 0.31. In a further refinement, the base layer is composed of zirconium carbonitride described by $Zr_{0.60}C_{0.10}N_{0.30}$.

[0062] In still another variation, base layer 22, the first interlayer 14, and additional interlayers 14' are independently composed of zirconium or titanium, carbon, and oxygen where zirconium is present in an amount of at least 50 mole percent with each of the carbon and oxygen present in an amount of at least 0.02 and 0.1 mole percent, respectively. In a refinement, base layer 22 and interlayers 14 independently are independently composed of a compound having the following formula:



where M is zirconium or titanium and x is 0.1 to 0.4 and y is 0.5 to 0.2. In a further refinement, the base layer is composed of zirconium oxycarbide described by $Zr_{0.50}O_{0.35}C_{0.15}$.

[0063] Bioactive layer 16 and any additional bioactive layers 16' can be any material with bioactive properties. In particular, the bioactive layer 16 and any additional bioactive layers 16' are antimicrobial layers. Therefore, bioactive layer 16 and any additional bioactive layers 16' can include

a material with antimicrobial properties. In a refinement, the bioactive layer 16 and any additional bioactive layers 16' can be composed of a metal or metal-containing compound with antimicrobial properties. For example, bioactive layer 16 and any additional bioactive layers 16' can be composed of a metal, a metal oxide, a metal alloy or any combination thereof. In another refinement, bioactive layer 16 and any additional bioactive layers 16' can be composed of a component selected from the group consisting of include copper alloys, or copper-containing compounds. Such copper-containing compounds include copper atoms in the +1 or +2 oxidation state or combinations of copper atoms thereof. Examples of copper-containing compounds include, but are limited to copper, copper oxides, copper nitrides, copper oxides containing carbon atoms, and combinations thereof. In one variation, copper alloys include copper and nickel. Typically, each copper alloy includes nickel in an amount from about 8 to 28 weight percent of the total weight of the bioactive layer with the copper being present in an amount from about 72 to 92 weight percent of the total weight of the bioactive layer. In a refinement, the copper alloy includes nickel in an amount from about 10 to 25 weight percent of the total weight of the bioactive layer and copper in an amount from about 75 to 90 weight percent of the total weight of the bioactive layer. In some variations, the copper alloy can independently include additional elements such as iron, zirconium, tungsten, chromium, and combinations thereof. In a refinement, each of these additional elements is independently present in an amount from about 0.01 to about 5 weight percent of the total weight of the bioactive layer. In a refinement, each of these additional elements are independently present in an amount from about 0.01 to about 5 weight percent of the total weight of the bioactive layer. Examples of copper alloys are CuVerro[®] White Bronze and CuVerro[®] Rose commercially available from Olin Brass located in Louisville, KY.

[0064] In other variations, the bioactive layer 16 and any additional bioactive layers 16' include silver, a silver alloy, a silver-containing compound (e.g., a silver oxide), or any combination thereof. Other metals that can exhibit antimicrobial properties include but are not limited to gallium (Ga), gold (Au), magnesium (Mg), titanium (Ti), and zinc (Zn). The bioactive layers 16 and 16' can include a combination of metals, metal oxides or metal alloys. This includes, for example, a bioactive layer 16 that includes copper (Cu) and silver (Ag).

[0065] In one refinement, each of the one or more of the bioactive layer 16 and any additional bioactive layers 16' are independently composed of CuO_x , where x is from 0.1 to 1.0. In another refinement, each of the one or more of the bioactive layers 16 and 16' independently composed of CuO_aN_b , where a is from 0.0 to 1.2 and b , is from 0.01 to 0.4. In still another refinement, each of the

one or more of the bioactive layer 16 and any additional bioactive layers 16' independently composed of CuO_cC_d , where c is from 0.0 to 1.2 and d, is from 0.01 to 0.4. In a variation, each of the one or more of the bioactive layers 16 and 16' independently composed of any combination of copper metal, CuO_x , CuO_aN_b , and CuO_cC_d ; Therefore, each of the one or more of the bioactive layers 16 and 16' independently composed of a combination of copper metal, CuO_x , CuO_aN_b , and CuO_cC_d or a combination of copper metal and CuO_x or a combination of copper metal and CuO_aN_b ; a mixture of copper metal and CuO_cC_d or a combination of copper metal, CuO_x , and CuO_aN_b or a combination of copper metal, CuO_x and CuO_cC_d or a combination of copper metal, CuO_aN_b , and CuO_cC_d or a combination of CuO_x , CuO_aN_b , and CuO_cC_d or a combination of CuO_x and CuO_aN_b or a combination of CuO_aN_b , and CuO_cC_d or a combination of CuO_x , CuO_aN_b , and CuO_cC_d . Some suitable bioactive layers can be composed of Cu_xO_y , Cu_xN_y , $\text{Cu}_x\text{O}_y\text{N}_z$, and $\text{Cu}_x\text{O}_y\text{C}_z$ where x can be 1, 2, or 3; y can be 1, 2, or 3; and z can be 1, 2, or 3.

[0066] Advantageously, topcoat layer 18 provides a number of useful properties to the bioactive coated substrate. For example, the topcoat layer 18 can provide improved abrasion resistance. In particular, the topcoat layer 18 can provide a higher abrasion resistance than outermost bioactive layer 16. A topcoat layer 18 with higher abrasion resistance can reduce wear to the surface of outermost bioactive layer 16. In another refinement, bioactive coated substrate 10 includes an antimicrobial layer and a topcoat layer 18 with a higher abrasion resistance can be suitable for a surgical tool or instrument. In addition to abrasion resistance, other useful properties of the topcoat layer 18 include determining the final color/appearance of the coating and corrosion resistance. The abrasion resistance can be determined by ISO 28080. The topcoat layer 18 is not limited to providing abrasion resistance. For example, the topcoat layer 18 can provide improved hardness, impact resistance and/or toughness. In another example, the topcoat layer 18 can provide an appealing or desired aesthetic effect. For example, the topcoat layer can be chromium. Topcoat layer 18 can also impart improved hardness to the bioactive coated substrate. The topcoat layer 18 can be applied by any suitable deposition technique such as PVD and CAE. In a refinement, topcoat layer 106 can be composed of carbides, gold, graphite, nitrides, platinum, titanium, or titanium nitride, Zr, ZrN, ZrCN, ZrON, ZrO_2 , ZrOC, Cr, CrN, CrCN, Ti, TiN, TiCN, TiON, TiO_2 , and TiOC.

[0067] In a variation, the layer immediately below the outermost bioactive layer 16 can be used as an indicator layer that the outermost bioactive layer 16 has worn away. Such an indicator layer can serve as a visual indication that the outermost bioactive layer 16 is compromised. For

example, the indicator can have a distinctly different color from the bioactive layer 16 and thus serve to visually alert a user that the outermost bioactive layer 16 is compromised. With respect to setting the color of the various layers so that color differences can be determined, it should be appreciated that the color of each of the layers set forth above can independently be changed by adjusting the thicknesses and or stoichiometries of the layer. In a refinement, the indicator layer can be another metal, alloy or metal-containing compound with a distinctly different color. Advantageously, the bioactive coated substrate is such that the color of the top most (from the substrate) bioactive antimicrobial layer has a visually perceivable color that is different from the color of the layer immediately below it.

[0068] With respect to the bioactive coated substrates 10 and 10' of Figures 1 and 2, there are two scenarios by which the wear can be visually detected. In the first scenario, wearing away of both topcoat 16 and outermost bioactive layer 16 is visually perceived because of the different colors of top layer 16 and the layer immediately below the top layer. In the second scenario, topcoat layer 18 and outermost bioactive layer 16 can be of a sufficiently different color such that wearing away of topcoat layer 18 is visually perceived.

[0069] In accessing color differences, it should be appreciated that the outermost bioactive layer 14 and the layer immediately below the outermost bioactive layer (as well as the substrate and other layers) can be characterized by Lab color space coordinates L^* , a^* , and b^* relative to CIE standard illuminant D50. In a refinement, at least one of Lab color space coordinates L^* , a^* , and b^* relative to CIE standard illuminant D50 of the outermost bioactive layer differs from that of the layer immediately below the outermost bioactive layer by at least in increasing order of preference, 5%, 10%, 15%, 20%, 25% or 50%. In another refinement, each of the Lab color space coordinates L^* , a^* , and b^* relative to CIE standard illuminant D50 of the outermost bioactive layer differ from those of the layer immediately below the outermost bioactive layer by at least in increasing order of preference, 5%, 10%, 15%, 20%, 25% or 50%. In a variation, Delta E (2000), which quantifies the distance between two points in the color space, can be used to quantify the difference between two colors. A visual or noticeable distinction between two colors can be impacted by various factors, including the viewer, the texture, and gloss. In a refinement, a delta E greater than or equal to 0.5 is a sufficient difference in color for the indicator. In another refinement, a delta E greater than or equal to 1.0 is a sufficient difference in color. In still another refinement, a delta E greater than or equal to 2.0 is a sufficient difference.

[0070] Referring to Figures 3A and 3B, schematic cross-sections of a substrate coated with a bioactive material having macroparticles that extend into the topcoat layer are provided. As set forth above, this coating system of Figure 2A can be used to form bioactive coated substrate 10 of Figure 1A, while the precursor substrate 10 can be used to form bioactive coated substrate 10 of Figure 1B. With reference to Figure 3A, precursor coated substrate 30 includes a base substrate 12, outermost bioactive layer 16 disposed over the substrate, a topcoat layer 18 disposed over the bioactive layer. Figure 3A shows macroparticles 32 extends from outermost bioactive layer 16 and from first interlayer 14 into topcoat layer 18. Similarly, Figure 3B shows that precursor coated substrate 30' includes a base substrate 12, an optional base layer 22 disposed over the substrate, outermost bioactive layer 16 disposed over the substrate and base layer if present, a topcoat layer 18 disposed over the outermost bioactive layer, and a plurality of alternating additional bioactive layers 16' and interlayers 14 interposed between base layer 22 and outermost bioactive layer 16. Topcoat layer 18 is disposed over outermost bioactive layer with the plurality of macroparticles extending into or embedded therein. Figure 3B shows macroparticles 32 extending from both interlayers and from bioactive layers. In a refinement, the plurality of macroparticles have an average diameter d_2 of about 50 nm to 0.1 microns. The plurality of macroparticles 108 can be loosely bound to bioactive layers 16 and to topcoat layer 18 such that the plurality of macroparticles 108 can be mechanically removed from the topcoat layer 18. For example, the plurality of macroparticles 22 can be removed by wiping the surface of the topcoat layer 106 with a dry cloth. Therefore, removing the plurality of macroparticles 22 yields a plurality of microscopic openings.

[0071] In another variation, an adhesion layer is disposed over the topcoat layer with a hydrophobic coating is disposed over the adhesion layer. The adhesion layer can be composed of metal oxide such as silicon dioxide (e.g., SiO_x adhesion layer where x is 0.5 to 1.2). In a refinement, the hydrophobic coating is composed of a polymeric material selected from the group consisting of fluorinated monomers, fluorinated oligomers, or fluorinated polymers. Typically, the hydrophobic coating is a hydrophobic coating. In a refinement, the polymeric coating includes a self-assembling monolayer of the polymeric material. A specific example of such a hydrophobic coating is alkoxy silane functionalized perfluoropolyether. Advantageously, the alkoxy silane functionalized portion attaches to the adhesion layer with the hydrophobic tail portion aligning to each other. Figure 4 depicts this variation in which adhesion layer 40 is disposed over and optionally contacts coated

substrate 10 or 10' as set forth above. Hydrophobic coating 42 is disposed over and optionally contacts adhesion layer 40.

[0072] In another embodiment, the bioactive coated substrate is included in an article. In a refinement, the useful article further includes an indicator layer as set forth above. Many healthcare or hospital surfaces may greatly benefit from a bioactive coated substrate. For example, useful articles can include but are not limited to bedrails, footboards, bed-side tables, knobs, handles, safety rails, carts, push plates, kick plates, mop plates, stretcher plates, spigots, drains, sinks, faucets, drain levers, water fountain components, sanitizers/ soap dispensers, hand dryers, commonly used buttons, headrest, showerheads, countertops, hinges, locks, latches, trim, toilet or urinal hardware, light switches, armrest, thermostat controls, telephones, floor tiles, ceiling tiles, wall tiles, instrument handles (e.g. drug delivery systems, monitoring systems, hospital beds, office equipment, operating room equipment, stands and fixtures), IV poles, trays, pans, walkers, wheelchairs, keyboards, computer mouse surfaces, exercise equipment, rehabilitation equipment, physical therapy equipment, lamps, lighting systems, lids, hangers, remotes, cup holders, toothbrush holders, gown snaps, and window sills. Likewise, popular or common areas in general could benefit from articles with bioactive coated substrate s. For example, some articles or surfaces can include but are not limited to shopping carts, shopping cart handles, child seats, handrails, register keypads, register housings, ATMs, lockers, elevator controls, paper towel dispensers, toilet paper dispensers, vending machines, and restroom surfaces. Similar articles and surfaces can benefit in housing areas, mass transit, laboratories, religious gathering facilities, or any commonly visited facilities. Other uses can include but are not limited to writing utensils, eyeglass frames, combs, phone covers, tablet covers, headphone, and bottle openers to name a few.

[0073] Referring to Figure 4, a flow chart depicting a method of forming the bioactive coated substrate set forth above is provided. The method includes step 60 of providing a base substrate. The method also includes step 62 of applying a first interlayer over the base substrate. The first interlayer has a plurality of macroparticles protruding from the surface of the first interlayer. The first interlayer can be applied by PVD in a manner that results in the deposit of a plurality of macroparticles. Advantageously, the bioactive layer can be applied by CAE for this purpose. At step 64, the method includes a step of applying an outermost bioactive layer over the first interlayer where the plurality of macroparticles extends into and typically through the outermost bioactive layer. The outermost bioactive active layer can be applied by PVD (e.g., sputtering, CAE). Finally, the method includes a

step of applying a topcoat layer at step 66. In a refinement, the topcoat layer can be applied by PVD. In a refinement, the topcoat layer can be applied by CAE. The method of applying a bioactive coated substrate can further include step 68 in which the plurality of macroparticles is removed. Typically, the plurality of macroparticles is mechanically removed. For example, the plurality of macroparticles can be removed by wiping with a dry cloth. In a refinement, the plurality of macroparticles can be removed by mass finishing the bioactive coated substrate.

[0074] In a variation, a plurality of alternating additional bioactive layers and additional interlayers are deposited over the base substrate prior to deposition of the first interlayer. In a refinement, at least a portion of the macroparticles extends from one or more of the additional interlayers to the topcoat layer. In refinement, at least a portion of the macroparticles extends from one or more of the additional bioactive layers to the topcoat layer. It should be appreciated that the layer that grows particles therein can be deposited by PVD (i.e., CAE) in a manner that results in the deposit of a plurality of macroparticles. Advantageously, the bioactive layer can be applied by CAE. Properties, thickness, and compositions for the layers and microscopic openings formed by the method of Figure 4 are the same as those set forth above.

[0075] The following examples illustrate the various embodiments of the present invention. Those skilled in the art will recognize many variations that are within the spirit of the present invention and scope of the claims.

[0076] A bioactive coated substrate including a stainless steel substrate coated with a copper oxide bioactive layer and a zirconium topcoat layer applied by cathodic arc evaporation had superior antimicrobial performance as compared with control substrates. The bioactive coated substrate had superior performance as compared with a stainless steel control substrate. As provided in Table 1, Cuprotesmo test was used to determine the presence of copper ions (e.g. Cu(I) and Cu(II)). This is not a direct test for bioactive or antimicrobial efficacy but without being bound by theory copper ions are believed to play a role is inhibit and/or destroy microbes. A reactive paper is used to determine the presence of copper ions by changing colors. The color pink indicates the presence of copper ions. Table 1(Figure 5) provides properties of the bioactive coated substrate (i.e., a bioactive coated onto a stainless steel substrate) along with a copper substrate (i.e., a penny) and a stainless steel substrate.

[0077] The bioactive coated substrate was also tested for its antibacterial activity and efficacy using the standard JIS 2801 method with a contact surface time of 24 hours at 35°C with *E. Coli*. The

test was run in reference to the control and measured in colony-forming units (CFU) per milliliter (mL). As shown by Table 1, the bioactive coated substrate has a lower quantity of colony-forming units by about 4.4 log counts compared with stainless steel, which indicates significant antimicrobial activity.

[0078] Table 2 (Figure 7) provides results for the growth of bacteria (i.e., *S. aureus*) on stainless steel, brass, a multilayer sample having a buried active layer with microscopic openings, and a sample with the bioactive layer on top. The results show that the multilayer sample having a buried bioactive layer with microscopic openings provides excellent inhibition of bacterial growth that is comparable to brass and the sample with sample with the bioactive layer on top.

[0079] Figure 8 provides top surface elemental mapping (EDS) showing that copper sublayers are exposed through the microscopic openings (i.e., pits).

[0080] Figure 9 provides SEM cross-section images that copper sublayers and the first interlayer are exposed through the microscopic openings (i.e., pits).

[0081] Example 1 (Multi-layer with Copper Nitride)

[0082] A vacuum thin film deposition chamber is pumped down to a pressure of 5.0×10^{-5} Torr. The chamber is then heated to a temperature of 100C using wall mounted resistive heating elements. On a carousel inside the chamber, stainless steel door handles are mounted on racks that rotate in a 2-axis planetary motion in between a wall mounted magnetron sputtering cathode and a centrally located cylindrical arc cathode. An ion etch surface preparation is carried out by backfilling with Argon gas to a pressure of 25.0 mTorr and a bias voltage of -500V is applied to parts for 5 minutes. A first Zirconium metal adhesion layer is applied to the handles by striking an arc on the arc cathode at a current of 300A. The chamber is backfilled by Argon to a pressure of 3.0 mTorr and a substrate bias of -50V is applied. This step lasts 5 minutes to build a layer of 50nm thick Zr metal. A second coating layer comprised of a Zirconium Nitride, is applied by continuing to run the arc on the Zr target but adding Nitrogen gas at flows of 150 sccm for a composition of approximately $ZrN_{0.50}$. This layer is built up to approximately 10nm in 1 minute. A third layer is applied by continuing to run the arc on the Zr target and flow the Argon and Nitrogen gases while powering a Copper magnetron sputtering cathode to 9.5 kW. This step lasts for 4 minutes to build a co-deposited mixed metal compound layer. In the third step, the Zirconium arc target is shut off while the Copper magnetron sputtering cathode

remains on as does the flow of Argon and Nitrogen. This sputter-only step lasts for 30 minutes to build a $\text{CuN}_{0.3}$ coating around 300 nm thick at which point the Cu sputtering cathode and the Nitrogen gas is shut off, leaving only Argon to continue to flow at a pressure of 3.0 mTorr. The shutter to the magnetron sputtering cathode is closed. After this, a fourth step of Zirconium metal adhesion layer is applied to the handles by striking an arc on the arc cathode at a current of 300A. The chamber is backfilled by Argon to a pressure of 3.0 mTorr and a substrate bias of -50V is applied for 5 minutes to build a layer of 50nm thick Zr metal. A fifth layer is added comprised of a Zirconium Nitride, which is applied by continuing to run the arc on the Zr target but adding Nitrogen gas at flows of 150 sccm for a composition of approximately $\text{ZrN}_{0.50}$. This layer is built up to about 300nm in 20 minutes. A sixth and final layer is added comprised of a Zirconium Oxide, which is applied by continuing to run the arc on the Zr target but shutting off both the Argon and Nitrogen flow while adding 500 sccm of Oxygen flow while maintaining a pressure of 1 mTorr to achieve a composition of approximately $\text{ZrO}_{0.50}$ for 37 seconds to deposit approximately 10nm.

[0083] Example 2 (Multi-layer with Copper Oxide)

[0084] A vacuum thin film deposition chamber is pumped down to a pressure of $5.0\text{e-}5$ Torr. On a carousel inside the chamber, chrome plated brass faucet spouts are fixtured on a rack that rotates on a single axis between the chamber wall mounted arc cathode and a centrally located cylindrical arc cathode. An ion etch surface preparation is carried out by backfilling with Argon gas to a pressure of 25.0 mTorr and a bias voltage of -500V is applied to parts for 5 minutes. A Copper Oxide layer is applied to the spouts by striking an arc on a Copper arc wall mounted cathode at a current of 350A. The chamber is backfilled by Oxygen to a pressure of 2.0 mTorr and a substrate bias of -50V is applied. This step lasts 8 minutes to build a layer of 200nm thick Copper Oxide for an approximate composition of $\text{CuO}_{0.3}$. A second coating layer is applied to the spouts by striking an arc on a Zirconium arc cathode at a current of 460A. The chamber is backfilled by Argon to a pressure of 3.0 mTorr and a substrate bias of -50V is applied. This step lasts 3 minutes to build a layer of 50nm thick of zirconium as an adhesion layer. A final layer is added comprised of a zirconium oxycarbide, which is applied by continuing to run the arc on the Zr target but shutting off the Nitrogen flow while adding 200 sccm of Oxygen and 100 sccm of methane flow while maintaining a pressure of 3 mTorr to achieve a composition of approximately $\text{ZrO}_{0.35}\text{C}_{0.15}$. This final layer is built up to 300nm in 20 minutes.

[0085] Example 3 (Zr and CuO_x multilayer coating)

[0086] A vacuum thin film deposition chamber is pumped down to a pressure of $8.0e-5$ Torr. Inside the chamber, stainless steel panels are mounted on racks that rotate in a 2-axis planetary motion between a wall mounted Copper magnetron sputtering cathode and a centrally located cylindrical arc Zirconium cathode. An ion etch surface preparation is carried out by backfilling with Argon gas to a pressure of 30.0 mTorr and a bias voltage of -500V is applied to parts. This step lasts 2.5 minutes after which the Argon gas is lowered to a pressure of 3.0 mTorr and a substrate bias of -50V is applied. A Zirconium adhesion layer is applied to the panels by striking an arc on the arc cathode at a current of 300A. This step lasts 10 minutes to build a layer of 250nm thick Zirconium. Then, the arc is turned off and oxygen gas is added to a flow rate of 60 sccm while maintaining the pressure of 3.0 mT. Then, the Copper magnetron sputter cathode is turned on to a power of 5 kW for 20 minutes to build a layer of copper oxide to a thickness of 2000 nm. Then, the Copper sputtering target is turned off, along with the oxygen gas, and the zirconium arc target is turned back on for 10 min at a current of 300A for the final zirconium coating. The resulting film is a total of 2500nm thick.

[0087] While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention. Additionally, the features of various implementing embodiments may be combined to form further embodiments of the invention.

WHAT IS CLAIMED IS:

1. A bioactive coated substrate comprising:
a base substrate;
a first interlayer disposed over the base substrate;
an outermost bioactive layer disposed on the first interlayer; and
a topcoat layer disposed on the outermost bioactive layer, wherein a plurality of microscopic openings extending through the topcoat layer and the outermost bioactive layer to expose the first interlayer and the outermost bioactive layer, the plurality of microscopic openings originating in the first interlayer.
2. The bioactive coated substrate of claim 1, wherein the plurality of microscopic openings have an average width of about 100 nm to 10 microns.
3. The bioactive coated substrate of claim 1, wherein the plurality of microscopic openings includes an opening type selected from the group consisting of pores, pinholes, pits, and combinations thereof.
4. The bioactive coated substrate of claim 1, wherein the outermost bioactive layer has a thickness from about 50 to 1500 nm and the topcoat layer has a thickness from about 50 to 1500 nm.
5. The bioactive coated substrate of claim 1, wherein the outermost bioactive layer is composed of a component selected from the group consisting of copper metal, copper alloy, copper oxides, copper nitrides, copper oxides containing carbon atoms, and combinations thereof.
6. The bioactive coated substrate of claim 1, wherein the outermost bioactive layer is composed of CuO_x , where x is from 0.1 to 1.0.
7. The bioactive coated substrate of claim 1, wherein the outermost bioactive layer is composed of CuO_aN_b , where a is from 0.0 to 1.2 and b, is from 0.01 to 0.4.

8. The bioactive coated substrate of claim 1, wherein the outermost bioactive layer is composed of CuO_cC_d , where c is from 0.0 to 1.2 and d, is from 0.01 to 0.4.

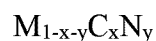
9. The bioactive coated substrate of claim 1 further comprising a base layer interposed between the base substrate and the outermost bioactive layer.

10. The bioactive coated substrate of claim 9, wherein the base layer has a thickness from about 20 to 300 nm.

11. The bioactive coated substrate of claim 10 further comprising a multilayer stack that includes one or more additional bioactive layers alternating with one or more additional interlayers, the multilayer stack being interposed between the base substrate and to the first interlayer, wherein additional microscopic openings extends to an opening bottom in the one or more additional interlayers such that each bioactive layer above the opening bottom and each interlayer above the opening bottom is exposed.

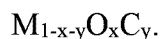
12. The bioactive coated substrate of claim 11 comprising 1 to 10 additional bioactive layers and 1 to 10 additional interlayers 22.

13. The bioactive coated substrate of claim 12, wherein the base layer, the first interlayer, and the additional interlayers are independently composed of a compound having formula:



where M is zirconium or titanium and x is 0.0 to 0.3 and Y is 0.1 to 0.5.

14. The bioactive coated substrate of claim 10, wherein the base layer, the first interlayer, and the additional interlayers are independently of a compound having formula:



where M is zirconium or titanium and x is 0.1 to 0.4 and y is 0.5 to 0.2.

15. The bioactive coated substrate of claim 10, wherein the additional bioactive layers are composed of copper metal, copper alloys, or copper-containing compounds, the copper-containing

compounds including copper atoms in a +1 or +2 oxidation state or combinations of copper atoms thereof.

16. The bioactive coated substrate of claim 10, wherein the topcoat layer is composed of a component selected from the group consisting of carbides, gold, graphite, nitrides, platinum, titanium, titanium nitride, Zr, ZrN, ZrCN, ZrON, ZrO₂, ZrOC, Cr, CrN, CrCN, Ti, TiN, TiCN, TiON, TiO₂, and TiOC, and combinations thereof.

17. The bioactive coated substrate of claim 10, further comprising a hydrophobic coating disposed over the topcoat layer, wherein the hydrophobic coating is composed of a polymeric material selected from the group consisting of fluorinated monomers, fluorinated oligomers, or a fluorinated polymers.

18. The bioactive coated substrate of claim 17, wherein the hydrophobic coating includes a self-assembling monolayer of the polymeric material.

19. A method of producing a bioactive coated substrate comprising:
providing a base substrate;
depositing a first interlayer over the base substrate, the first interlayer having a plurality of macroparticles protruding from a surface of the first interlayer;
depositing an outermost bioactive layer over the first interlayer, the plurality of macroparticles extending into the outermost bioactive layer;
depositing a topcoat layer on the outermost bioactive layer, the plurality of macroparticles extending into the topcoat layer; and
removing at least a portion of the plurality of macroparticles to form a plurality of microscopic openings in the topcoat layer.

20. The method of claim 19, wherein the outermost bioactive layer is composed of a component selected from the group consisting of copper metal, copper oxides, copper nitrides, copper oxides containing carbon atoms, and combinations thereof.

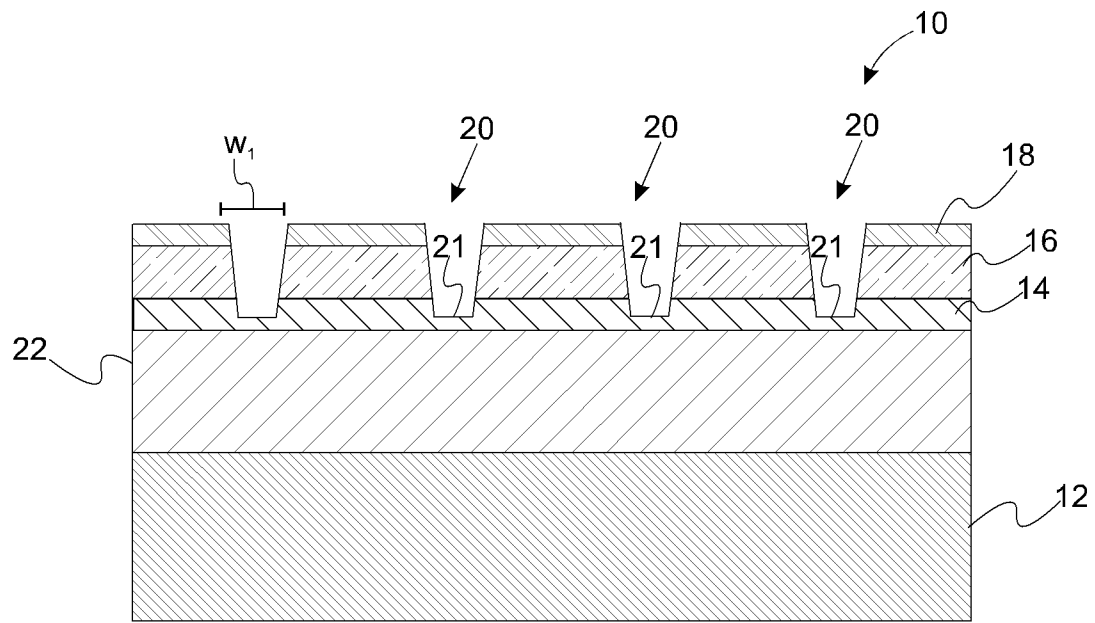
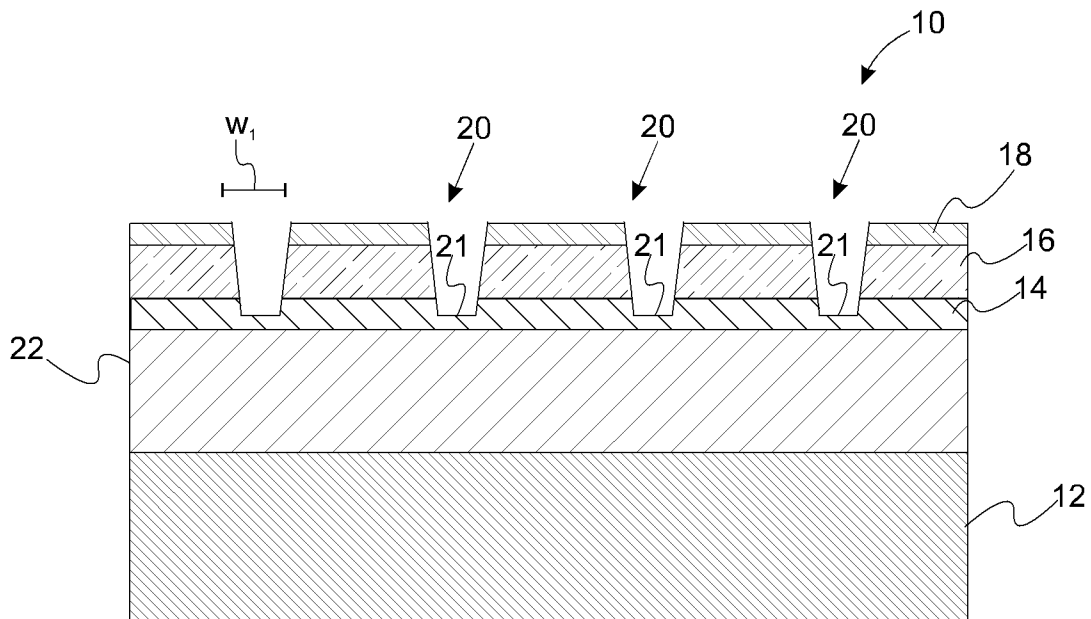
21. The method of claim 20, wherein the outermost bioactive layer is applied by cathodic arc evaporation.

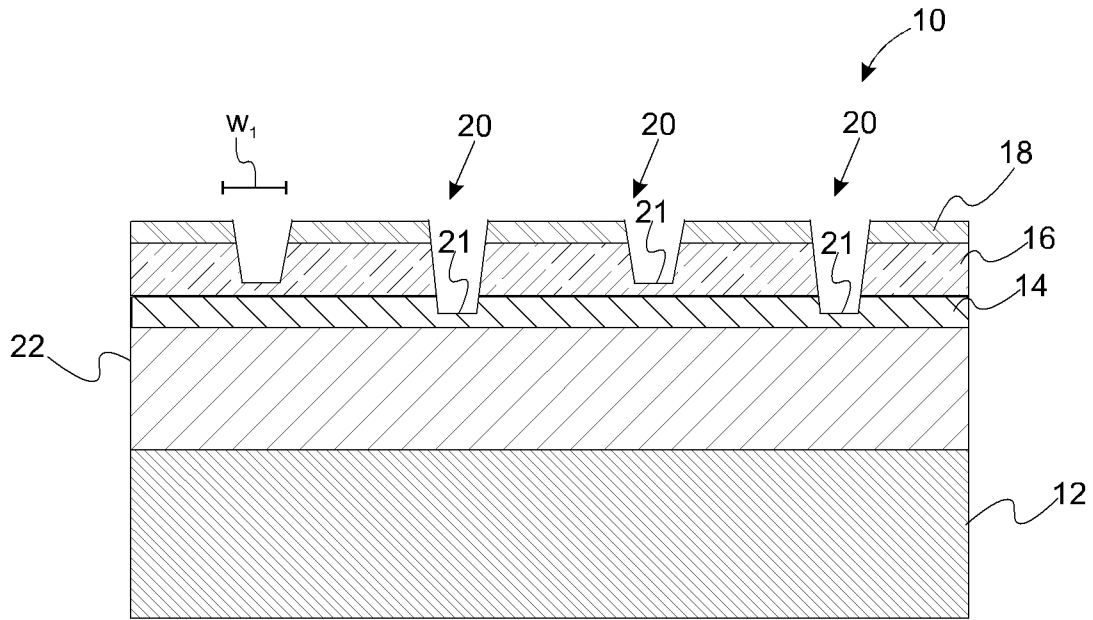
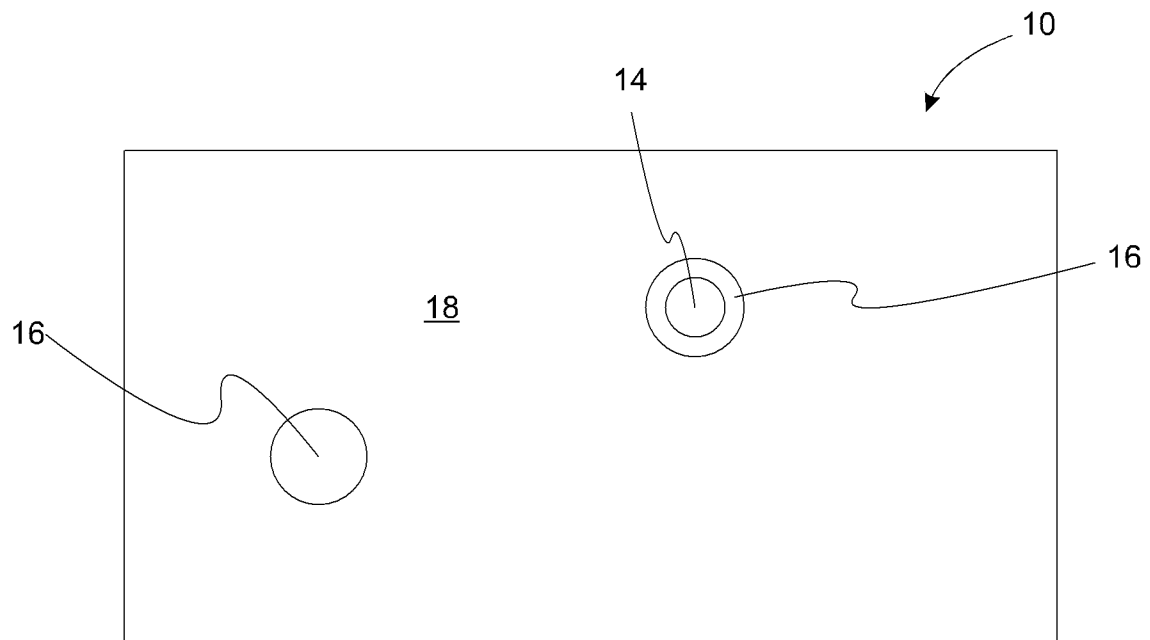
22. The method of claim 20, wherein the first interlayer is applied by cathodic arc evaporation.

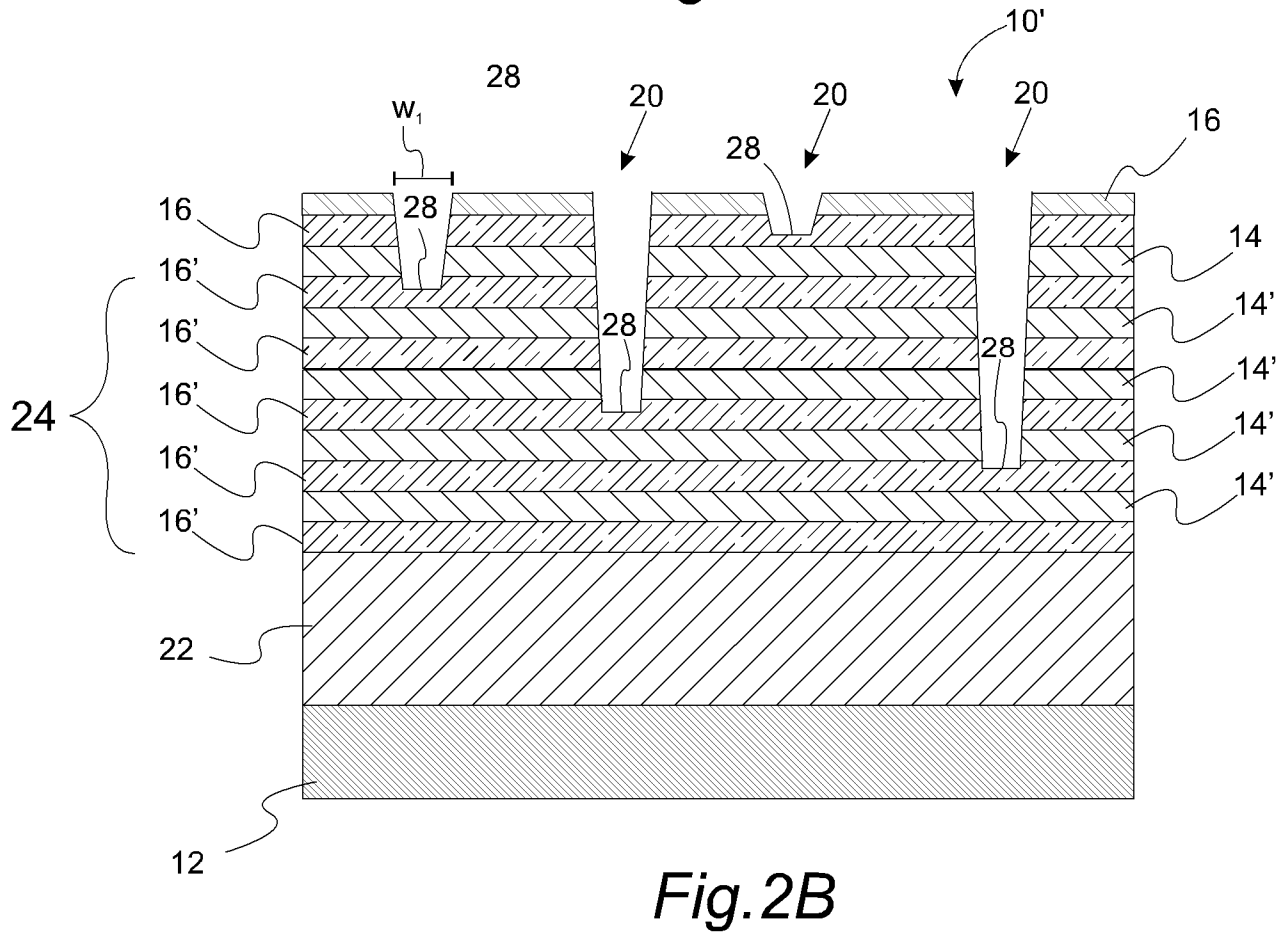
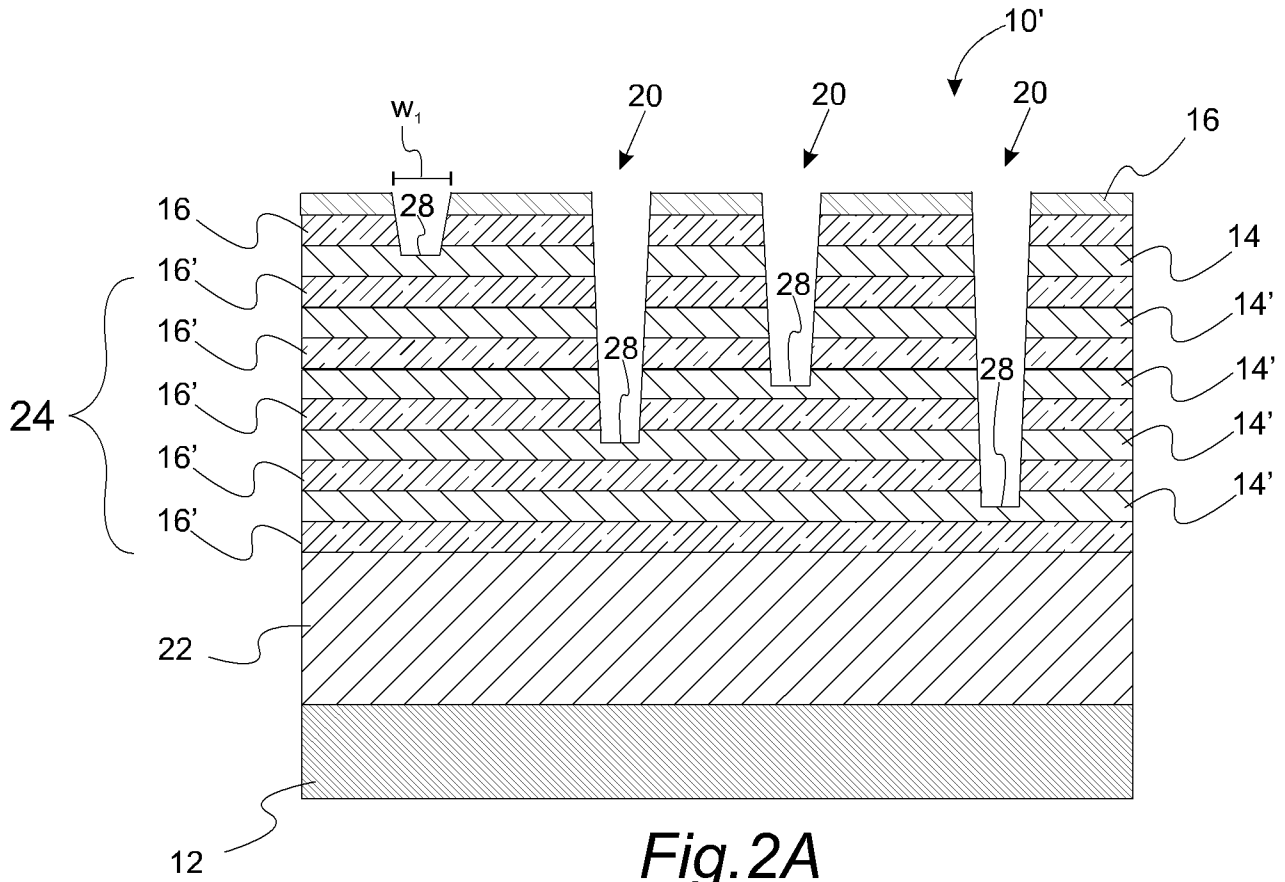
23. The method of claim 19 wherein a plurality of alternating additional bioactive layers and additional interlayers are deposited over the base substrate prior to deposition of the first interlayer.

24. The method of claim 23 wherein at least a portion of the macroparticles extend from one or more of the additional interlayers to the topcoat layer.

25. The method of claim 23 wherein at least a portion of the macroparticles extend from one or more of the additional bioactive layers to the topcoat layer.

*Fig. 1A**Fig. 1B*

*Fig. 1C**Fig. 1D*



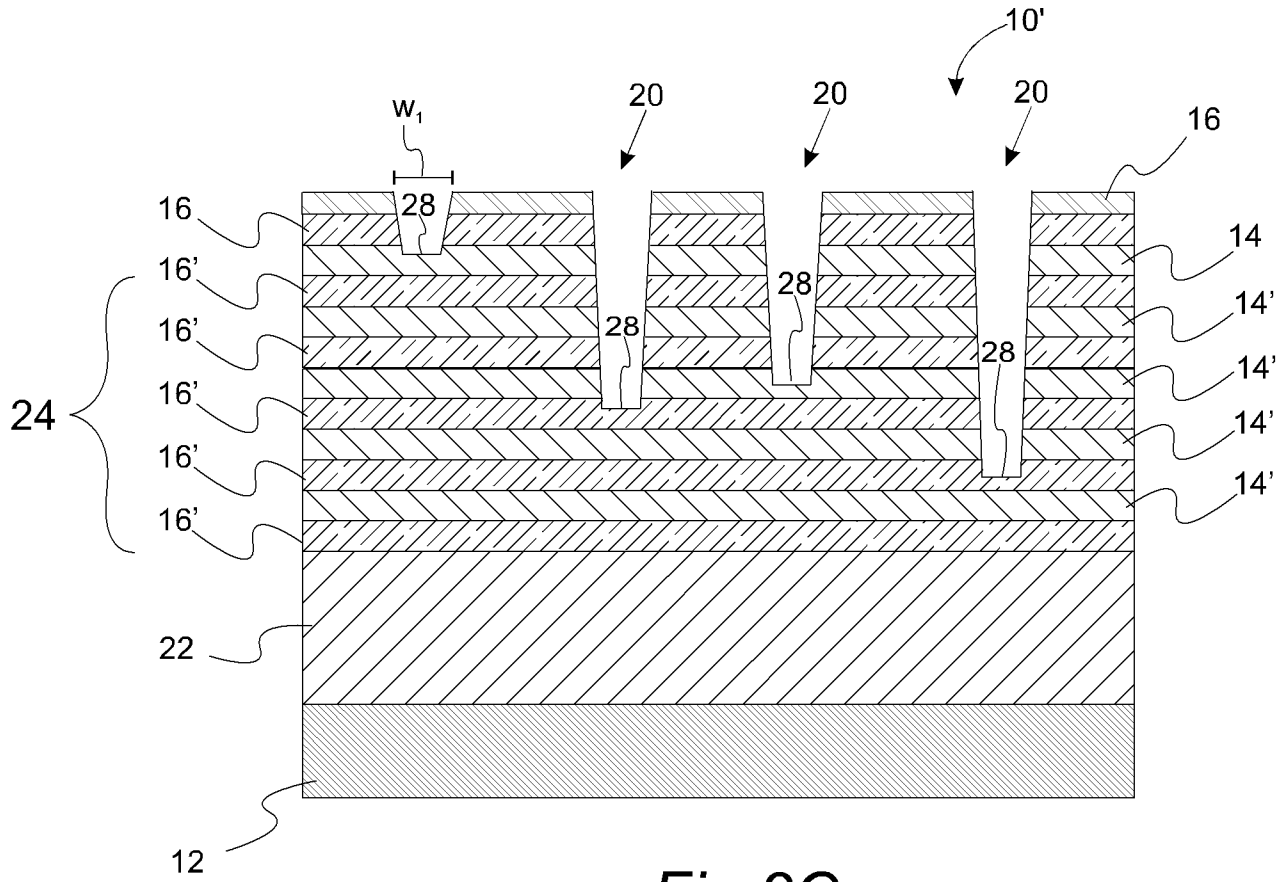


Fig. 2C

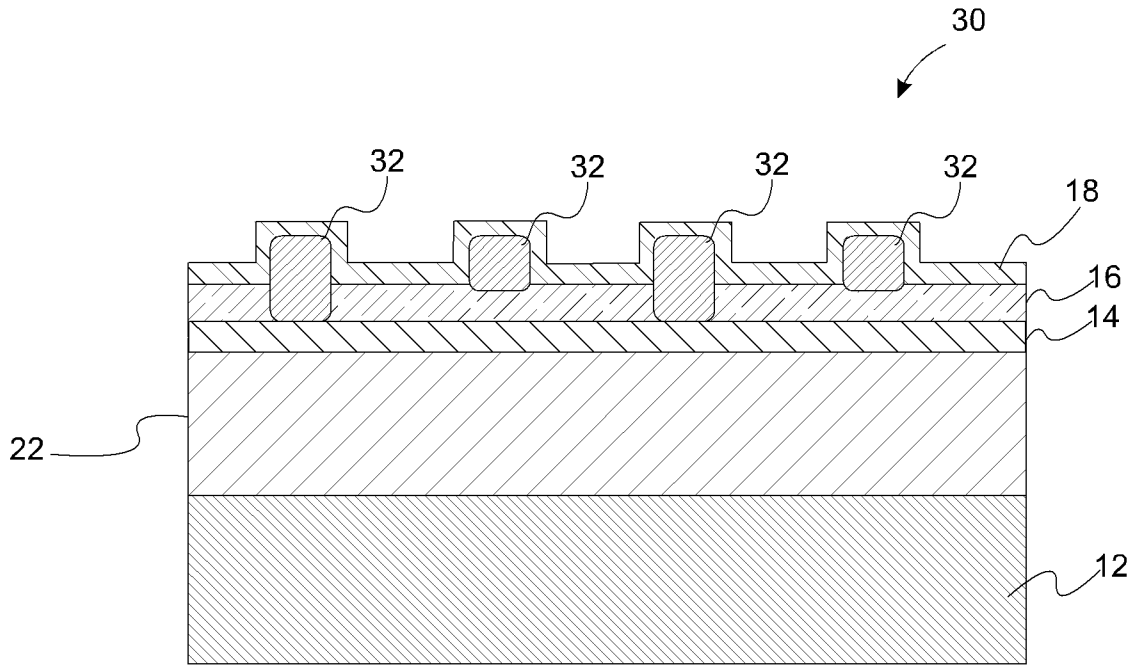


Fig.3A

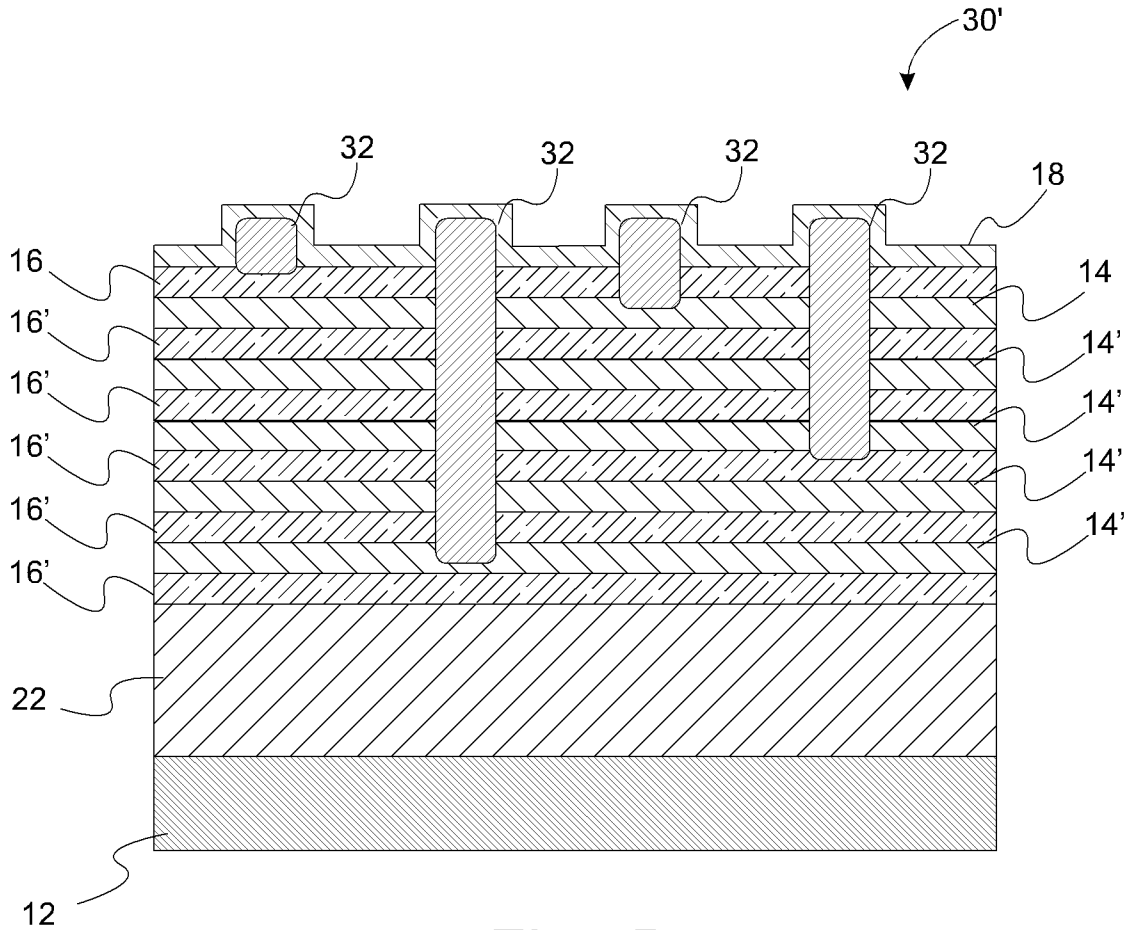


Fig.3B

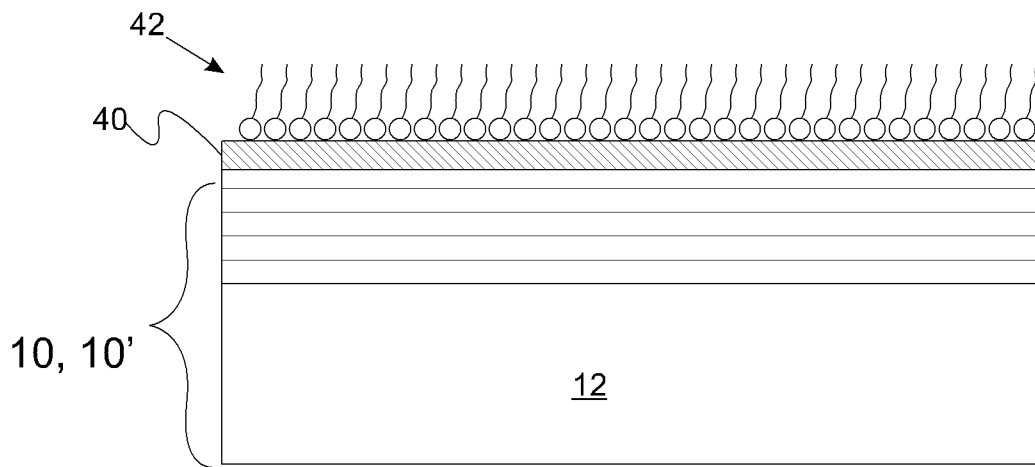


Fig.4

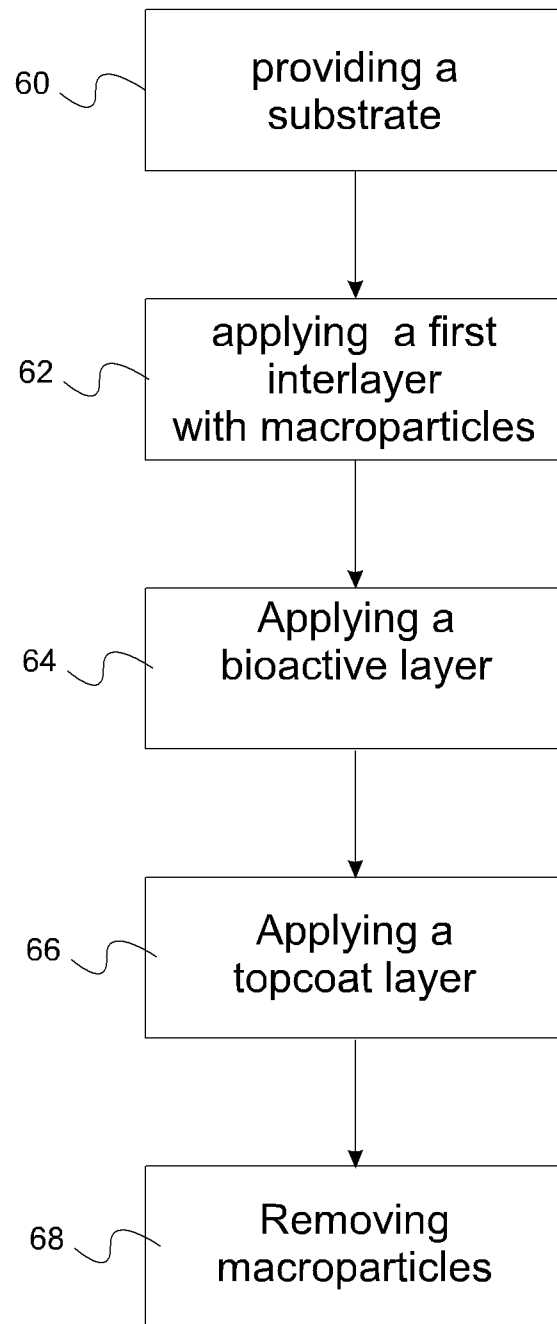


Fig.5

Table 1. Properties of a bioactive coated substrate and a copper and stainless steel substrate.

Substrate	Bioactive Layer		Topcoat Layer			Cuprotesmo*		JIS 2801**		
	Material	Process	Date	Material	Process	Date	white, yellow, pink	Cu ions (yes/no)	Sample (LOG counts)	Control (LOG counts)
Stainless steel	Cu ₂ O	Cathodic Arc	3/19/20	Zr	Cathodic Arc	3/22/20	yellow-pink	Yes	2.2	--
Copper penny				Control (no coating)			Pink	Yes	--	--
Stainless steel				Control (no coating)			White	No	--	6.6

*Cuprotesmo is a test for presence of Cu ions, Cu(I) and Cu(II), which are thought to play a key role in destroying microbes. However, this is not a test for antimicrobial efficacy. Note that the Cuprotesmo paper reacts with copper by changing color from pale yellow to pink or crimson.

** JIS 2801 is a standard antimicrobial test, contact surface time is 24 hrs, T = 35°C, active organism is E. Coli, referenced to control, units CFU/ml

Fig. 6

S. aureus, Run at 23.3oC 30% RH		Organisms grown on Tryptic Soy Broth for Inoculum and resuspended in PBS					
Organism	Time Period						
S. aureus	1 hr 55 min						
Plate Counts (CFU/mL)							
Sample	Rep 1	Rep 2	Rep 3	Average			
Stainless Control	38,000	18,800	40,000	32,267			
Stainless Control Duplicate Plate	40,000	24,000	48,000	37,333		log redux	% redux
				34,800	Ave	0.00	0.0%
Brass Control	0	0	0	0			
Brass Control Duplicate Plate	0	0	0	0			
				0	Ave	4.54	100.0%
2364-2	20	0	0	7			
2364-2 Duplicate Plate	0	0	0	0			
				3	Ave	4.02	99.99%
2365-1	0	0	20	7			
2365-1 Duplicate Plate	0	0	0	0			
				3	Ave	4.02	99.99%
Triton-X100	Neg						
Leethen Broth	Neg						
Fetal Bovine Serum	Neg						

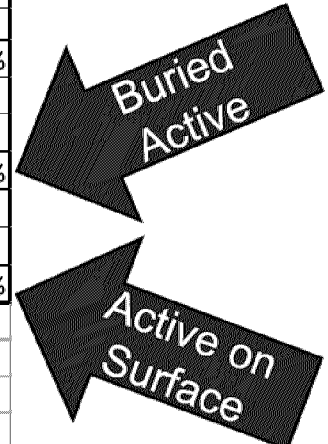


Fig.7

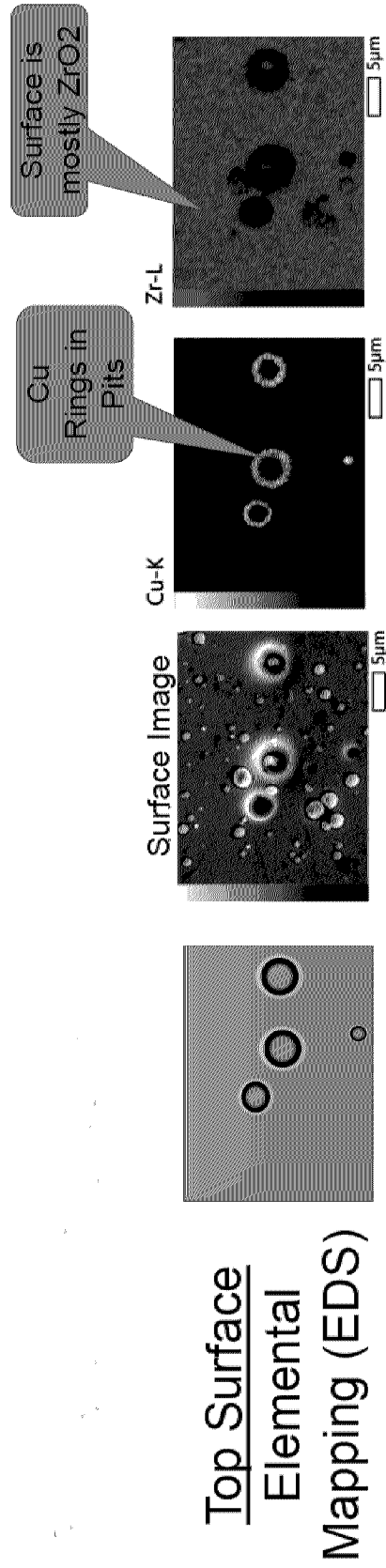
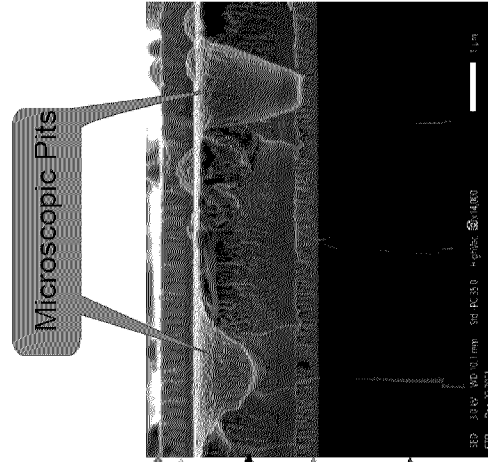


Fig.8

Composition
Elemental
Analysis
(XRF)



Cross Section
SEM Image

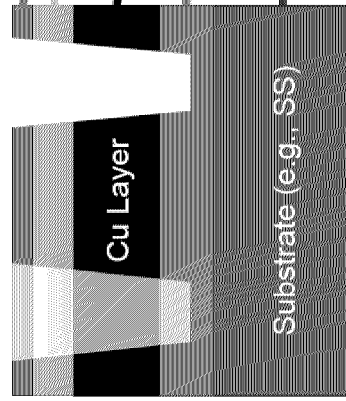


Fig.9

