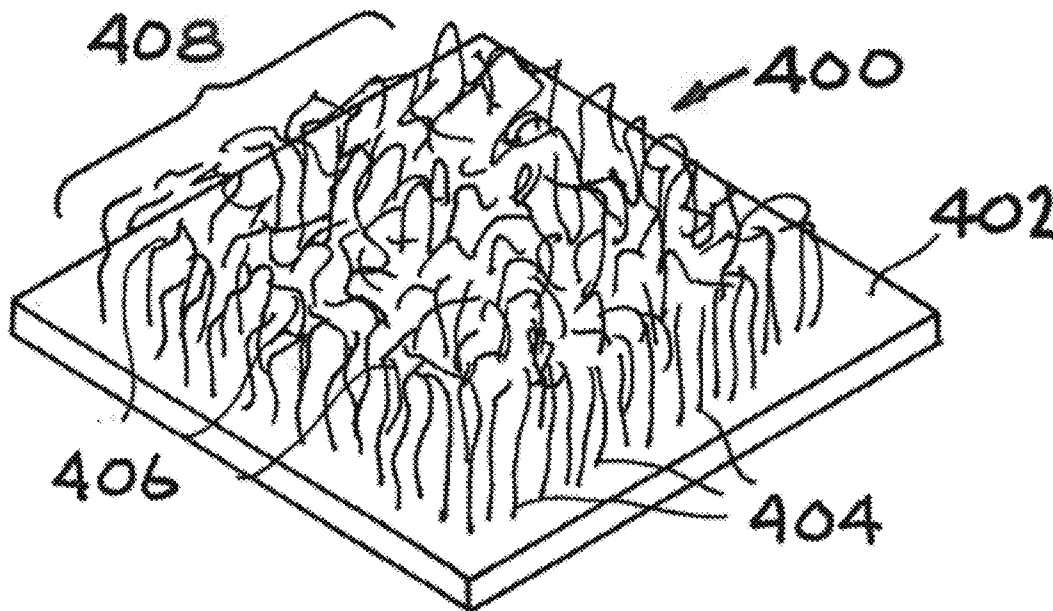


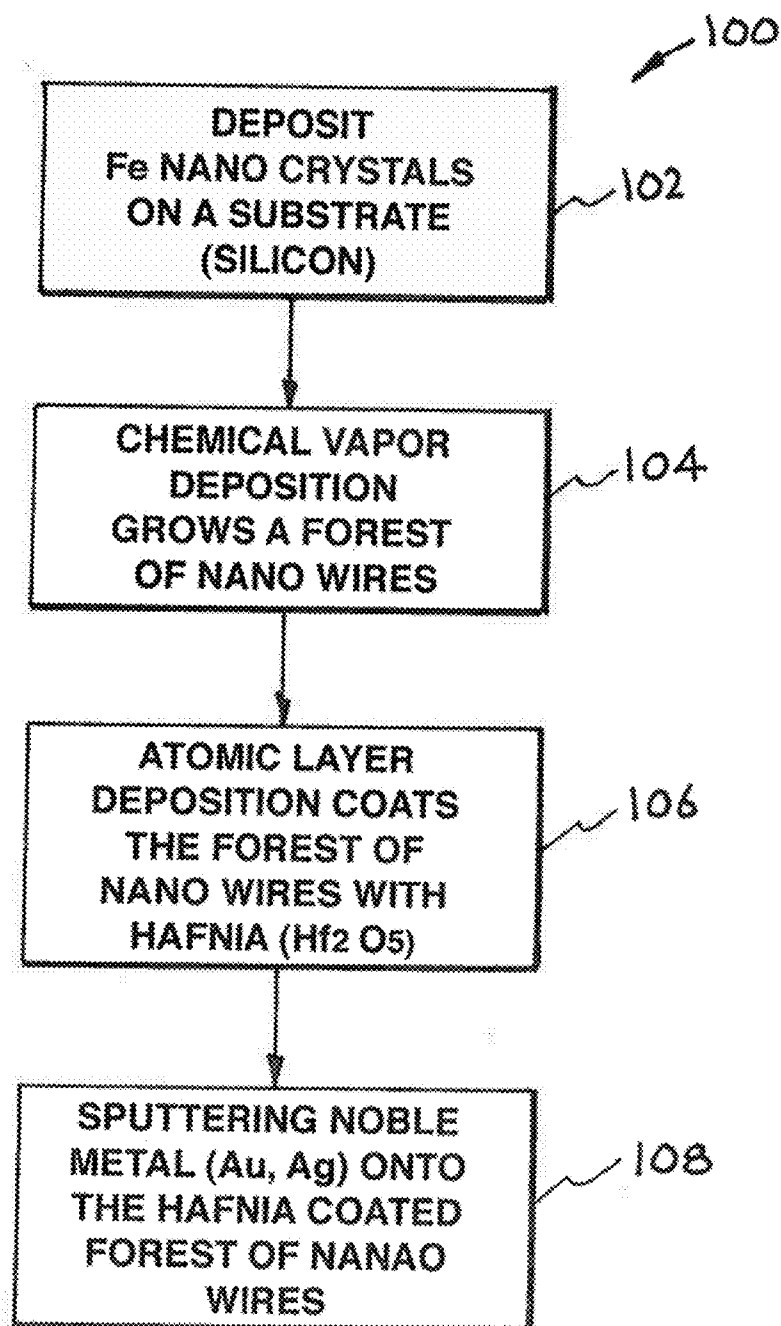


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Bond et al.(10) **Pub. No.: US 2015/0036132 A1**(43) **Pub. Date: Feb. 5, 2015**(54) **METAL-DIELECTRIC-CNT NANOWIRES
FOR SURFACE-ENHANCED RAMAN
SPECTROSCOPY***C23C 16/455* (2006.01)*G01N 21/03* (2006.01)(71) Applicants: **Lawrence Livermore National
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ETH Zurich, Zurich (CH)(52) **U.S. Cl.**CPC *C23C 16/26* (2013.01); *G01N 21/03*
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16/45555 (2013.01); *G01N 2021/0378*
(2013.01); *G01N 21/658* (2013.01)(72) Inventors: **Tiziana C. Bond**, Livermore, CA (US);
Ali Altun, Zurich (CH); **Hyung Gyu
Park**, Zurich (CH)USPC **356/244**; 427/162; 118/715(21) Appl. No.: **14/450,633**(22) Filed: **Aug. 4, 2014****Related U.S. Application Data**(60) Provisional application No. 61/862,405, filed on Aug.
5, 2013.**Publication Classification**(51) **Int. Cl.***C23C 16/26* (2006.01)*C23C 16/06* (2006.01)(57) **ABSTRACT**

A sensor with a substrate includes nanowires extending vertically from the substrate, a hafnia coating on the nanowires that provides hafnia coated nanowires, and a noble metal coating on the hafnia coated nanowires. The top of the hafnia and noble metal coated nanowires bent onto one another to create a canopy forest structure. There are numerous randomly arranged holes that let through scattered light. The many points of contact, hot spots, amplify signals. The methods include the steps of providing a Raman spectroscopy substrate, introducing nano crystals to the Raman spectroscopy substrate, growing a forest of nanowires from the nano crystals on the Raman spectroscopy substrate, coating the nanowires with hafnia providing hafnia coated nanowires, and coating the hafnia coated nanowires with a noble metal or other metal.



**FIG. 1**

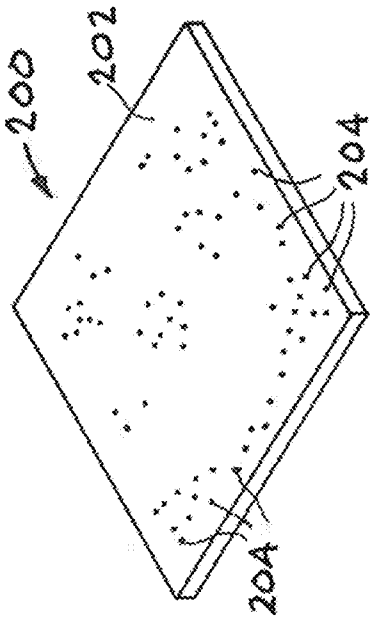


FIG. 2

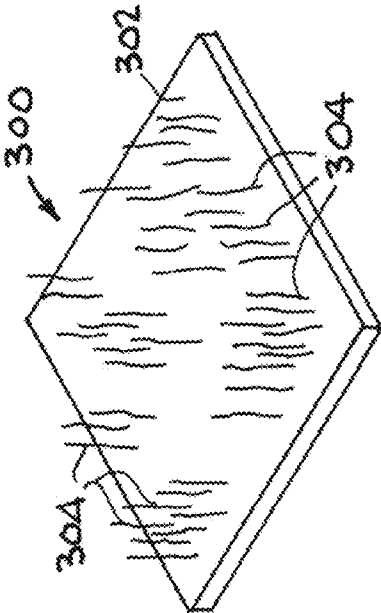


FIG. 3

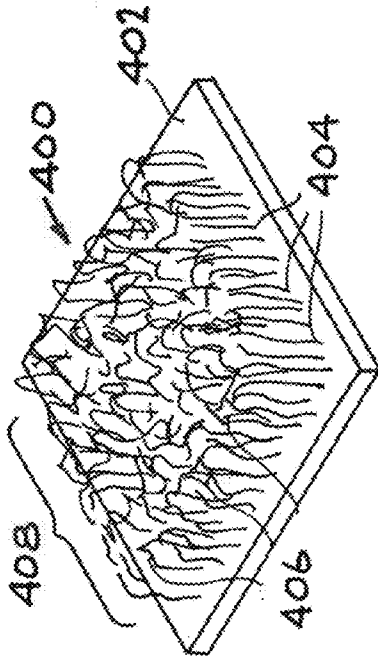


FIG. 4

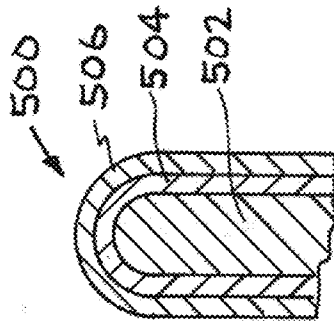


FIG. 5

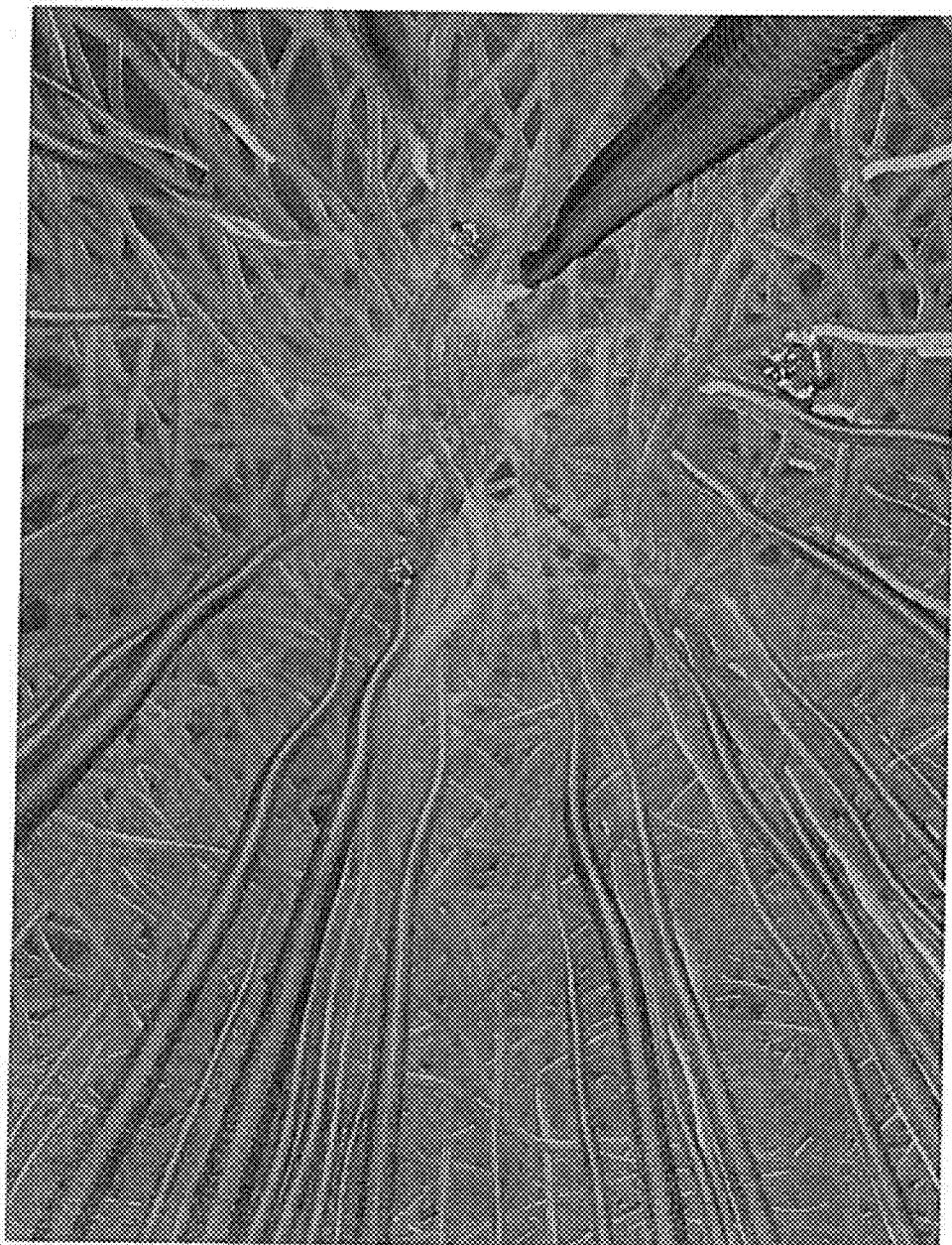


FIG. 6

METAL-DIELECTRIC-CNT NANOWIRES FOR SURFACE-ENHANCED RAMAN SPECTROSCOPY

STATEMENT AS TO RIGHTS TO APPLICATIONS MADE UNDER FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0001] The United States Government has rights in this application pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC for the operation of Lawrence Livermore National Laboratory.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application claims priority to and benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 61/862,405 filed Aug. 5, 2013 entitled "Reusable Template Based on Metal-Dielectric-CNT Nanowires for Surface-Enhanced Sensitivity," the content of which is hereby incorporated by reference in its entire for all purposes.

BACKGROUND

[0003] 1. Field of Endeavor

[0004] The present application relates to Raman spectroscopy and more particularly to surface-enhanced Raman spectroscopy (SERS).

[0005] 2. State of Technology

[0006] This section provides background information related to the present disclosure which is not necessarily prior art.

[0007] Surface enhanced Raman spectroscopy (SERS) has attracted considerable interest since its discovery and highlighted single-molecule detection. This interesting phenomenon has been primarily explained by two theories: electromagnetic effect and chemical effect. The chemical enhancement theory is explained through charge transfer complex formation that requires a chemical bond between the molecule and the surface. Electromagnetic enhancement theory, on the other hand, is associated with a local electromagnetic field enhanced by excited surface plasmons on a metal surface, featured by the fourth power field enhancement. The main objective for many researchers has been to fabricate a substrate that can provide a large number of sites of strong field enhancement, so called hotspots. Methods of achieving this target involve localization (sharp tips), coupling (narrow or slightly touching gaps), and resonance (regularity of the metal structure) of surface plasmons, practically enabled by advanced nanomanufacturing techniques.

SUMMARY

[0008] Features and advantages of the disclosed apparatus, systems, and methods will become apparent from the following description. Applicant is providing this description, which includes drawings and examples of specific embodiments, to give a broad representation of the apparatus, systems, and methods. Various changes and modifications within the spirit and scope of the application will become apparent to those skilled in the art from this description and by practice of the apparatus, systems, and methods. The scope of the apparatus, systems, and methods is not intended to be limited to the particular forms disclosed and the application covers all

modifications, equivalents, and alternatives falling within the spirit and scope of the apparatus, systems, and methods as defined by the claims.

[0009] Applicant's apparatus, systems, and methods provide a sensor that greatly amplifies the sensitivity of commonly used but typically weak vibrational spectroscopic methods, such as Raman spectroscopy. This type of sensor makes it possible to detect molecules present in the tiniest of concentrations.

[0010] In various embodiments Applicant's methods include the steps of providing a Raman spectroscopy substrate, introducing nano crystals to the Raman spectroscopy substrate, growing a forest of nanowires from the nano crystals on the Raman spectroscopy substrate, coating the nanowires with hafnia providing hafnia coated nanowires, and coating the hafnia coated nanowires with a noble metal or other metal.

[0011] In various embodiments Applicant's Raman spectroscopy substrate apparatus includes a Raman spectroscopy substrate, nanowires extending vertically from the Raman spectroscopy substrate, a hafnia coating on the nanowires that provides hafnia coated nanowires, and a noble metal coating on the hafnia coated nanowires. The top of the nanoforest of the hafnia and noble metal coated nanowires does not end up with entirely vertical tips but rather with a canopy of CNTs bent onto one another to create numerous junctions. Such a canopy forest structure offers a great template for a SERS substrate. The crossings of nanowires (or kissing nanowires) leads to superior SERS performance. The tips of the CNTs are sharply curved. There are numerous randomly arranged holes that let through scattered light, and the many points of contact—the 'hot spots'—amplify the signals.

[0012] Applicant's apparatus, systems, and methods have use in defense, environmental and pollution monitoring, chem-bio detection, energy harnessing, batteries, capacitors, photovoltaics, surface chemistry monitoring and controls, water filtration, biomedical, and biomedical and applications.

[0013] The apparatus, systems, and methods are susceptible to modifications and alternative forms. Specific embodiments are shown by way of example. It is to be understood that the apparatus, systems, and methods are not limited to the particular forms disclosed. The apparatus, systems, and methods cover all modifications, equivalents, and alternatives falling within the spirit and scope of the application as defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings, which are incorporated into and constitute a part of the specification, illustrate specific embodiments of the apparatus, systems, and methods and, together with the general description given above, and the detailed description of the specific embodiments, serve to explain the principles of the apparatus, systems, and methods.

[0015] FIG. 1 illustrates one embodiment of Applicant's apparatus, systems, and methods.

[0016] FIG. 2 shows a substrate with nano crystals.

[0017] FIG. 3 shows a substrate with a forest of nanowires.

[0018] FIG. 4 shows a substrate with a forest of nanowires and the very top part of the nanowires has a canopy of bent nanowires.

[0019] FIG. 5 shows a cross section of a nanowire with hafnia and gold coatings.

[0020] FIG. 6 is an illustration of the carbon nanotubes having curved tips with numerous gaps to let through the Raman scattered light that is an important feature of Applicant's high-sensitivity sensor.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0021] Referring to the drawings, to the following detailed description, and to incorporated materials, detailed information about the apparatus, systems, and methods is provided including the description of specific embodiments. The detailed description serves to explain the principles of the apparatus, systems, and methods. The apparatus, systems, and methods are susceptible to modifications and alternative forms. The application is not limited to the particular forms disclosed. The application covers all modifications, equivalents, and, alternatives falling within the spirit and scope of the apparatus, systems, and methods as defined by the claims.

[0022] Applicant's apparatus, systems, and methods provide a surface enhanced Raman spectroscopy (SERS) substrate based on a metal-dielectric-CNT nanowire structure. Applicants fabricated a highly sensitive substrate for surface enhanced Raman spectroscopy (SERS) enabled by arrays of gold coated vertically aligned (VA-) carbon nanowires (CNTs) having high-k dielectric (hafnia, HfO_2) layer in between as a potential barrier. Applicant's substrate for surface enhanced Raman spectroscopy provided a demonstration of femtomolar-level detection sensitivity and repeated use. Applicants have found, that a nanometer thick layer of hafnia inserted between gold and CNT and random stacks of the gold-hafnia-CNT nanowires are sufficient to enhance the SERS detection performance considerably, demonstrated by femtomolar detection of BPE. The term "nanowires" as used in this application means nanowires and other forms of nano structures including nanotubes.

[0023] Referring now to the drawings and in particular to FIG. 1, one embodiment of Applicant's apparatus, systems, and methods is illustrated. This embodiment of Applicant's apparatus, systems, and methods is designated generally by the reference numeral 100. FIG. 1 is a flow chart illustrating this embodiment 100 of the making of a surface enhanced Raman spectroscopy substrate.

[0024] In step 102 iron nanoparticles (average sizes between one and two nanometers) are deposited on a silicon substrate coated with aluminum oxide (with thickness between ten and twenty nanometers). It is to be understood that substrates other than silicon substrates are contemplated in the apparatus, systems, and methods of this application. Other substrates include but are not limited to aluminum oxide substrates, glass substrates and other substrates. It is to be understood that nanoparticles of the species other than iron are contemplated in the apparatus, systems, and methods of this application. Other nanoparticles include but are not limited to nickel nanoparticles, platinum nanoparticles and other nano crystals.

[0025] In step 104 chemical vapor deposition (CVD) is used to grow a forest of nanowires from the nano crystals on the substrate. Chemical vapor deposition is a process where solids form out of a gaseous phase and the nanowires are grown from the nano crystals on the substrate. It is to be understood that other metals can be used as the nano crystals and that other methods can be used for growing the nanowires from the nano crystals on the substrate. For example, sputter-

ing and e-beam evaporation methods can be used for growing the nanowires from the nano crystals on the substrate.

[0026] In step 106 the nanowires are coated with hafnia by atomic layer deposition. In step 108 the hafnia coated nanowires are coated with a noble metal, for example gold. Applicants introduced atomic layer deposition (ALD) of hafnia on CNT samples prior to the gold evaporation. Hafnia in particular was selected due to its high dielectric constant and band-gap ($\epsilon_r=25$, $E_g=6$ eV). In Applicants embodiment 100, VA-CNT substrates were conformally coated with hafnia of various thicknesses and then coated with gold of various thicknesses in order to optimize the SERS effect created by the CNT array template via suppression of plasmon leakage.

[0027] The very top part of Applicant's hafnia-gold coated nanowires has a canopy of bent nanowires and the resultant structure resembles a horizontally or obliquely stacked gold-hafnia-CNT nanowires. Applicants found that there exists optimal gold thickness of 10.5-21 nm that, along with the dielectric insert of hafnia, allows for the best SERS performance. The estimated total gold-hafnia-CNT nanowire thickness lies between 35 nm and 56 nm).

[0028] The top of the nanoforest does not end up with entirely vertical tips but rather with a canopy of CNTs bent onto one another to create numerous functions. Such a canopy forest structure offers a great template for a SERS substrate when coated with noble metal. The crossings of nanowires (or kissing nanowires) leads to superior SERS performance. The bent tips of the dense VA-CNT array enables the kissing nanowire effect when coated with an optimal thickness of noble metal.

[0029] Applicant's apparatus, systems, and methods 100 have use in defense, environmental and pollution monitoring, chem-bio detection, energy harnessing, batteries, capacitors, photovoltaics, surface chemistry monitoring and controls, water filtration, biomedical, and biomedical applications. Applicant's vertically aligned (VA) carbon nanowires (CNTs) offers an extremely dense and rough nanostructure as a viable template for the SERS substrate. This nanoforest of VA-CNTs is particularly attractive, since it provides vertical arrays of nanowires with a variety of diameters from tens of angstroms to hundreds of nanometers.

[0030] Referring now to FIG. 2, additional embodiments of Applicant's apparatus, systems, and methods are illustrated. The additional embodiments of Applicant's apparatus, systems, and methods provide methods of making a substrate for surface enhanced Raman spectroscopy that include the steps of providing a Raman spectroscopy substrate, introducing nano crystals to the Raman spectroscopy substrate, growing a forest of nanowires from the nano crystals on the Raman spectroscopy substrate, coating the nanowires with hafnia providing hafnia coated nanowires, and coating the hafnia coated nanowires with a noble metal. The methods produce a surface enhanced Raman spectroscopy substrate apparatus that includes a Raman spectroscopy substrate, nanowires extending vertically from the Raman spectroscopy substrate, a hafnia coating on the nanowires that provides hafnia coated nanowires, and a noble metal coating on the hafnia coated nanowires. One of the additional embodiments is illustrated in FIG. 2 and is designated generally by the reference numeral 200.

[0031] As shown in FIG. 2 a substrate 202 is provided. The substrate 202 can be a silicon substrate or a substrate of other material. Iron nano crystals 204 or other nano crystals are introduced to the substrate 202. It is to be understood that

FIG. 2 is not to scale and that the nano crystals **204** are shown greatly enlarged for illustration purposes.

[0032] Referring now to FIG. 3, additional embodiments of Applicant's apparatus, systems, and methods are illustrated. The additional embodiment illustrated is designated generally by the reference numeral **300**. As shown in FIG. 3 a substrate **302** is provided. The substrate **302** can be a silicon substrate or a substrate of other material. Chemical vapor deposition was used to grow a forest of nanowires **304** on the substrate **302**. The nanowires **304** were coated with hafnia by atomic layer deposition and the hafnia coated nanowires **304** were coated with a noble metal, for example gold. It is to be understood that FIG. 3 is not to scale and that the nanowires **304** are shown greatly enlarged for illustration purposes.

[0033] Referring now to FIG. 4, additional embodiments of Applicant's apparatus, systems, and methods are illustrated. The additional embodiment illustrated is designated generally by the reference numeral **400**. As shown in FIG. 4 a substrate **402** is provided. The substrate **402** can be a silicon substrate or a substrate of other material. Chemical vapor deposition was used to grow a forest of nanowires **404** on the substrate **402**. The nanowires **404** were coated with hafnia by atomic layer deposition and the hafnia coated nanowires **404** were coated with a noble metal or other metal. The hafnia coated nanowires **404** can be coated with aluminum, silver, gold, and various noble metals.

[0034] The very top part **406** of Applicant's hafnia-gold coated nanowires **404** produces a canopy **408** of bent nanowires. The resultant structure, is a canopy of horizontally or obliquely stacked gold-hafnia-CNT nanowires. Applicants found that there exists optimal gold thickness of 10.5-21 nm that, along with the dielectric insert of hafnia, allows for the best SERS performance. The estimated total gold-hafnia-CNT nanowire thickness lies between 35 nm and 56 nm. It is to be understood that FIG. 4 is not to scale and that the nanowires **404**, the top part **406** of the nanowires **404**, and the canopy **408** are shown greatly enlarged for illustration purposes.

[0035] Referring now to FIG. 5, a cross section of a nanowire with hafnia and gold coatings is illustrated. The additional embodiment illustrated is designated generally by the reference numeral **500**. The nanowires **502** are shown coated with hafnia **504** and the hafnia coated nanowires are shown coated with a noble metal, for example gold **506**. It is to be understood that FIG. 5 is not to scale and that the nanowires **502** are shown greatly enlarged for illustration purposes.

[0036] Applicant's apparatus, systems, and methods provide a substrate for surface enhanced Raman spectroscopy. The methods include the steps of providing a Raman spectroscopy substrate, introducing nano crystals to the Raman spectroscopy substrate, growing a forest of nanowires from the nano crystals on the Raman spectroscopy substrate, coating the nanowires with hafnia providing hafnia coated nanowires, and coating the hafnia coated nanowires with a noble metal. The methods produce a surface enhanced Raman spectroscopy substrate apparatus that includes a Raman spectroscopy substrate, nanowires extending vertically from the Raman spectroscopy substrate, a hafnia coating on the nanowires that provides hafnia coated nanowires, and a noble metal coating on the hafnia coated nanowires.

[0037] Referring again to FIG. 4 a surface enhanced Raman spectroscopy substrate apparatus that is produced by the methods is shown. The top **406** of the nanoforest of the hafnia and noble metal coated nanowires **404** does not end up with

entirely vertical tips but rather with a canopy **408** of CNTs bent onto one another to create numerous junctions. Such a canopy forest **408** structure offers a great template for a SERS substrate. The crossings of nanowires (or kissing nanowires) leads to superior SERS performance. The bent tips of the dense VA-CNT array enables the kissing nanowire effect when coated with an optimal thickness of noble metal.

[0038] The top of the nanoforest provides a canopy **408** of CNTs bent onto one another to create numerous junctions. The tips **406** of the CNTs **404** are sharply curved. The point of contact between the surface of the canopy **408** and the sample resembles a plate of spaghetti. However, between the strands of spaghetti, there are numerous randomly arranged holes that let through scattered light and the many points of contact—the 'hot spots'—amplify the signals. The nano-spaghetti structure with metal-coated CNT tips is perfect for maximizing the density of these contact points. The wide distribution of metallic nano-crevices in the nanometer range, well recognized to be responsible for extreme electromagnetic enhancement (or hot spots) and highly pursued by many research groups, has been easily and readily achieved by Applicants, resulting in the intense and reproducible enhancements.

[0039] Applicant's apparatus, systems, and methods have use in defense, defense, environmental and pollution monitoring, chem-bio detection, energy harnessing, batteries, capacitors, photovoltaics, surface chemistry monitoring and controls, water filtration, biomedical, and biomedical and applications. Applicant's vertically aligned (VA) carbon nanowires (CNTs) offers an extremely dense and rough nano-structure as a viable template for the SERS substrate. This nanoforest of VA-CNTs is particularly attractive, since it provides vertical arrays of nanowires with a variety of diameters from tens of angstroms to hundreds of nanometers.

[0040] Applicant's apparatus, systems, and methods provide a sensor that greatly amplifies the sensitivity of commonly used but typically weak vibrational spectroscopic methods, such as Raman spectroscopy. This type of sensor makes it possible to detect molecules present in the tiniest of concentrations. Referring now to FIG. 6 the carbon nanotubes having curved tips with numerous gaps to let through the Raman scattered light that is an important feature of Applicant's high-sensitivity sensor are illustrated.

[0041] FIG. 6 is a view from inside Applicant's surface-enhanced Raman spectroscopy structure looking upward from the base of the structure. The long squiggly darker lines are the nano wires as grown by the chemical vapor deposition step **104** described above and illustrated in FIG. 1. The nanowires extend vertically from the Raman spectroscopy substrate. The hafnia coating on the nanowires provides hafnia coated nanowires and there is a noble metal coating on the hafnia coated nanowires. The top of the nanoforest of the hafnia and noble metal coated nanowires does not end up with entirely vertical tips but rather with a canopy of CNTs bent onto one another to create numerous junctions. Such a canopy forest structure offers a great template for a SERS substrate.

[0042] Although the description above contains many details and specifics, these should not be construed as limiting the scope of the application but as merely providing illustrations of some of the presently preferred embodiments of the apparatus, systems, and methods. Other implementations, enhancements and variations can be made based on what is described and illustrated in this patent document. The features of the embodiments described herein may be combined

in all possible combinations of methods, apparatus, modules, systems, and computer program products. Certain features that are described in this patent document in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments.

[0043] Therefore, it will be appreciated that the scope of the present application fully encompasses other embodiments which may become obvious to those skilled in the art. In the claims, reference to an element in the singular is not intended to mean “one and only one” unless explicitly so stated, but rather “one or more.” All structural and functional equivalents to the elements of the above-described preferred embodiment that are known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the present claims. Moreover, it is not necessary for a device to address each and every problem sought to be solved by the present apparatus, systems, and methods, for it to be encompassed by the present claims. Furthermore, no element or component in the present disclosure is intended to be dedicated to the public regardless of whether the element or component is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. 112, sixth paragraph, unless the element is expressly recited using the phrase “means for.”

[0044] While the apparatus, systems, and methods may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the application is not intended to be limited to the particular forms disclosed. Rather, the application is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the application as defined by the following appended claims.

1. A method of making a substrate for surface enhanced Raman spectroscopy, comprising the steps of:
 providing a Raman spectroscopy substrate,
 introducing nano crystals to said Raman spectroscopy substrate,
 growing a forest of nanowires from said nano crystals on said Raman spectroscopy substrate,
 coating said nanowires with hafnia providing hafnia coated nanowires, and
 coating said hafnia coated nanowires with a noble metal.

2. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of growing a forest of nanowires from said nano crystals on said Raman spectroscopy substrate comprises growing a forest of verti-

cally aligned nanowires from said nano crystals on said Raman spectroscopy substrate.

3. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of growing a forest of nanowires from said nano crystals on said Raman spectroscopy substrate comprises using chemical vapor deposition for growing a forest of nanowires from said nano crystals on said Raman spectroscopy substrate.

4. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of coating said nanowires with hafnia providing hafnia coated nanowires comprises coating said nanowires with high-k dielectric hafnia HfO_2 providing hafnia coated nanowires.

5. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of coating said nanowires with hafnia providing hafnia coated nanowires comprises using atomic layer deposition to coat said nanowires with hafnia providing hafnia coated nanowires.

6. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of coating said hafnia coated nanowires with a noble metal comprises coating said hafnia coated nanowires with gold.

7. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said step of coating said hafnia coated nanowires with a noble metal comprises coating said hafnia coated nanowires with gold to a thickness of 10.5-21 nm.

8. The method of making a substrate for surface enhanced Raman spectroscopy of claim 1 wherein said nanowires have ends and further comprising the step of enabling said ends of said nanowires to bend and form a canopy of bent nanowire ends.

9. The method of making a substrate for surface enhanced Raman spectroscopy of claim 8 wherein said step of enabling said ends of said nanowires to bend and form a canopy bent nanowire ends includes allowing holes to be formed between said bent nanowire ends.

10. The method of making a substrate for surface enhanced Raman spectroscopy of claim 8 wherein said step of enabling said ends of said nanowires to bend and form a canopy bent nanowire ends includes allowing points of contact of said bent nanowire ends to be formed.

11. An apparatus for making a surface enhanced Raman spectroscopy substrate, comprising:

a Raman spectroscopy substrate,
 means for introducing nano crystals to said Raman spectroscopy substrate,
 means for growing a forest of nanowires from said nano crystals on said Raman spectroscopy substrate,
 means for coating said nanowires with hafnia providing hafnia coated nanowires, and
 means for coating said hafnia coated nanowires with a noble metal.

12. The apparatus for making a surface enhanced Raman spectroscopy substrate of claim 11 wherein said nanowires have ends and further comprising the means for enabling said ends of said nanowires to bend and form a canopy bent nanowire ends.

13. A surface enhanced Raman spectroscopy substrate apparatus, comprising:

a Raman spectroscopy substrate,
 nanowires extending vertically from said Raman spectroscopy substrate,

a hafnia coating on said nanowires that provides hafnia coated nanowires, and

a noble metal coating on said hafnia coated nanowires.

14. The surface enhanced Raman spectroscopy substrate apparatus of claim **13** wherein said hafnia coating on said nanowires that provides hafnia coated nanowires comprises a high-k dielectric hafnia HfO_2 coating on said nanowires that provides high-k dielectric hafnia HfO_2 coated nanowires.

15. The surface enhanced Raman spectroscopy substrate apparatus of claim **13** wherein said noble metal coating on said hafnia coated nanowires comprises a gold coating on said hafnia coated nanowires.

16. The surface enhanced Raman spectroscopy substrate apparatus of claim **13** wherein said noble metal coating on said hafnia coated nanowires comprises a 10.5-21 nm thick gold coating on said hafnia coated nanowires.

17. The surface enhanced Raman spectroscopy substrate apparatus of claim **13** wherein said nanowires have bent ends and further comprising a canopy of bent nanowire ends.

18. The surface enhanced Raman spectroscopy substrate apparatus of claim **17** wherein said canopy of bent nanowire ends includes holes between said bent nanowire ends.

19. The surface enhanced Raman spectroscopy substrate apparatus of claim **17** wherein said canopy of bent nanowire ends includes points of contact of said bent nanowire ends.

* * * * *