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(54) Title: TUNNELING NANOMECHANICAL SWITCHES AND TUNABLE PLASMONIC NANOGAPS

(57) Abstract: Devices comprising at least two electrodes with a layer disposed therebetween are disclosed. In some embodiments, the layer disposed therebetween may be an insulator. In some embodiments, the layer may be capable of being deformed. Deforming the layer may cause a change in one or more materials properties of the device, such as the electrical properties and/or the optical properties of the device.

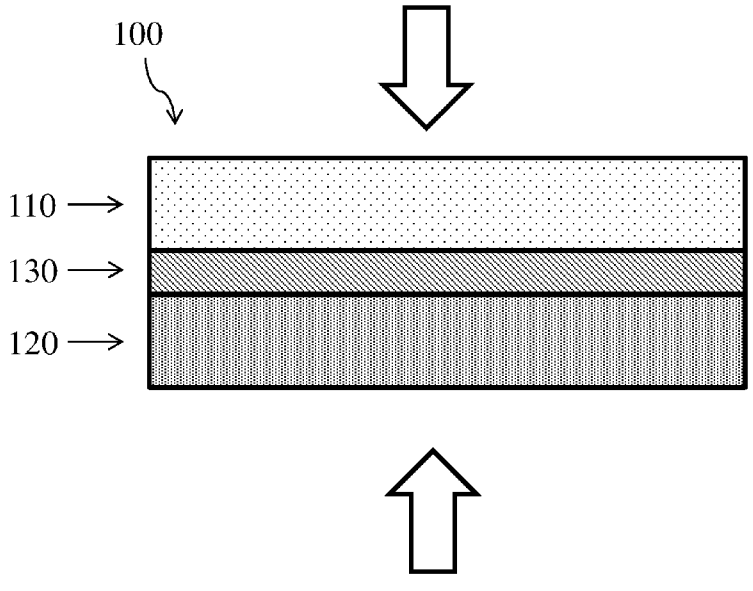

FIG. 2

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TUNNELING NANOMECHANICAL SWITCHES AND TUNABLE PLASMONIC NANOGAPS

RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 62/252,771, filed November 9, 2015 and entitled "Tunneling Nanomechanical Switches" and to U.S. Provisional Patent Application Serial No. 62/252,762, filed November 9, 2015 and entitled "Tunable Plasmonic Nanogaps", both of which are incorporated herein by reference in its entirety for all purposes.

FIELD

The present invention relates generally to nanoscale mechanical devices that use nanoscale mechanical deformation to adjust electrical, optical, plasmonic properties of the system with applications in electromechanical devices (e.g. switches), and optomechanical devices, among others.

BACKGROUND

Nanoscale and microscale electromechanical switches and optomechanical devices have been developed for various applications.

In digital electronics there is a desire for improved efficiency. Conventional switches are implemented by semiconductor devices (e.g., transistors). Electromechanical switches have been considered as one option to improve efficiency. There is a desire for improved electromechanical devices to meet this need and others.

There is a desire for improved optomechanical devices for efficient optical communication and information processing, sensors and actuators, displays and other applications.

SUMMARY

Methods and articles related to electromechanical switches as well as related components and methods associated therewith are provided. The subject matter of the present invention involves, in some cases, interrelated products, alternative solutions to a particular problem, and/or a plurality of different uses of one or more systems and/or articles.

In one embodiment, a device comprises a first electrode, a second electrode, and a deformable layer positioned between the first electrode and the second electrode. The first

electrode may be electrically isolated. In some embodiments, the first electrode may be a mechanically floating electrode. In some embodiments, the deformable layer is configured such that tunneling may occur between the first electrode and the second electrode when the deformable layer is compressed.

In another embodiment, a device comprises a first electrode, a second electrode, and a deformable layer positioned between the first electrode and the second electrode. Both the first electrode and the second electrode may have a surface roughness of less than or equal to 0.5 nm. The deformable layer may be configured such that tunneling may occur between the first electrode and the second electrode when the deformable layer is compressed.

In another embodiment, a device comprises a first electrode, a second electrode, and a deformable layer positioned between the first electrode and the second electrode, wherein deformation of the deformable layer causes the plasmon resonance wavelength to shift from a first wavelength to a second wavelength.

In another embodiment, a method of operating a device comprises receiving or applying a force at at least one of a first electrode and a second electrode that deforms a deformable layer positioned between a first electrode and a second electrode such that the plasmon resonance wavelength shifts from a first wavelength to a second wavelength.

Other advantages and novel features of the present invention will become apparent from the following detailed description of various non-limiting embodiments of the invention when considered in conjunction with the accompanying figures. In cases where the present specification and a document incorporated by reference include conflicting and/or inconsistent disclosure, the present specification shall control. If two or more documents incorporated by reference include conflicting and/or inconsistent disclosure with respect to each other, then the document having the later effective date shall control.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting embodiments of the present invention will be described by way of example with reference to the accompanying figures, which are schematic and are not intended to be drawn to scale. In the figures, each identical or nearly identical component illustrated is typically represented by a single numeral. For purposes of clarity, not every component is labeled in every figure, nor is every component of each embodiment of the invention shown where illustration is not necessary to allow those of ordinary skill in the art to understand the invention. In the figures:

FIG. 1 shows, according to some embodiments, a schematic illustration of a device comprising a first electrode, a second electrode, and a layer positioned between the first electrode and the second electrode;

FIG. 2 shows, according to some embodiments, a schematic illustration of the application of force to a device;

FIG. 3 shows, according to some embodiments, a schematic illustration of a device comprising a first electrode, a second electrode, a layer positioned between the first electrode and the second electrode, and a conductive layer positioned within the layer positioned between the first electrode and the second electrode;

FIG. 4 shows, according to some embodiments, various materials that may be employed in electromechanical devices;

FIG. 5 shows, according to some embodiments, various materials that may be employed in electromechanical devices;

FIG. 6 shows, according to some embodiments, various materials that may be employed in electromechanical devices;

FIG. 7 shows, according to some embodiments, various materials that may be employed in electromechanical devices;

FIG. 8 shows, according to some embodiments, a schematic illustration of a device comprising three electrodes;

FIG. 9 shows, according to some embodiments, a schematic illustration of a device comprising four electrodes;

FIG. 10 shows, according to some embodiments, a schematic illustration of a split gate device;

FIG. 11 shows, according to some embodiments, a schematic illustration of the application of a voltage to a device;

FIG. 12 shows, according to some embodiments, the tunneling current as a function of applied voltage;

FIG. 13 shows, according to some embodiments, a schematic illustration of a device comprising graphene top and bottom electrodes;

FIG. 14 shows, according to some embodiments, micrographs of nanocubes and nanoplates;

FIG. 15 shows, according to some embodiments, a schematic illustration of the application of a voltage to a device and a micrograph of a nanocube;

FIG. 16 shows, according to some embodiments, micrographs of nanoplates;

FIG. 17 shows, according to some embodiments, a schematic illustration of a templated assembly process and a micrograph of a template;

FIG. 18 shows, according to some embodiments, a schematic illustration of chemical interactions between a layer and one or more electrodes;

FIG. 19 shows, according to some embodiments, a schematic illustration of a device comprising a gold nanocube monolayer;

FIG. 20 shows, according to some devices, a schematic illustration of devices comprising gold nanocubes;

FIG. 21 shows, according to some embodiments, a schematic illustration of the application of force to a device; and

FIG. 22 shows, according to some embodiments, a schematic illustration of a device comprising a nanocube electrode and micrographs showing the plasmon resonances from devices.

DETAILED DESCRIPTION

Articles and methods involving electromechanical devices are generally provided. In certain embodiments, a device includes a first electrode and a second electrode. In some embodiments, a device may include a first electrode, a second electrode, and a layer positioned between the first electrode and the second electrode. In some embodiments, the layer may be deformable while in other embodiments the layer may be non-deformable. In certain embodiments, the layer may be an insulator.

In some embodiments, the devices may have one or more beneficial properties. For instance, in certain embodiments a voltage applied to at least one of the first electrode and the second electrode may cause tunneling current to flow between the first electrode and the second electrode.

In some embodiments, the device may have a plasmon resonance wavelength in the visible range (e.g., greater than or equal to 500 nm and less than or equal to 900 nm). In some embodiments, the device may have a plasmon resonance wavelength in the infrared range, or any other range. Without wishing to be bound by theory, a plasmon resonance is an oscillation of electrons at the surface or surfaces of a conductor under resonance conditions. Plasmon resonances occurring at surfaces in close proximity to each other may couple to produce a plasmon resonance characteristic of the structure. When a plasmon resonance is optically excited, it may cause light at the resonance wavelength to be scattered. In some

embodiments, the device may be exposed to light, and light that is scattered, reflected, and/or transmitted may be detected.

In some embodiments, it may be possible to vary the distance between the first electrode and the second electrode by deforming the layer positioned between the first electrode and the second electrode. The first electrode and the second electrode may be brought closer together, or may be moved further apart. In certain embodiments, changing the distance between the first electrode and the second electrode may cause one or more of the electrical, optical or other properties of the device to change. For instance, the magnitude of the tunneling current between the first electrode and the second electrode may change as the distance between the first electrode and the second electrode changes, and/or the plasmon resonance wavelength of the device may change as the distance between the first electrode and the second electrode changes.

In some embodiments, the device may comprise a deformable layer which may be compressed or expanded. Compression or expansion of the deformable layer may be caused by mechanical force on one or more of the electrodes. Such a force may be produced in any of a variety of ways. For example, the force may be produced electrically by establishing a voltage difference between the first electrode and the second electrode and/or by applying a charge to an electrode that generates a mirror charge in the opposing electrode. Alternatively or additionally, the force can be produced mechanically due to physical contact with an object, application of a pressure due to a fluid (e.g., a liquid or gas), and/or an acoustic wave that impinges on an electrode, merely by way of example. As another example, the force may be produced as a result of a chemical reaction that expands or compresses the deformable material. The force can also be produced as a result of the application of light and/or heat to one or more device components.

The devices disclosed herein may be used in many suitable applications. In some embodiments, the device may serve as a tunneling switch. In some embodiments, the tunneling current through the device may be capable of being switched on or off by compression or expansion of the deformable layer. When the electrodes are brought within certain proximity, a tunneling current can flow between them, such that the switch is turned on. Conversely, moving the electrodes farther apart significantly reduces and/or eliminates the tunneling current, such that the switch is turned off.

In some embodiments, the device may be employed as an actuator. For instance, the device may transform electrical energy in the form of a voltage difference to mechanical energy in the form of a deformation of the deformable layer.

In certain embodiments, the device may be used as a sensor. For example, a change in the distance between the first electrode and the second electrode may cause a shift in the plasmon resonance wavelength. As another example, a change in the chemical composition of the layer positioned between the first electrode and the second electrode may cause a shift in the plasmon resonance wavelength.

Fig. 1 shows one non-limiting embodiment of a device. Device 100 comprises first electrode 110, second electrode 120, and layer 130 positioned between the first electrode and the second electrode. As described above, in some embodiments layer 130 may be a deformable layer.

As used herein, the term electrode refers to a layer that is electronically conducting or semiconducting. In some embodiments, an electrical potential may be applied to one or more electrodes. In some embodiments, an electrical potential may not be applied to one or more electrodes (e.g., a potential may not be applied to first electrode 110, or a potential may not be applied to second electrode 120). In some embodiments, an electrical potential may not be applied to any electrodes (e.g., a potential may be applied to neither of first electrode 110 and second electrode 120).

In some embodiments, the first electrode 110 may be electrically isolated. As used herein, an electrode is electrically isolated when it is not in electrical communication with any other conductor, aside from the capability of exchanging a tunneling current with another electrode (e.g., second electrode 120). That is, the electrode is topologically surrounded by insulators.

In some embodiments, the first electrode 110 may be a mechanically floating electrode. As used herein, a mechanically floating electrode is an electrode that can move as layer 120 deforms. Without wishing to be bound by theory, mechanically floating electrodes may provide certain advantages, such as allowing for the use of top electrode materials that may be challenging to fabricate as non-mechanically floating electrodes, including smooth electrodes and/or electrodes with nanoscale dimensions. In some embodiments, mechanically floating electrodes may be capable of being moved across a distance with a lower input energy than otherwise equivalent non-floating electrodes. Such electrodes will be described in further detail below.

As described above, in some embodiments, the layer 130 positioned between the first electrode and the second electrode may be a deformable layer. As used herein, a deformable layer is a layer that is capable of undergoing a change in size (i.e., a deformation) during normal operation of the device. The deformation may be reversible, or the deformation may

be non-reversible; that is, in some embodiments it may be possible for the deformable layer to return to its initial shape after deformation while in some embodiments it may not be possible for the deformable layer to return to its initial shape after deformation. In some embodiments, the layer 130 positioned between the first electrode and the second electrode may be a reversibly deformable layer, and may be capable of deforming under the influence of an applied force and then transforming back to its original shape once the force is removed. That is, the deformable layer may be capable of undergoing elastic deformation and/or functioning like a spring. Deformation of a deformable layer may comprise compression of the deformable layer such that the first electrode and the second electrode are brought closer together, or may comprise expansion of the deformable layer such that the first electrode and the second electrode are brought further apart. In some embodiments, the first layer 110 may float on the deformable layer, and the deformable layer may be capable of undergoing compression like a spring.

In some embodiments, the layer positioned between the first electrode 110 and the second electrode 120 may be a deformable layer, and it may be possible to change the distance between the first electrode and the second electrode by applying a force to the first electrode, the second electrode, or both. Fig. 2 shows a schematic depiction of this process, showing the application of a force to device 100 such that layer 130 compressibly deforms so that top electrode 110 is brought closer to bottom electrode 120. In some, but not necessarily all, embodiments, device 100 may return to the configuration shown in Fig. 1 after removal of the force.

In some embodiments, changing the distance between the first electrode 110 and the second electrode 120 may be particularly advantageous. For example, the device may not be capable of supporting a tunneling current at a relatively large distance between the first electrode 110 and the second electrode 120 but may be capable of supporting a tunneling current at a sufficiently small distance between the first electrode 110 and the second electrode 120. Changing the distance between the first electrode 110 and the second electrode 120 may thus allow for tunneling between the first electrode 110 and the second electrode 120 to be switched on and off. Further examples of electromechanical switches are disclosed in International Patent Application No. PCT/US2014/013403, filed January 28, 2014 and entitled "Electromechanical Device", herein incorporated by reference in its entirety for all purposes, are also contemplated.

In some embodiments, when placed in a closed switch position, the current that flows between the first electrode 110 and the second electrode 120 is greater than 10^{-8} A, greater

than 10^{-7} A, greater than 10^{-6} A, greater than 10^{-5} A, greater than 10^{-4} A, greater than 10^{-3} A, greater than 10^{-2}A, greater than 10^{-1} A, greater than 1.0 A, between 10^{-8} A and 1.0 A, between 10^{-7} 10 A and 10^{-1} A, between 10^{-6} A and 10^{-2} A, or between 10^{-5} A and 10^{-3} A. The current (e.g., tunneling) that flows between the first electrode 110 and the second electrode 120 when the device is placed in a closed switch position may fall within ranges defined by any of the end points listed above, or may fall outside of the above-noted ranges.

Conversely, when the device is in an open switch position with the electrodes farther apart, the direct tunneling current that flows between the first electrode 110 and the second electrode 120 is negligible. In some embodiments, when placed in an open switch position, the current that flows between the first electrode 110 and the second electrode 120 is less than 10^{-6} A, less than 10^{-7} A, less than 10^{-8} A, less than 10^{-9} A, less than 10^{-10} A, less than 10^{-11} A, less than 10^{-12} A, less than 10^{-13} A, between 10^{-6} A and 10^{-13} A, between 10^{-7} A and 10^{-12} A, between 10^{-8} A and 10^{-11} A, or between 10^{-9} A and 10^{-10} A. The current that flows between first electrode 110 and the second electrode 120 when the device is placed in an open switch position may fall within ranges defined by any of the end points listed above, or may fall outside of the above-noted ranges.

In certain embodiments, the ratio of the tunneling current that flows between the first electrode 110 and the second electrode 120 when the switch is closed to the tunneling current that flows between the first electrode 110 and the second electrode 120 when the device is open is relatively high. In some embodiments, the ratio of the tunneling current that flows between the first electrode 110 and the second electrode 120 when the switch is closed to the tunneling current that flows between the first electrode and the second electrode when the device is open is greater than or equal to 10^{3} A, greater than or equal to 10^{4} A, greater than or equal to 10^{5} A, greater than or equal to 10^{6} A, or greater than or equal to 10^{7} A. In some embodiments, the ratio of the tunneling current that flows between the first electrode 110 and the second electrode 120 when the switch is closed to the tunneling current that flows between the first electrode 110 and the second electrode 120 when the device is open is less than or equal to 10^{8}, less than or equal to 10^{7} A, less than or equal to 10^{6} A, less than or equal to 10^{5} A, or less than or equal to 10^{4}. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 10^{4} A and less than or equal to 10^{8} A). Other ranges are also possible.

In some embodiments, changing the distance between the first electrode 110 and the second electrode 120 (e.g., through deformation of a deformable layer positioned therebetween) may cause a change in the plasmon resonance wavelength. For instance, the

device may have a first plasmon resonance wavelength at a first distance between the first electrode and the second electrode and a second plasmon resonance wavelength at a second distance between the first electrode 110 and the second electrode 120. In some embodiments, it may be advantageous to modify the plasmon resonance wavelength as desired, or to shift it from the first wavelength to the second wavelength and/or back from the second wavelength to the first wavelength. For instance, it may be beneficial to change the plasmon resonance wavelength from a non-visible wavelength to a visible wavelength or from a first visible wavelength to a second visible wavelength for display applications. As another example, it may be beneficial to change the plasmon resonance from a wavelength that is not of interest to a wavelength that is of interest (e.g., changing the wavelength from one which would not trigger an optical sensor to one which would trigger the optical sensor).

In some embodiments, the plasmon resonance wavelength of a device may be dependent on the material or materials used to form the device components, the indices of refraction of the device components, and the thickness of the layer 130.

In some embodiments, the first plasmon resonance wavelength (or the plasmon wavelength prior to deformation of the deformable layer) may be greater than or equal to 500 nm, greater than or equal to 550 nm, greater than or equal to 600 nm, greater than or equal to 650 nm, greater than or equal to 700 nm, greater than or equal to 750 nm, greater than or equal to 800 nm, greater than or equal to 850 nm, greater than or equal to 900 nm, greater than or equal to 1000 nm, greater than or equal to 1200 nm, greater than or equal to 1300 nm, greater than or equal to 1400 nm, or greater than or equal to 1500 nm. In some embodiments, the first plasmon resonance wavelength may be less than or equal to 1600 nm, less than or equal to 1500 nm, less than or equal to 1400 nm, less than or equal to 1300 nm, less than or equal to 1200 nm, less than or equal to 1000 nm, less than or equal to 900 nm, less than or equal to 850 nm, less than or equal to 800 nm, less than or equal to 750 nm, less than or equal to 700 nm, less than or equal to 650 nm, less than or equal to 600 nm, or less than or equal to 550 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 500 nm and less than or equal to 900 nm). Other ranges are also possible.

In some embodiments, the second plasmon resonance wavelength (or the plasmon wavelength after deformation of the deformable layer) may be greater than or equal to 500 nm, greater than or equal to 550 nm, greater than or equal to 600 nm, greater than or equal to 650 nm, greater than or equal to 700 nm, greater than or equal to 750 nm, greater than or equal to 800 nm, greater than or equal to 850 nm, greater than or equal to 900 nm, greater

than or equal to 1000 nm, greater than or equal to 1200 nm, greater than or equal to 1300 nm, greater than or equal to 1400 nm, or greater than or equal to 1500 nm. In some embodiments, the second plasmon resonance wavelength may be less than or equal to 1600 nm, less than or equal to 1500 nm, less than or equal to 1400 nm, less than or equal to 1300 nm, less than or equal to 1200 nm, less than or equal to 1000 nm, less than or equal to 900 nm, less than or equal to 850 nm, less than or equal to 800 nm, less than or equal to 750 nm, less than or equal to 700 nm, less than or equal to 650 nm, less than or equal to 600 nm, or less than or equal to 550 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 500 nm and less than or equal to 900 nm). Other ranges are also possible.

A force may be applied to either or both of the first electrode 110 and the second electrode 120 by any suitable means, non-limiting examples of which include externally-applied mechanical pressure (e.g., by use of a clamp, lever, pressure applicator, manual compression, pressure from a surrounding fluid or gas, and the like), and/or by mechanical pressure applied by the one or more device components upon response to a stimulus (e.g., a stimulus such as electric field, light, heat, magnetic field, chemical environment, biological reaction, and the like).

In some embodiments, it may be possible to apply a force to the first electrode 110 by applying a voltage to the second electrode 120. Without wishing to be bound by theory, applying a voltage to the second electrode 120 may induce a charge of opposite sign on the surface of the first electrode 110. This may cause the first electrode 110 to be attracted to the second electrode 120 by electrostatic attraction. The electrostatic attraction between the first electrode 110 and the second electrode 120 may cause a compressive force to be exerted on the deformable layer 130, and may cause it to deform such that the first electrode 110 is moved closer to the second electrode 120. Applying a voltage to the second electrode 120 without applying a voltage to the first electrode 110 may be preferred in some embodiments, such as when the first electrode 110 is electrically isolated. In some embodiments, applying a voltage to the first electrode 110,the second electrode 120, or both causes tunneling to flow between the first electrode 110 and the second electrode 120.

Any suitable voltage or charge may be applied to the second electrode 120 (i.e., the bottom electrode) to generate a voltage difference between the first electrode 110 and the second electrode 120. The voltage may be positive or negative. In some embodiments, a voltage difference between the first electrode 110 and the second electrode 120 may be sufficient to cause deformation of the deformable layer 130. In some embodiments, the

voltage difference sufficient to cause deformation of the deformable layer 130 may be less than 1.0 V, less than 0.8 V, less than 0.5 V, less than 0.3 V, less than 100 mV, between 0.1 V and 1.0 V, between 0.1 V and 0.5 V, between 0.1 V and 0.3 V, etc. These voltage differences that result in suitable deformation may be appropriate for CMOS applications. Though, devices in accordance with the present disclosure may be suitable for use in other applications. In some embodiments, the magnitude of the voltage adequate to cause deformation of the deformable layer 130 is less than 15.0 V, less than 12.0 V, less than 10.0 V, less than 8.0 V, less than 6.0 V, less than 4.0 V, less than 2.0 V, less than 1.0 V, less htan 100 mV, between 0.1 V and 10.0 V, between 0.5 V and 5.0 V, between 1.0 V and 5.0 V, or between 5.0 V and 10.0 V. It can be appreciated that a voltage difference appropriate to cause deformation of the deformable layer 130 may fall within ranges defined by any of the end points listed above, or may fall outside of the above-noted ranges.

In some embodiments, it may be possible to apply a force to the first electrode 110 by causing one or more molecules in the layer positioned between the first electrode and the second electrode 130 to undergo an electrically-induced conformational change. For example, charges may be inserted or extracted from the layer, and/or the layer may undergo a piezoelectric response to an applied voltage.

In some embodiments, it may be possible to apply a magnetic force to the first electrode 110. For instance, both first electrode 110 and second electrode 120 may comprise one or more magnetic components. If a magnetic field is induced electromagnetically or by the use of an external source, the first electrode 110 and the second electrode 120 may be attracted to each other.

In some embodiments, the application of temperature may cause a force to be applied to the first electrode 110. A change in temperature may cause a conformational change in one or more molecules positioned in layer 130, or it may drive an expansion or compression of layer 130 if there is a thermal expansion coefficient mismatch between layer 130 and either first electrode 110 or second electrode 120.

In some embodiments, the application of light may cause a force to be applied to the first electrode 110. Exposure of layer 130 to light may directly cause a conformational change of at least some of the molecules in the layer, or may indirectly cause a conformational change of at least some of the molecules in the layer by changing the temperature of the layer. In some embodiments, optical forces exerted by light may be sufficient to cause deformation of layer 130.

In some embodiments, it may be possible to apply a force to the first electrode 110 by applying a chemical stimulus or a biological stimulus to layer 130 that results in a conformational change of at least some of the molecules in layer 130.

In some embodiments, applying a force to the first electrode 110, the second electrode 120, or both may result in a relatively low amount of deformation of the deformable layer 130. This may result in a relatively small change in distance between the first electrode 110 and the second electrode 120. In some embodiments, it may be possible to change the distance between the first electrode 110 and the second electrode 120 by a distance of less than or equal to 90% of the initial thickness of layer 130, less than or equal to 80% of the initial thickness of layer 130, less than or equal to 70% of the initial thickness of layer 130, less than or equal to 60% of the initial thickness of layer 130, less than or equal to 50% of the initial thickness of layer 130, less than or equal to 40% of the initial thickness of layer 130, less than or equal to 30% of the initial thickness of layer 130, less than or equal to 20% of the initial thickness of layer 130, less than or equal to 10% of the initial thickness of layer 130, or less than or equal to 5% of the initial thickness of layer 130. In some embodiments, it may be possible to change the distance between the first electrode 110 and the second electrode 120 by a distance of greater than or equal to 2.5% of the initial thickness of layer 130, greater than or equal to 5% of the initial thickness of layer 130, greater than or equal to 10% of the initial thickness of layer 130, greater than or equal to 20% of the initial thickness of layer 130, greater than or equal to 30% of the initial thickness of layer 130, greater than or equal to 40% of the initial thickness of layer 130, greater than or equal to 50% of the initial thickness of layer 130, greater than or equal to 60% of the initial thickness of layer 130, greater than or equal to 70% of the initial thickness of layer 130, or greater than or equal to 80% of the initial thickness of layer 130. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 2.5% of the initial thickness of layer 130 and less than or equal to 90% of the initial thickness of layer 130). Other ranges are also possible.

The first electrode 110 may be spaced at any distance from the second electrode 120 prior to applying a force to the first electrode 110, the second electrode 120, or both. In some embodiments, the distance between the first electrode 110 and the second electrode 120 prior to applying a force to the first electrode 110, the second electrode 120, or both may be greater than or equal to 3.0 nm, greater than or equal to 3.5 nm, greater than or equal to 4.0 nm, greater than or equal to 4.5 nm, greater than or equal to 5.0 nm, greater than or equal to 6.0 nm, greater than or equal to 7.0 nm, greater than or equal to 8.0 nm, greater than or equal to 9.0 nm, greater than or equal to 10.0 nm, greater than or equal to 20.0 nm, greater than or

equal to 30.0 nm, greater than or equal to 40.0 nm, or greater. In some embodiments, the distance between the first electrode 110 and the second electrode 120 prior to applying a force to the first electrode 110, the second electrode 120, or both may be less than or equal to 50.0 nm, less than or equal to 40.0 nm, less than or equal to 30.0 nm, 20.0 nm, less than 15.0 nm, less than or equal to 10.0 nm, less than or equal to 9.0 nm, less than or equal to 8.0 nm, less than or equal to 7.0 nm, less than or equal to 6.0 nm, less than or equal to 5.0 nm, or less.

The first electrode 110 may be spaced at any distance from the second electrode 120 as a force is being applied to the first electrode 110, the second electrode 120, or both. In some embodiments, the distance between the first electrode 110 and the second electrode 120 as a force is being applied to the first electrode 110, the second electrode 120, or both may be less than or equal to 50.0 nm, less than or equal to 40.0 nm, less than or equal to 30.0 nm, less than or equal to 20.0 nm, less than or equal to 10.0 nm, less than or equal to 9.0 nm, less than or equal to 8.0 nm, less than or equal to 7.0 nm, less than or equal to 6.0 nm, less than or equal to 5.0 nm, less than or equal to 4.0 nm, less than or equal to 3.5 nm, less than or equal to 3.0 nm, less than or equal to 2.5 nm, less than or equal to 2.0 nm, less than or equal to 1.5 nm, less than or equal to 1.0 nm, less than or equal to 0.5 nm, or less. In some embodiments, the distance between the first electrode 110 and the second electrode 120 as a force is being applied to the first electrode 110, the second electrode 120, or both may be greater than or equal to 1.0 nm, greater than or equal to 2.0 nm, greater than or equal to 2.5 nm, greater than or equal to 3.0 nm, greater than or equal to 3.5 nm, greater than or equal to 4.0 nm, greater than or equal to 5.0 nm, greater than or equal to 6.0 nm, greater than or equal to 7.0 nm, greater than or equal to 8.0 nm, greater than or equal to 9.0 nm, greater than or equal to 10.0 nm, greater than or equal to 20.0 nm, greater than or equal to 30.0 nm, greater than or equal to 40.0 nm, or greater.

In some embodiments, the deformable layer 130 may comprise a conductive layer positioned within the bulk of the layer 130 positioned between the first electrode and the second electrode. Fig. 3 illustrates one such embodiment, where layer 130 comprises conducive layer 140. The conductive layer 140 may comprise a film that is conductive (e.g., a metal film), or it may comprise a region of the layer positioned between the first electrode 110 and the second electrode 120 that is conductive (e.g., the layer positioned between the first electrode 110 and the second electrode 120 may comprise molecules with a conductive region, and the conductive regions may positioned with respect to each other such that a conductive layer is formed). In such embodiments, the distance between the first electrode 110 and the second electrode 120 prior to applying a force to the first electrode 110, the

second electrode 120, or both and/or while applying a force to the first electrode 110, the second electrode 120, or both may be a multiple of one of the numbers above. That is, the numbers above should be taken to refer to distances between conductive layers in addition to distances between electrodes. Without wishing to be bound by theory, the presence of a conductive layer within the deformable layer 130 may allow for tunneling between the first electrode 110 and the second electrode 120 through the conductive layer 140. In other words, tunneling currents may be established between both the first electrode 110 and the conductive layer 140 and between the conductive layer 140 and the second electrode 120 simultaneously. This may allow for the first electrode 110 and the second electrode 120 to be spaced farther apart while still allowing for tunneling.

In some embodiments, the deformable layer 130 may be capable of undergoing a desirable amount of deformation while being subject to a relatively low amount of pressure. In some such embodiments, the deformable layer 130 may have a relatively low Young's modulus. In some embodiments, the deformable layer 130 may have a Young's modulus of less than 15.0 MPa, less than 10.0 MPa, less than 9.0 MPa, less than 8.0 MPa, less than 7.0 MPa, less than 6.5 MPa, less than 6.0 MPa, less than 5.5 MPa, less than 5.0 MPa, less than 4.0 MPa, less than 3.0 MPa, less than 2.0 MPa, less than 1.0 MPa, etc. For example, the deformable layer may have a Young's modulus of between 1.0 MPa and 6.5 MPa, between 2.0 MPa and 6.0 MPa, between 1.0 MPa and 3.0 MPa, between 3.0 MPa and 5.0 MPa, between 5.0 MPa and 10.0 MPa or other ranges between end values provided herein. In certain embodiments, the deformable layer 130 may have a relatively higher Young's modulus. In some embodiments, the deformable layer 130 may have a Young's modulus of less than 150.0 MPa, less than 120.0 MPa, less than 100.0 MPa, less than 90.0 MPa, less than 80.0 MPa, less than 70.0 MPa, less than 60.0 MPa, less than 50.0 MPa, less than 40.0 MPa, less than 30.0 MPa, less than 20.0 MPa, less than 10.0 MPa, etc. For example, the deformable layer 130 may have a Young's modulus of between 1.0 MPa and 100.0 MPa, between 5.0 MPa and 50.0 MPa, between 10.0 MPa and 20.0 MPa, or other ranges between end values provided herein. It can be appreciated that the deformable layer 130 may exhibit a Young's modulus that falls outside of the above-noted ranges. The stiffness of the deformable layer 130 may be measured by methods known in the art, for example, by current-voltage extrapolation, interferometry measurements, atomic force microscopy, or other suitable techniques. In some embodiments, deformable layer 130 may have linear mechanical properties, or may behave like a spring (i.e., the Young's modulus may be considered to be analogous to spring constant of the layer). In other embodiments, deformable layer 130 may

have non-linear mechanical properties. That is, the Young's modulus may not be constant during compression and expansion of deformable layer 130.

In certain embodiments, the first electrode 110 may have one or more beneficial material properties, such as a very low level of surface roughness. Without wishing to be bound by theory, it is believed that low levels of surface roughness may be advantageous for one or more regions. For instance, low levels of surface roughness may enable the distance between the first electrode 110 and the second electrode 120 to be relatively constant across the surface of the first electrode, which may result in more uniform electrical and/or optical properties. In some embodiments, low levels of surface roughness of the first electrode 110 may be achieved by employing a single crystalline material for the first electrode. In certain embodiments, the first electrode may comprise a single crystalline material with a crystal facet oriented parallel to surface 122. The crystal facet may be atomically smooth; that is, it may be a crystal plane with minimal or no defects. In some embodiments, the first electrode 110 may have a surface roughness of less than or equal to 1 nm, less than or equal to 0.9 nm, less than or equal to 0.8 nm, less than or equal to 0.7 nm, less than or equal to 0.6 nm, less than or equal to 0.5 nm, less than or equal to 0.4 nm, less than or equal to 0.3 nm, or less than or equal to 0.2 nm. In some embodiments, the first electrode 110 may have a surface roughness of greater than or equal to 0.1 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.4 nm, greater than or equal to 0.5 nm, greater than or equal to 0.6 nm, greater than or equal to 0.7 nm, greater than or equal to 0.8 nm, or greater than or equal to 0.9 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 0.1 nm and less than or equal to 0.5 nm). Other ranges are also possible. In certain embodiments, the surface roughness may be less than or equal to half of the distance between the first electrode 110 and the second electrode 120. The surface roughness of the first electrode may be determined by atomic force microscopy.

The first electrode 110 may comprise any suitable material. In some embodiments, the first electrode 110 may comprise a two-dimensional material or a stack of two dimensional materials. As used herein, a two-dimensional material is a material that extends macroscopically in two dimensions but has sub-nanometer scale dimensions in a third dimension. One non-limiting example of a two-dimensional material is graphene.

In some embodiments, the first electrode 110 may comprise a nanomaterial. As used herein, a nanomaterial is a material that has at least one side length or diameter that is less than 200 nm. Non-limiting examples of nanomaterials include nanocubes (nanomaterials which have a cubic shape) and nanoplates (nanomaterials that are significantly thinner in one

dimension than in the other two). In some embodiments, the first electrode 110 may comprise a nanocube and the nanocube side length may be greater than or equal to 50 nm, greater than or equal to 75 nm, greater than or equal to 100 nm, greater than or equal to 125 nm, greater than or equal to 150 nm, or greater than or equal to 175 nm. In some embodiments, the first electrode 110 may comprise a nanocube and the nanocube side length may be less than or equal to 200 nm, less than or equal to 175 nm, less than or equal to 150 nm, less than or equal to 125 nm, less than or equal to 100 nm, or less than or equal to 75 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 50 nm and less than or equal to 200 nm). Other ranges are also possible. The nanocube side length may be determined by measurement using scanning electron microscopy, transmission electron microscopy, atomic force microscopy and/or optical interferometry.

In some embodiments, the first electrode 120 may comprise a metal, a semiconductor, or a semimetal. In certain embodiments, the first electrode 110 may comprise a transition metal. In some embodiments, the first electrode may comprise gold. In some embodiments, it may be preferred for the first electrode 110 to comprise a gold nanocube.

In certain embodiments, the second electrode 120 may have one or more beneficial materials properties, such as a very low level of surface roughness. In some embodiments, low levels of surface roughness of the second electrode 120 may be achieved by employing a single crystalline material for the second electrode 120. In certain embodiments, the second electrode 120 may comprise a single crystalline material with a crystal facet oriented parallel to surface 112. The crystal facet may be atomically smooth; that is, it may be a crystal plane with minimal or no defects. In some embodiments, the second electrode 120 may have a surface roughness of less than or equal to 1 nm, less than or equal to 0.9 nm, less than or equal to 0.8 nm, less than or equal to 0.7 nm, less than or equal to 0.6 nm, less than or equal to 0.5 nm, less than or equal to 0.4 nm, less than or equal to 0.3 nm, or less than or equal to 0.2 nm. In some embodiments, the second electrode 120 may have a surface roughness of greater than or equal to 0.1 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.4 nm, greater than or equal to 0.5 nm, greater than or equal to 0.6 nm, greater than or equal to 0.7 nm, greater than or equal to 0.8 nm, or greater than or equal to 0.9 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 0.1 nm and less than or equal to 0.5 nm). Other ranges are also possible. The surface roughness of the second electrode may be determined by atomic force microscopy.

The second electrode 120 may comprise any suitable material. In some embodiments, the second electrode 120 may comprise a two-dimensional material or a stack of two dimensional materials. In some embodiments, the second electrode 120 may comprise graphene. In certain embodiments, it may be preferable for both the first electrode 110 and the second electrode 120 to comprise graphene.

In some embodiments, the second electrode 120 may comprise a nanomaterial, such as a nanocube or a nanoplate. In certain embodiments, it may be preferable for the first electrode 110 to comprise a nanocube and the second electrode 120 to comprise a nanoplate.

In some embodiments, the second electrode 120 may comprise a metal, a semiconductor, or a semimetal. In certain embodiments, the second electrode 120 may comprise a transition metal. In some embodiments, the second electrode 120 may comprise gold. In some embodiments, the second electrode 120 may comprise a gold nanoplate.

The layer 130 positioned between the first electrode 110 and the second electrode 120 may have any suitable composition. In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may be an insulator. In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may comprise both conductive and insulating molecules, or both conductive nanomaterials and insulating molecules. The insulating molecules may be mixed with the conductive molecules and/or with the conductive nanomaterials, or the conductive molecules and/or nanomaterials may take the form of a conductive layer or layers dispersed within an insulating layer.

In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may comprise one or more molecules that are responsive to a stimuli such as electrical stimuli, optical stimuli, chemical stimuli, and/or thermal stimuli.

In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may comprise one or more organic molecules. Figs. 4-7 provide examples of suitable materials for the layer 130 positioned between the first electrode 110 and the second electrode 120, or organic thin film molecules, that may be incorporated in electromechanical devices described herein. In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may include molecules that form a self-assembled monolayer (SAM). In some embodiments, the molecules may include one or more functional groups that are capable of forming bonds with either or both of electrode 110 and electrode 120. Non-limiting examples of such groups include thiol groups, which may form covalent bonds with gold electrodes via gold-sulfur bonds. In some embodiments,

the SAM may be comprise at least one of polyethylene glycol thiol, polyethylene glycol dithiol, and fluorinated alkanethiol. In some embodiments, at least a portion of the molecules forming the SAM may include at least two functional groups, so that they may be capable of forming bonds with both electrodes.

In some embodiments, molecules making up the layer 130 positioned between the first electrode 110 and the second electrode 120 (e.g., self-assembled monolayers) may have a length of at least 1 nm, at least 2 nm, at least 3 nm, at least 4 nm, at least 5 nm, at least 7 nm, at least 10 nm, or other suitable length. Or, the molecules may have a length of less than 25 nm, less than 20 nm, less than 15 nm, less than 10 nm, or less than 5 nm, etc. The molecules of the layer 130 positioned between the first electrode 110 and the second electrode 120 may have a length that falls within ranges defined by any of the end points described above, or may fall outside of the above noted ranges.

As noted herein, the density of the molecules in a self-assembled monolayer may also be appropriately tailored. For example, a self-assembled monolayer may have a relatively low packing density, allowing the organic layer to exhibit a suitably low stiffness. In some embodiments, the packing density of a self-assembled monolayer for an elastically deformable material may be between 20% and 80%, between 30% and 70%, between 40% and 60% (e.g., approximately 50%), etc., or suitable for the layer 130 positioned between the first electrode 110 and the second electrode 120 to compress in an appropriate manner. It can be appreciated that such molecules may also have functional groups that will affect their overall stiffness. For instance, in some cases, fluorinated alkane thiol molecules may be employed, resulting in relatively straight molecular chains due to mutual repulsion of fluorine atoms from one another. Such self-assembled monolayers may be formed using a mixture of fluorinated thiols and semifluorinated thiols, such as those shown in Figs. 5-6.

Approaches in accordance with the present disclosure may give rise to a self-assembled monolayer that has a relatively dense collection of fluorine atoms on one side with a sparsely packed alkyl self-assembled monolayer located on an opposite side. The densely packed fluorous region may be relatively rigid, stabilizing the self-assembled monolayer so as to promote self-assembly. The sparse alkyl portion, on the other hand, may allow for compression of the overall layer by, for example, increasing the void space. As alkyl and perfluoroalkyl molecules exhibit generally unfavorable intermolecular forces (repulsive) with respect to one another, the open switch position of the device will be thermodynamically favored. In other words, when the device is actuated to a closed switch position, where alkyl and perfluoroalkyl molecules are bunched together, the repulsive nature of the molecules

promote recovery, allowing the open switch position to be restored upon removal of the actuation voltage/force.

In some embodiments, the layer 130 positioned between the first electrode 110 and the second electrode 120 may include an evaporated or spin-coated organic layer, such as triptycene, dibenzocyclooctatetraene, or any other suitable molecule. Such molecules may exhibit generally 3D structures, which may naturally nestle amongst one another as the thin film is squeezed or otherwise compressed. These materials may also have properties such that the tunneling barrier between electrodes changes when the molecule is compressed or that the plasmon resonance of the device is changed when the molecule is compressed. For example, the tunneling barrier threshold therethrough may be substantially lowered upon compression of the molecule(s). In such cases, despite the possibility for the molecule(s) of the layer positioned between the first electrode 110 and the second electrode 120 to be relatively stiff, the molecule(s) may undergo a conformational change upon compression, resulting in a substantial tunneling current to arise between electrodes. As another example, the compression of the molecules will result in a reduction in distance between first electrode 110 and second electrode 120, which will change the coupling between the surface plasmon resonances of these electrodes and thus change the plasmon resonance of the device.

Dibenzocyclooctatetraene (dibenzoCOT), shown in Figs. 5 and 7, is a small-molecule, which takes on an arched, tub-like shape in its ground state so as to avoid an unfavorable anti-aromatic thermodynamic state. However, dibenzoCOT can be forced to a substantially flattened anti-aromatic state as shown in Fig. 7. This results in a conformational change in structure where a significant restoring force is generated due to the chemical instability of the anti-aromatic system.

As described above, when the electrodes are brought closer together, the tunneling length therebetween decreases. When the elastically deformable layer includes dibenzoCOT, the tunneling barrier may be further decreased, as dibenzoCOT, in a compressed flat state, may allow for the overlap of delocalized cyclic pi-systems. That is, the compressed dibenzoCOT may allow for a greater amount of current therethrough than when in the arched tub-like shape. Accordingly, when compressed, the presence of dibenzoCOT may increase the total current between electrodes as they are brought closer together.

Among other small organic molecules that may be used to develop electromechanical devices in accordance with the present disclosure are tris-(8-hydroxyquinoline)aluminum (alq3), triptycene and triptycene derivatives. The chemical structures of these molecules may give rise to a tendency for the molecules to form thin-films having a relatively low packing

density. When such molecules exhibit a low packing density, the formed layer may possess a relatively low stiffness, allowing for low voltage actuation of the device from open to closed switch positions.

The layer 130 positioned between the first electrode 110 and the second electrode 120 may include any other suitable composition. In various embodiments, the elastically deformable material may include dendrimers (e.g., repetitively branched molecules often substantially symmetric around a core), star polymers, biopolymers (e.g., collagen, carbohydrates, peptides, etc.), hydrogen-bonded matrices, organic nanoparticles, modified carbon nanotubes, redox-sensitive polymers, or other appropriate material.

It should be understood that the layer 130 positioned between the first electrode 110 and the second electrode 120 is not limited to the compositions discussed herein, as the use of other suitable compositions are within the scope of the present disclosure.

In some embodiments, the layer positioned between the first electrode 110 and the second electrode 120 is bonded to one or both of the first electrode 110 and the second electrode 120. The layer 130 positioned between the first electrode 110 and the second electrode 120 may be bonded to an electrode by any suitable means, such as by a non-covalent interaction, by a covalent interaction, by a hydrophobic-hydrophilic interaction, and by electrostatic attraction. In some embodiments, layer 130 positioned between the first electrode 110 and the second electrode 120 is bonded to an electrode by one or more of an adamantane-cyclodextrin interaction and a gold-thiol interaction.

In some embodiments, the device may further comprise a third electrode, a fourth electrode, or more electrodes. It should be understood that any of the properties described above in relation to two electrode devices may also be present for devices comprising three, four, or more electrodes. For example, the device may function as an electromechanical switch, tunneling may be selectively turned off and on by modulating the distance between the first electrode and the second and third electrodes, and/or the plasmon resonance may be tuned by modulating the distance between the first electrode and the second and third electrodes.

In certain embodiments, the device comprises a third electrode (or a fourth electrode) and the third electrode (or fourth electrode) is positioned on a side of the layer positioned between the first electrode and the second electrode opposite the first electrode (e.g., a side of the deformable layer opposite the first electrode). In some embodiments, the first electrode bridges the second electrode and the third electrode. Fig. 8 shows one non-limiting example of a device, where device 800 comprises first layer 810, second electrode 820, third electrode

825, and layer 830. Although Fig. 8 shows layer 830 as being present in the regions of space directly between first electrode 810 and second electrode 820 and between first electrode 810 and third electrode 825 but not in any other region of space, other configurations of the layer and the electrode are also possible (e.g., any portion or no portion of the region of space between first electrode 810 and second electrode 820, any portion or no portion of the region of space between first electrode 810 and second electrode 825, and/or any portion or no portion of the region of space not directly between any electrodes). In some embodiments, it may be preferable for the first electrode 810 to be both mechanically floating and electrically isolated.

In some embodiments, the device may comprise a third electrode 825 and may be a two terminal device. That is, the device may comprise two points at which electrical contact can be made. In some embodiments, the two terminals are the second electrode 820 and the third electrode 825. In some such embodiments, the second electrode 820 may be the source and the third electrode 825 may be the drain. A voltage difference may be established between the second electrode 820 and the third electrode 825 that causes a tunneling current to flow from the second electrode 820 to the first electrode 810, and from the first electrode 810 to the third electrode 825.

In some embodiments, the device may comprise three electrodes and may be a three terminal device. One example of a three terminal device is a device that can be operated in a similar manner to a MOSFET, as shown illustratively in Fig. 9. Without wishing to be bound by theory, a MOSFET device is a device comprising a source, a drain, and a gate. The gate may control the level of current that flows between the source and the drain. As shown in Fig. 9, a MOSFET may comprise first electrode 810, second electrode 820, third electrode 825, and gate 850. Applying a charge to the gate 850 produces an image charge in electrode 810 that produces an electrostatic force that pulls electrode 810 closer to the source electrode 820 and the drain electrode 825. When the distance is small enough, a tunneling current flows between the source electrode 820 and the electrode 810 and between the electrode 810 and the drain electrode 825.

In some embodiments, the MOSFET may be a split drain device. For example, the first electrode may be the source electrode and the second and third electrodes may be the drain electrodes. In some embodiments, the device is a MOSFET device with a split gate. One non-limiting example of such a device is shown in Fig. 10, where device 801 comprises first electrode 810, second electrode 820, third electrode and split gate 855. Other MOSFETs are also contemplated, as are other three terminal devices.

It should also be noted that three terminal devices may also be designed that do not require a tunneling current to be formed during operation in order for the desired properties to be present. For example, three terminal devices with tunable plasmonic properties are also contemplated. Such a device may comprise a first electrode 810 that is capable of being translated with respect to second electrode 820 and third electrode 825 to various positions with various different plasmon resonances. The plasmon resonances may be present in the absence of a tunneling current between any of the electrodes.

In certain embodiments, the third electrode 825 may have one or more beneficial materials properties, such as a very low level of surface roughness. In some embodiments, low levels of surface roughness of the third electrode 825 may be achieved by employing a single crystalline material for the third electrode 825. In certain embodiments, the third electrode 825 may comprise a single crystalline material with a crystal facet oriented parallel to surface 812. The crystal facet may be atomically smooth; that is, it may be a crystal plane with minimal or no defects. In some embodiments, the third electrode 825 may have a surface roughness of less than or equal to 1 nm, less than or equal to 0.9 nm, less than or equal to 0.8 nm, less than or equal to 0.7 nm, less than or equal to 0.6 nm, less than or equal to 0.5 nm, less than or equal to 0.4 nm, less than or equal to 0.3 nm, or less than or equal to 0.2 nm. In some embodiments, the third electrode 825 may have a surface roughness of greater than or equal to 0.1 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.4 nm, greater than or equal to 0.5 nm, greater than or equal to 0.6 nm, greater than or equal to 0.7 nm, greater than or equal to 0.8 nm, or greater than or equal to 0.9 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 0.1 nm and less than or equal to 0.5 nm). Other ranges are also possible. The surface roughness of the second electrode may be determined by atomic force microscopy.

The third electrode 825 may comprise any suitable material. In some embodiments, the third electrode 825 may comprise a two-dimensional material or a stack of two dimensional materials. In some embodiments, the third electrode 825 may comprise graphene. In certain embodiments, it may be preferable for each of the first electrode 810, the second electrode 820, and the third electrode 825 to comprise graphene.

In some embodiments, the third electrode 825 may comprise a nanomaterial, such as a nanocube or a nanoplate. In certain embodiments, it may be preferable for the first electrode 810 to comprise a nanocube and both the second and third electrodes 820 and 825 to comprise nanoplates.

In some embodiments, the third electrode 825 may comprise a metal, a semiconductor, or a semimetal. In certain embodiments, the third electrode 825 may comprise a transition metal. In some embodiments, the third electrode 825 may comprise gold. In some embodiments, the third electrode 825 may comprise a gold nanoplate.

In some embodiments, the third electrode 825 may be positioned at a distance from the second electrode 820 that is advantageous for one or more applications. For example, in some embodiments the third electrode 825 may be positioned sufficiently far from the second electrode 820 that tunneling will not occur between the second electrode 820 and the third electrode 825 (e.g., the distance between the second electrode 820 and the third electrode 825 may be greater than the distance between the second electrode 820 and the first electrode 810). This may force the tunneling current to flow from the second electrode 820 through the first electrode 810 to the third electrode 825. In certain embodiments, the third electrode 825 may be positioned at a distance from the second electrode 820 such that the optical properties are enhanced. For instance, the distances between the first, second, and third electrodes 810, 820, and 825 may be selected so that the plasmon resonance is an appropriate value when the layer 830 positioned between the first electrode 810 and the second electrode 820 is undeformed and/or when the layer 830 positioned between the first electrode 810 and the second electrode 820 is deformed. In some embodiments, third electrode 825 is positioned sufficiently far from second electrode 820 in comparison to the distance between first electrode 810 and second electrode 820 such that the plasmon resonance of the deivce is dominated by the distance between first electrode 810 and second electrode 820. In some other embodiments, third electrode 825 may be positioned relatively close to second electrode 820. In either case, the plasmon resonance will shift when the layer 830 is deformed.

In some embodiments, the distance between the second electrode 820 and the third electrode 825 in the plane of the second electrode 820 may be less than or equal to 200 nm, less than or equal to 100 nm, less than or equal to 75 nm, less than or equal to 50 nm, less than or equal to 40 nm, less than or equal to 30 nm, less than or equal to 20 nm, or less than or equal to 10 nm. In some embodiments, the distance between the second electrode 820 and the third electrode 825 may be greater than or equal to 5 nm, greater than or equal to 10 nm, greater than or equal to 20 nm, greater than or equal to 30 nm, greater than or equal to 40 nm, greater than or equal to 50 nm, greater than or equal to 75 nm, or greater than or equal to 100 nm. Combinations of the above-referenced ranges are also possible (e.g., less than or equal to 100 nm and greater than or equal to 5 nm). Other ranges are also possible.

In some embodiments, the distance between the first electrode 810 and the second electrode 820 may be fairly close to the distance between the first electrode 810 and the third electrode 825. In certain embodiments, the distance between the first electrode 810 and the second electrode 820 may be within 1% of the distance between the first electrode 810 and the second electrode 825, within 2% of the distance between the first electrode 810 and the second electrode 825, within 5% of the distance between the first electrode 810 and the second electrode 825, within 10% of the distance between the first electrode 810 and the second electrode 825, or within 20% of the distance between the first electrode 810 and the second electrode 825.

In certain embodiments, a fourth and or fifth electrode may be present, and the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may have one or more beneficial materials properties, such as a very low level of surface roughness. In some embodiments, low levels of surface roughness of the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may be achieved by employing a single crystalline material for the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855). In certain embodiments, the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may comprise a single crystalline material with a crystal facet oriented parallel to surface 812. The crystal facet may be atomically smooth; that is, it may be a crystal plane with minimal or no defects. In some embodiments, the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may have a surface roughness of less than or equal to 1 nm, less than or equal to 0.9 nm, less than or equal to 0.8 nm, less than or equal to 0.7 nm, less than or equal to 0.6 nm, less than or equal to 0.5 nm, less than or equal to 0.4 nm, less than or equal to 0.3 nm, or less than or equal to 0.2 nm. In some embodiments, the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may have a surface roughness of greater than or equal to 0.1 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.4 nm, greater than or equal to 0.5 nm, greater than or equal to 0.6 nm, greater than or equal to 0.7 nm, greater than or equal to 0.8 nm, or greater than or equal to 0.9 nm. Combinations of the above-referenced ranges are also possible (e.g., greater than or equal to 0.1 nm and less than or equal to 0.5 nm). Other ranges are also possible. The surface roughness of the fourth and/or fifth electrode (e.g., electrode 850, electrodes 855) may be determined by atomic force microscopy.

In some embodiments, a device may comprise a sixth electrode, a seventh electrode or more electrodes. If present, these electrodes may also have any of the values of surface roughness as described above in relation to the fourth and/or fifth electrodes.

The fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855), if present, may comprise any suitable material. In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise a two-dimensional material or a stack of two dimensional materials. In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise graphene.

In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise a nanomaterial, such as a nanocube or a nanoplate.

In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise a metal, a semiconductor, or a semimetal. In certain embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise a transition metal. In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise gold. In some embodiments, the fourth and/or fifth electrodes (e.g., electrode 850, electrodes 855) may comprise a gold nanoplate.

In some embodiments, a device may comprise a sixth electrode, a seventh electrode or more electrodes. If present, these electrodes may also comprise any of the same materials as described above for the fourth and/or fifth electrodes.

Devices disclosed herein may be fabricated in any suitable manner. In some embodiments, one or more device components may be directly deposited. Deposition methods may include evaporation onto a substrate, dip coating, spin coating, and any other suitable method.

In certain embodiments, one or more device components may be fabricated by using a self-assembly process and/or a directed assembly process. For instance, one or more electrodes may be made to assemble at the interface between two immiscible fluids. As another example, two or more electrodes (e.g., a first electrode 810 and a second electrode 820 or a second electrode 820 and a third electrode 825) may be functionalized with molecules that are capable of bonding with each other. The functionalized electrodes may be exposed to each other such that a bond forms between them. Non-limiting examples of bonds that may be formed include bonds formed due to click chemistry such as adamantane-cyclodextrin chemistry, bonds formed due to gold-thiol interactions, and bonds formed due to electrostatic attraction and other non-covalent interactions.

In certain embodiments, a template may be employed to assist in device fabrication. External stimuli such as electric field, magnetic field or light may also be used in assembly of the device components.

EXAMPLE 1

Tunneling nanoelectromechanical (NEM) switches based on molecular thin films (referred to as squitches) may operate through electromechanical modulation of tunneling current through a molecular layer forming the switching gap. In this approach, an applied electric field across two electrodes sandwiching a molecular layer provides sufficient force to cause mechanical compression of the molecules. As the molecules are compressed, the tunneling gap decreases, causing an exponential increase in the current which turns on the switch. As the voltage is removed, the elastic restoring force of the molecular film helps overcome surface adhesive forces to move the top contact to the original OFF-state position. Such a device can be fabricated by utilizing metal-molecule-graphene tunneling junctions. The graphene provides a locally atomically smooth surface which helps form a well-defined switching gap. The graphene can be grown through a chemical vapor deposition technique and transferred onto the molecular layer. However, other techniques for graphene preparation such as mechanical or chemical exfoliation can also be used. A schematic of the switching mechanism and a sample current-voltage plot of such a device are shown in Fig. 11 and Fig. 12, respectively

The tunneling NEM switches can also be formed using switching gaps with graphene forming both the bottom and top electrodes, as shown in Fig. 13. This may further assist in the development of a well-defined molecular gap with minimal surface roughness, thus allowing for more uniform and repeatable switching performance.

It should also be noted that the above switches may also be incorporated into multi-terminal device designs with applications relevant to integrated systems.

The tunneling NEM switches can also be fabricated using chemically-synthesized nanomaterials, including gold (Au) nanocubes and nanoplates (see Fig. 14). These single crystalline structures may have smooth surfaces with sub-nanometer roughness that can assist in forming well-defined nanometer-scale molecular switching gaps. Furthermore, through chemical synthesis the shape and size of the particles can be tuned.

Fabrication of devices based on these nanoparticles may employ a multi-step directed assembly process which can be achieved through engineering the surfaces and/or interfaces. In one design, Au nanoplates placed within 100 nm of each other may form the bottom electrodes while an Au nanocube bridging the gap may form the top contact as shown in Fig. 15. The Au plates may be assembled such that they are within 100 nm of each other by first modifying the Au nanoplate surface and then allowing the nanoplates to assemble at the interface between two immiscible liquids. This is illustrated in Fig. 16, which shows an

image of two gold nanoplates on a surface aligned side by side and separated by a 20 nm gap. Gold bonding pads, for example, could be deposited over the nanoplates at their far extremes to provide for conductivity.

Several strategies have been developed to locate nanocubes on the molecular film bridging the nanogap between the Au plates. One is physical, and involves using templates that preferentially guide the nanocubes to the desired location. An example of this process is shown in Fig. 17. Other strategies employ chemical interactions of the molecular layer, such as noncovalent click chemistry, directed chemical bond formation, and electrostatic attraction of chemical groups (Fig. 18). A combination of both chemical and physical approaches can also be utilized.

In an alternative design, the device can be fabricated by forming bottom contacts separated by a gap either through the use of self-assembled Au plates or direct metal deposition techniques. The gap is then bridged using a self-assembled monolayer of Au cubes surface functionalized with a molecular thin film of desired thickness (see Fig. 19). An application of a voltage between the bottom electrodes causes a decrease in the spacing between the neighboring Au nanocubes. The device can also be fabricated by alignment of a nanocube at the edge of the bottom electrode in a structure similar to shoes shown in Fig. 20.

It should also be noted that the tunneling NEM squitches formed through use of chemically synthesized and assembled nanoparticles can also be used to fabricate multi-terminal devices.

EXAMPLE 2

In this example, a tunable plasmonic gap in which a compressible molecular layer is used to define the few nanometer thin gap between metallic surfaces is proposed. The molecular film may allow for controlled tuning of the metal-metal distance as it is mechanically compressed through an applied external force. The process may be reversible if the molecular film provides an elastically restoring force. A schematic representation of this process is shown in Fig. 21. Surface plasmons of two metallic surfaces separated by a nanoscape gap may couple to one another, and the coupling may vary with the distance between the metal surfaces. The plasmon resonance of such a nanogap shifts for different metal-metal distances, and can be detectable through a shift in the scattering and reflection spectra of the nanostructure (Fig. 22). Controlled tuning of the nanogap by utilizing molecular films may allow for the development of a dynamically tunable plasmonic gap with

applications in areas such as metrology tools for probing nanoscale mechanical motion and mechanical properties of molecular films sensors, actuators, and nanoantennas.

The plasmonic nanogaps can be fabricated using gold bottom contact and can be formed either through direct deposition techniques or through the use of chemically synthesized gold nanoplates. The molecular film can then be formed through thin film deposition techniques, self-assembly through chemical bond formation, or electrostatic interaction between chemical groups. To form the top metal surface, chemically synthesized Au nanoparticles such as gold nanocubes can be synthesized and functionalized onto the molecular layer surface. Fig. 14 shows scanning electron micrographs of chemically synthesized Au nanoplates and nanocubes.

Alternatively, systems based on individual tunable nanogaps can also be implemented. Such a system can be fabricated using chemically-synthesized nanomaterials, such as gold (Au) nanocubes and nanoplates while utilizing a multi-step process to direct assembly of the desired structures. The assembly process may be implemented through engineering the surfaces and/or interfaces. In one design, Au nanoplates are placed within 100 nm of each other to form the bottom electrodes and a Au nanocube is placed such that it bridges the gap (Fig. 15). In this design, the application of a voltage between the bottom electrodes may provide an electrostatic force that can cause mechanical compression of the molecular film as the top electrode moves closer to the bottom contacts. A shift in the plasmon resonance peak of the system can then be detected as the gap is reduced due to the applied voltage.

While several embodiments of the present invention have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the functions and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the present invention. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the teachings of the present invention is/are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, the invention may be

practiced otherwise than as specifically described and claimed. The present invention is directed to each individual feature, system, article, material, kit, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the scope of the present invention.

All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

The indefinite articles "a" and "an," as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean "at least one."

The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B", when used in conjunction with open-ended language such as "comprising" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of," or, when used in the claims, "consisting of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e. "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of," or "exactly one of." "Consisting essentially of," when used in the claims, shall have its ordinary meaning as used in the field of patent law.

As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element

selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

In the claims, as well as in the specification above, all transitional phrases such as "comprising," "including," "carrying," "having," "containing," "involving," "holding," "composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

Any terms as used herein related to shape, orientation, alignment, and/or geometric relationship of or between, for example, one or more articles, structures, forces, fields, flows, directions/trajectories, and/or subcomponents thereof and/or combinations thereof and/or any other tangible or intangible elements not listed above amenable to characterization by such terms, unless otherwise defined or indicated, shall be understood to not require absolute conformance to a mathematical definition of such term, but, rather, shall be understood to indicate conformance to the mathematical definition of such term to the extent possible for the subject matter so characterized as would be understood by one skilled in the art most closely related to such subject matter. Examples of such terms related to shape, orientation, and/or geometric relationship include, but are not limited to terms descriptive of: shape - such as, round, square, circular/circle, rectangular/rectangle, triangular/triangle,

cylindrical/cylinder, elliptical/ellipse, (n)polygonal/(n)polygon, etc.; angular orientation - such as perpendicular, orthogonal, parallel, vertical, horizontal, collinear, etc.; contour and/or trajectory – such as, plane/planar, coplanar, hemispherical, semi-hemispherical, line/linear, hyperbolic, parabolic, flat, curved, straight, arcuate, sinusoidal, tangent/tangential, etc.; direction – such as, north, south, east, west, etc.; surface and/or bulk material properties and/or spatial/temporal resolution and/or distribution – such as, smooth, reflective, transparent, clear, opaque, rigid, impermeable, uniform(ly), inert, non-wettable, insoluble, steady, invariant, constant, homogeneous, etc.; as well as many others that would be apparent to those skilled in the relevant arts. As one example, a fabricated article that would described herein as being " square" would not require such article to have faces or sides that are perfectly planar or linear and that intersect at angles of exactly 90 degrees (indeed, such an article can only exist as a mathematical abstraction), but rather, the shape of such article should be interpreted as approximating a " square," as defined mathematically, to an extent typically achievable and achieved for the recited fabrication technique as would be understood by those skilled in the art or as specifically described. As another example, two or more fabricated articles that would described herein as being " aligned" would not require such articles to have faces or sides that are perfectly aligned (indeed, such an article can only exist as a mathematical abstraction), but rather, the arrangement of such articles should be interpreted as approximating "aligned," as defined mathematically, to an extent typically achievable and achieved for the recited fabrication technique as would be understood by those skilled in the art or as specifically described.

CLAIMS

What is claimed is:

1. A device, comprising:

a first electrode;

a second electrode; and

a deformable layer positioned between the first electrode and the second electrode, wherein the first electrode is electrically isolated, wherein the first electrode is a mechanically floating electrode, and wherein the deformable layer is configured such that tunneling may occur between the first electrode and the second electrode when the deformable layer is compressed.

2. A device, comprising:

a first electrode;

a second electrode; and

a deformable layer positioned between the first electrode and the second electrode, wherein both the first electrode and the second electrode have a surface roughness of less than or equal to 0.5 nm, and wherein the deformable layer is configured such that tunneling may occur between the first electrode and the second electrode when the deformable layer is compressed.

3. A device, comprising:

a first electrode;

a second electrode; and

a deformable layer positioned between the first electrode and the second electrode, wherein deformation of the deformable layer causes the plasmon resonance wavelength to shift from a first wavelength to a second wavelength.

4. A method of operating a device, comprising:

receiving or applying a force at at least one of a first electrode and a second electrode that deforms a deformable layer positioned between a first electrode and a second electrode such that the plasmon resonance wavelength shifts from a first wavelength to a second wavelength.

5. A method or device as in any previous claim, wherein the device further comprises a third electrode.

6. A method or device as in claim 5, wherein the third electrode is positioned on a side of the deformable layer opposite the first electrode.

7. A method or device as in any of claims 5-6, wherein the device further comprises a fourth electrode.

8. A method or device as in claim 7, wherein the fourth electrode is positioned on a side of the deformable layer opposite the first electrode.

9. A method or device as in any previous claim, wherein the device is a split drain device.

10. A method or device as in any previous claim, wherein the device is a split gate device.

11. A method or device as in any one of claims 5-10, wherein the first electrode bridges the second electrode and the third electrode.

12. A method or device as in any previous claim, wherein at least one of the first electrode and the second electrode comprises graphene.

13. A method or device as in any previous claim, wherein both the first electrode and the second electrode comprise graphene.

14. A method or device as in any previous claim, wherein the first electrode comprises a nanocube.

15. A method or device as in any previous claim, wherein a side length of the nanocube between 50 nm and 200 nm.

16. A method or device as in any previous claim, wherein the second electrode comprises a nanoplate.

17. A method or device as in any one of claims 5-16, wherein the third electrode comprises a nanoplate.

18. A method or device as in any previous claim, wherein at least one of the first electrode and the second electrode are single crystalline.

19. A method or device as in any previous claim, wherein both the first electrode and the second electrode are single crystalline.

20. A method or device as in any one of claims 5-19, wherein a distance between the second electrode and the third electrode is less than or equal to 100 nm.

21. A method or device as in any one of claims 5-20, wherein a distance between the first electrode and the second electrode is within 5% of a distance between the first electrode and the third electrode.

22. A method or device as in any previous claim, wherein the deformable layer comprises an organic molecule.

23. A method or device as in any previous claim, wherein the deformable layer is adhered to one or more electrodes by a non-covalent interaction.

24. A method or device as in any previous claim, wherein the deformable layer is adhered to one or more electrodes by a covalent interaction.

25. A method or device as in any previous claim, wherein the deformable layer is adhered to one or more electrodes by electrostatic attraction.

26. A method or device as in any previous claim, wherein the deformable layer is adhered to one or more electrodes by one or more of an adamantane-cyclodextrin interaction and a gold-thiol interaction.

27. A method or device as in any previous claim, wherein both the first wavelength and the second wavelength are visible wavelengths.

28. A method as in any one of claims 4-27, further comprising releasing the force, wherein releasing the force causes the plasmon resonance to shift from the second wavelength to the first wavelength.

29. A method as in any one of claims 4-28, wherein applying a force comprises forming a potential difference between the first electrode and the second electrode.

30. A method as in any one of claims 5-29, wherein applying a force comprises forming a potential difference between the second electrode and a third electrode.

31. A method as in any one of claims 4-30, further comprising exposing the device to light.

32. A method as in any one of claims 5-31, wherein applying a voltage comprises forming a potential difference between the second electrode and a third electrode.

33. A method or device as in any one of the preceding claims, wherein the device is a sensor.

34. A method or device as in any one of the preceding claims, wherein the device is employed in a display application.

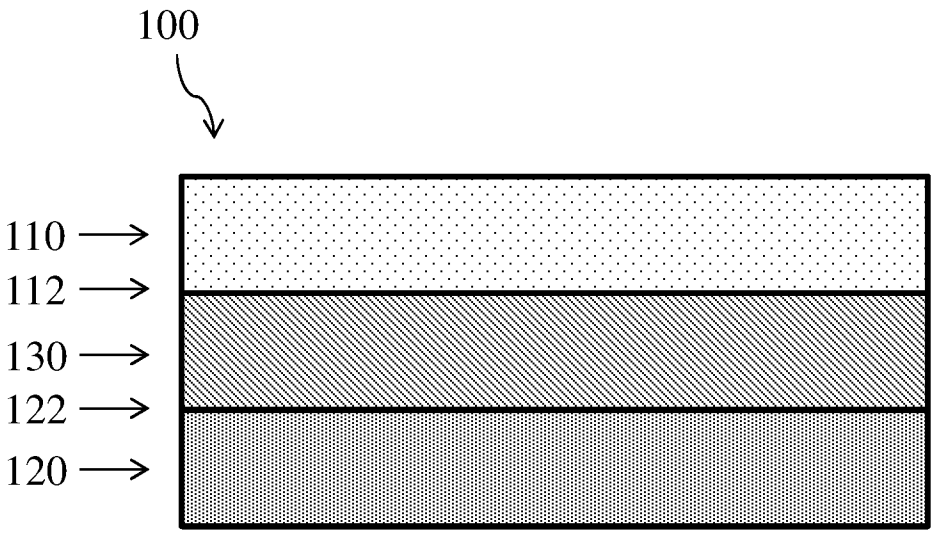


FIG. 1

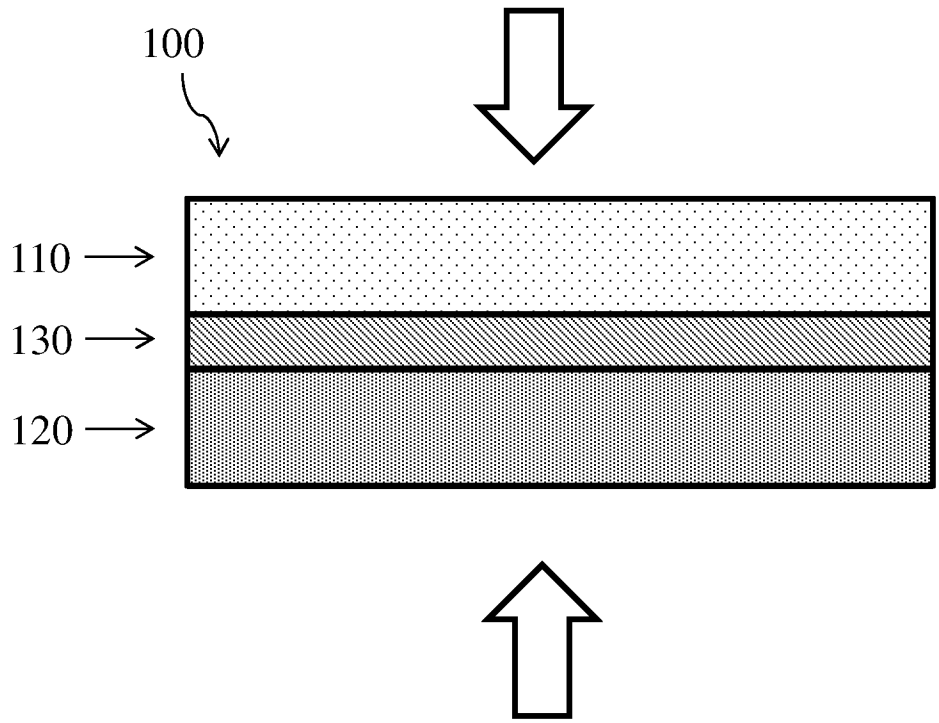


FIG. 2

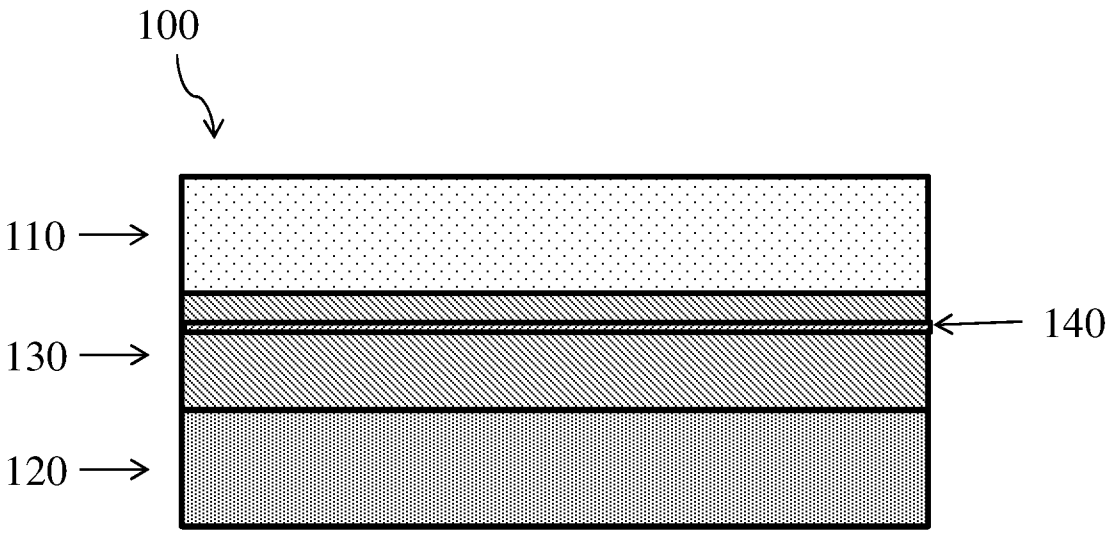


FIG. 3

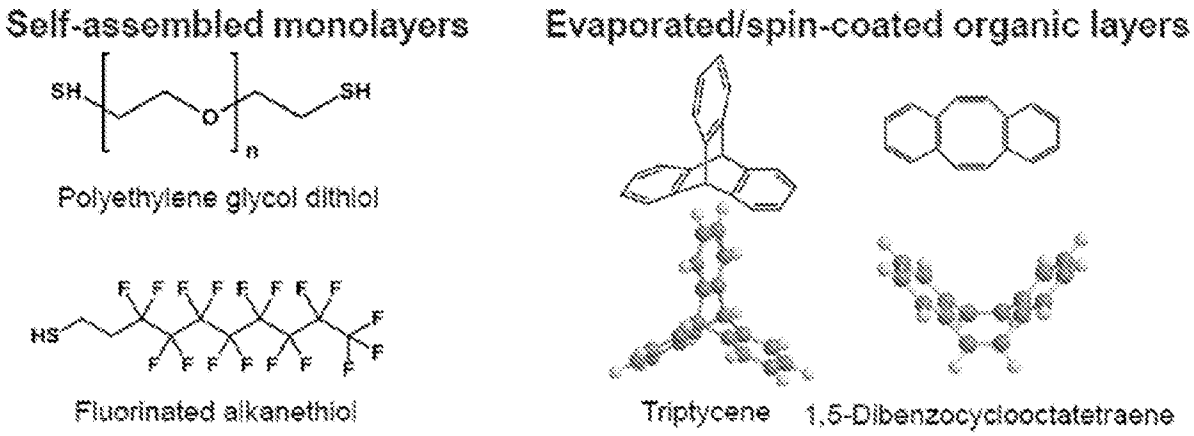

Self-assembled monolayers
Evaporated/spin-coated organic layers
SH
SH
O
n
Polyethylene glycol dithiol
HS
Fluorinated alkanethiol
Triptycene
1,5-Dibenzocyclooctatetraene

FIG. 4

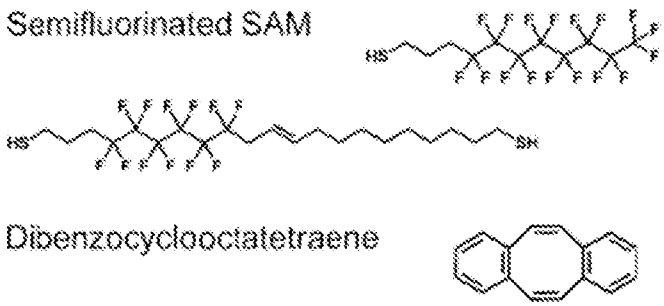
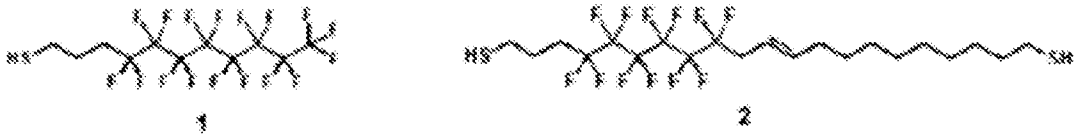

Semifluorinated SAM
HS
HS
SH
Dibenzocyclooctatetraene

FIG. 5



1 2

FIG. 6

FIG. 7

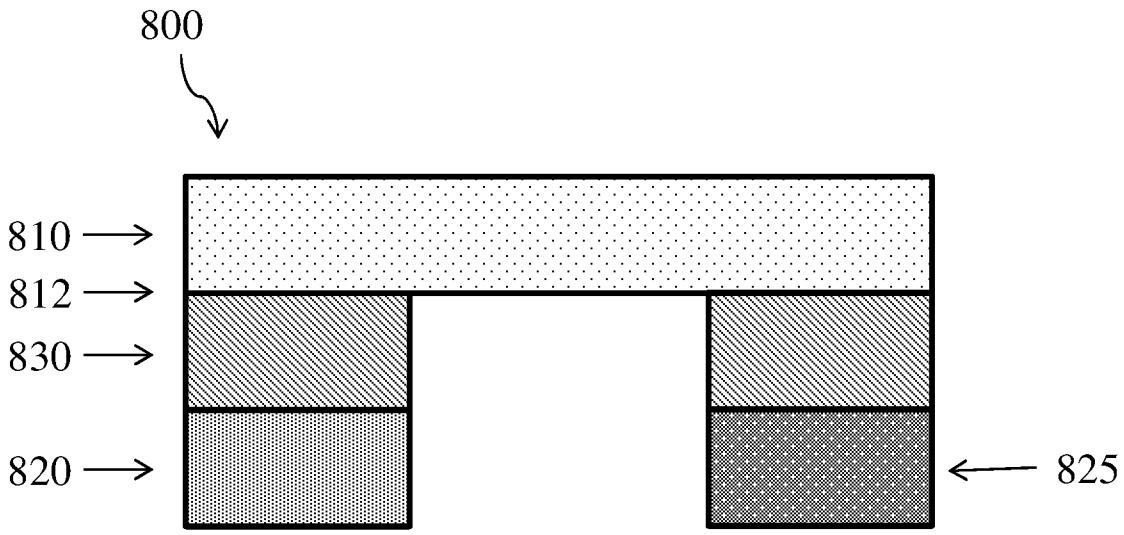


FIG. 8

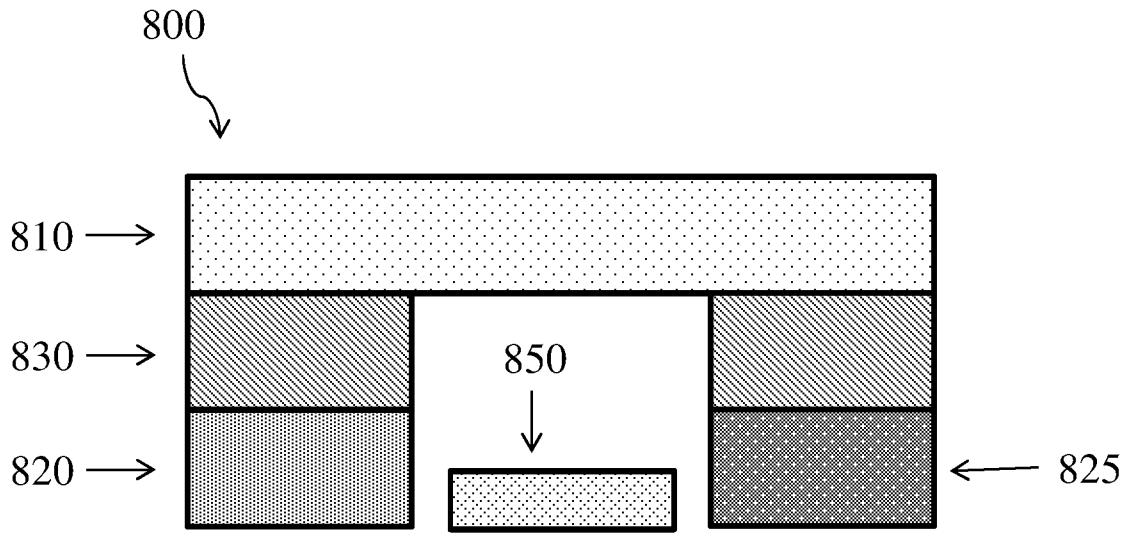


FIG. 9

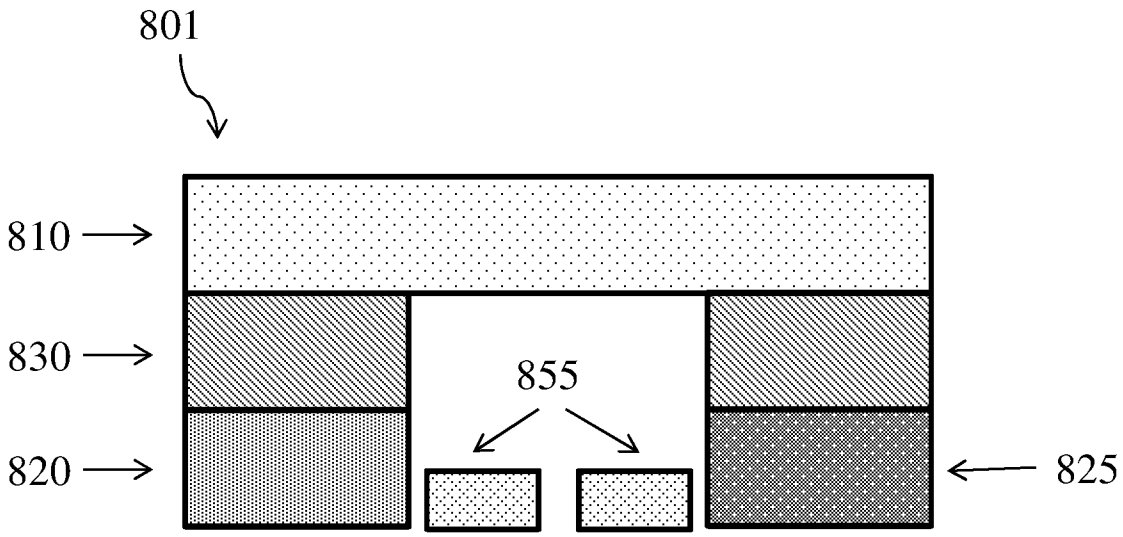


FIG. 10

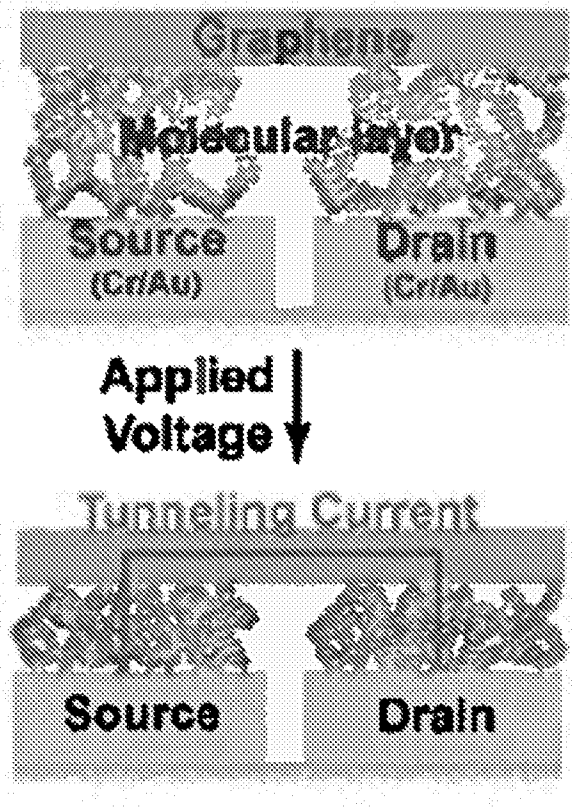

Graphene
Molecular layer
Source
(Cr/Au)
Drain
(Cr/Au)
Applied
Voltage
Tunneling Current
Source
Drain

FIG. 11

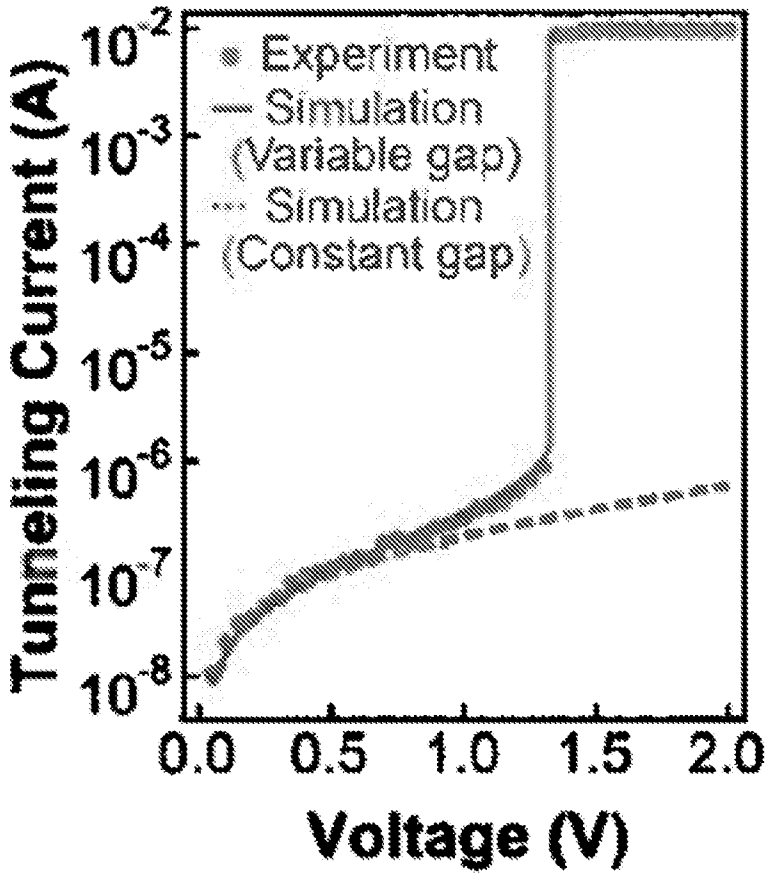

Tunneling Current (A)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Experiment
Simulation (Variable gap)
Simulation (Constant gap)
0.0
0.5
1.0
1.5
2.0
Voltage (V)

FIG. 12

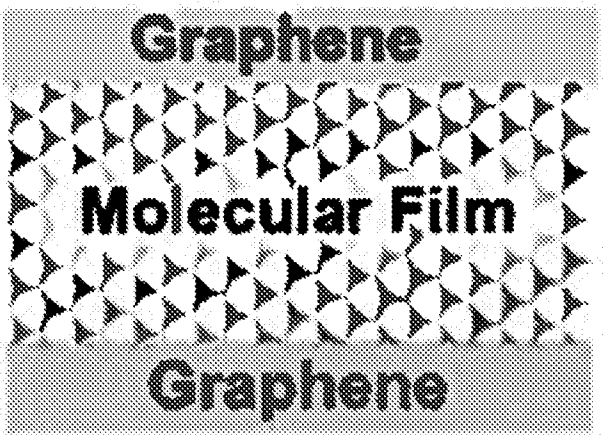


FIG. 13

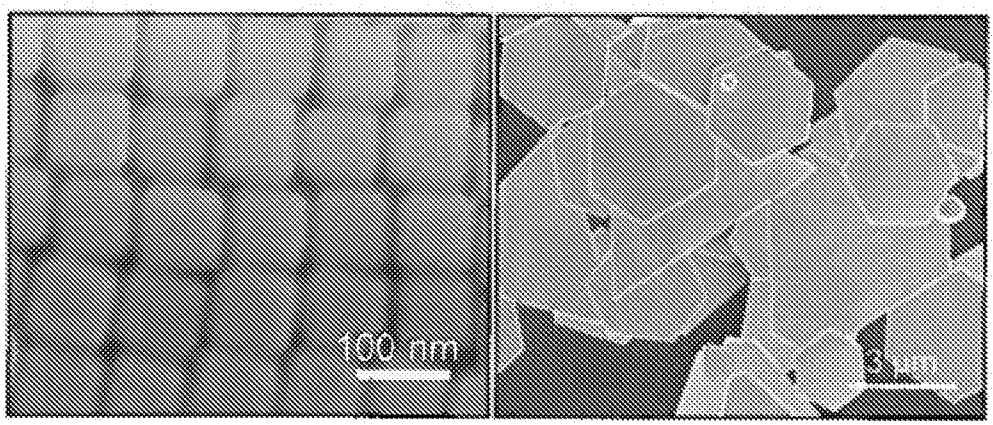


FIG. 14

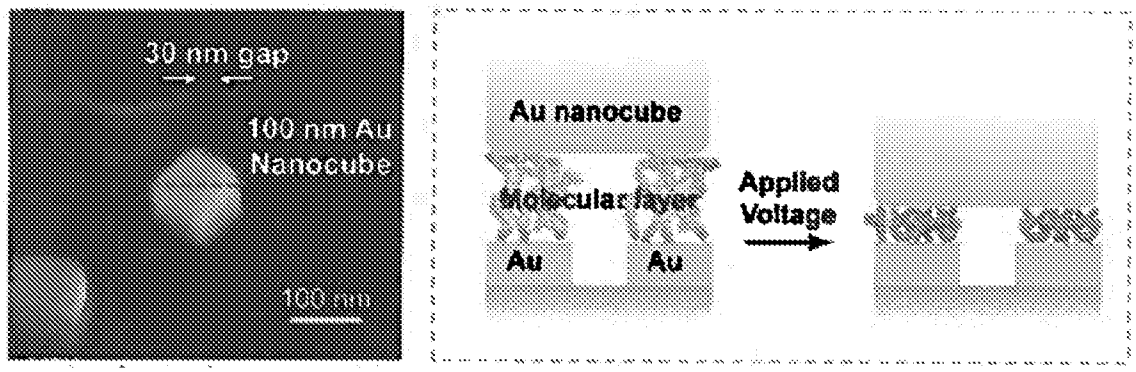

30 nm gap
100 nm Au
Nanocube
100 nm
Au nanocube
Molecular layer
Au
Au
Applied
Voltage

FIG. 15

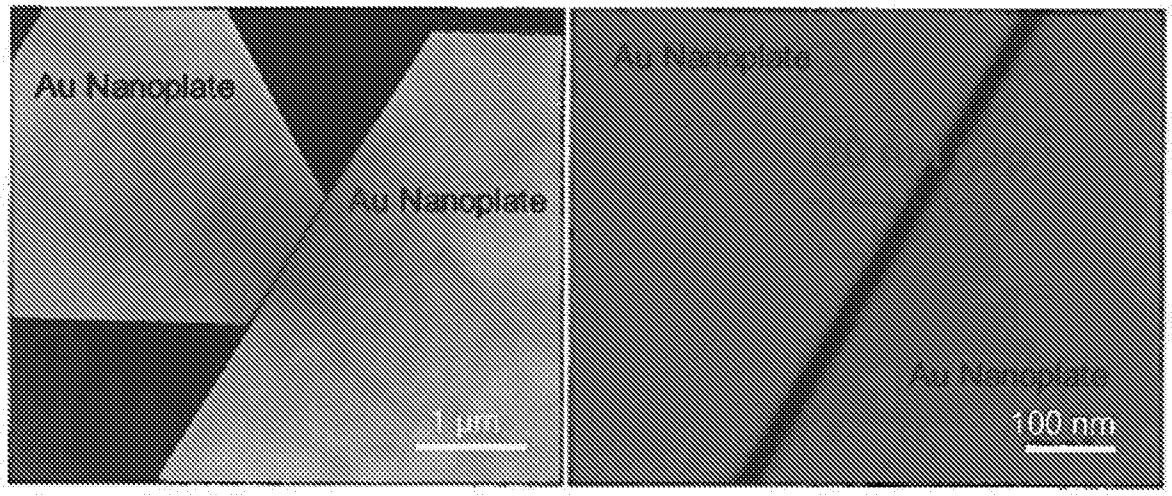

Au Nanoplate
Au Nanoplate
1 μm
100 nm

FIG. 16

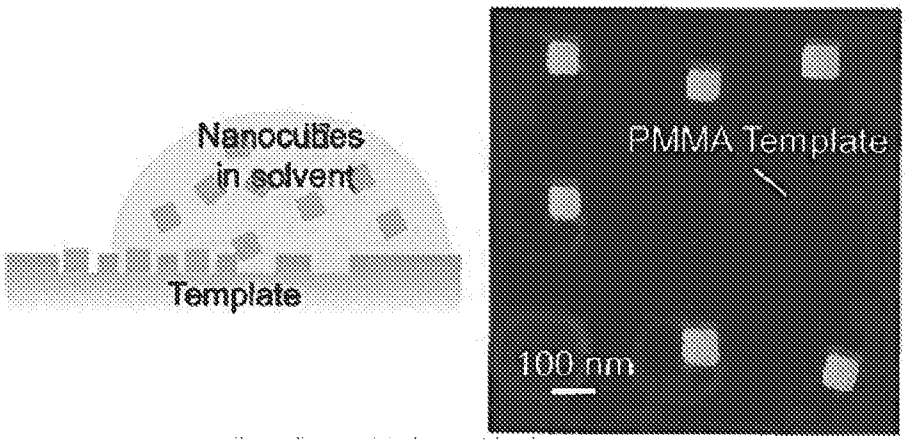

Nanocubes
in solvent
Template
PMMA Template
100 nm

FIG. 17

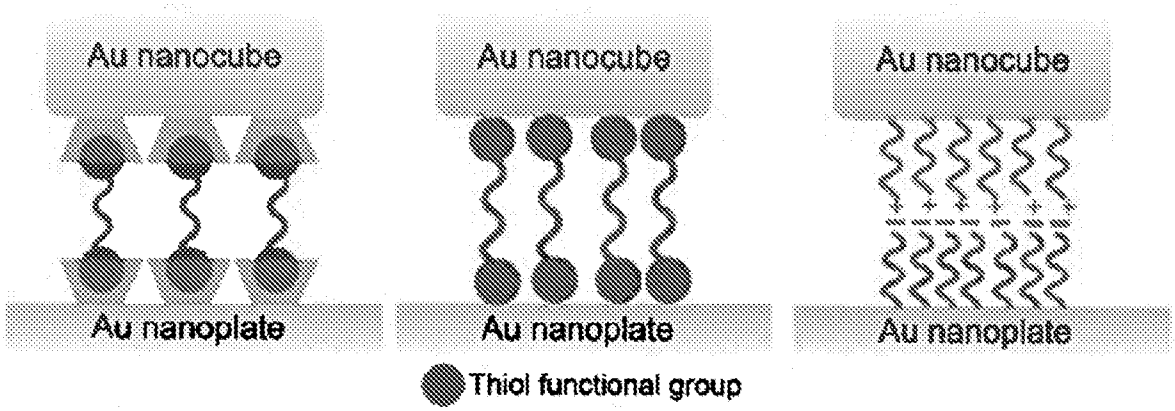

Au nanocube
Au nanoplate
Au nanocube
Au nanoplate
Au nanocube
Au nanoplate
Thiol functional group

FIG. 18

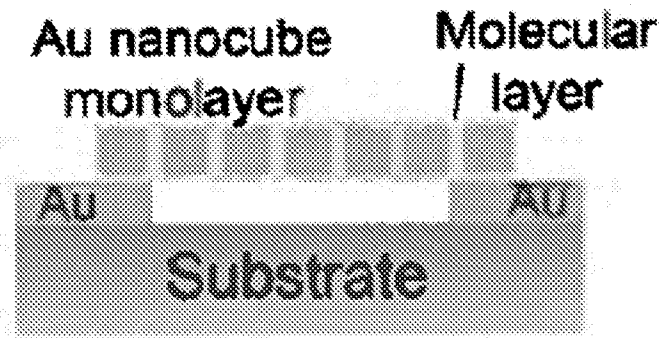

Au nanocube monolayer
Molecular layer
Au
Au
Substrate

FIG. 19

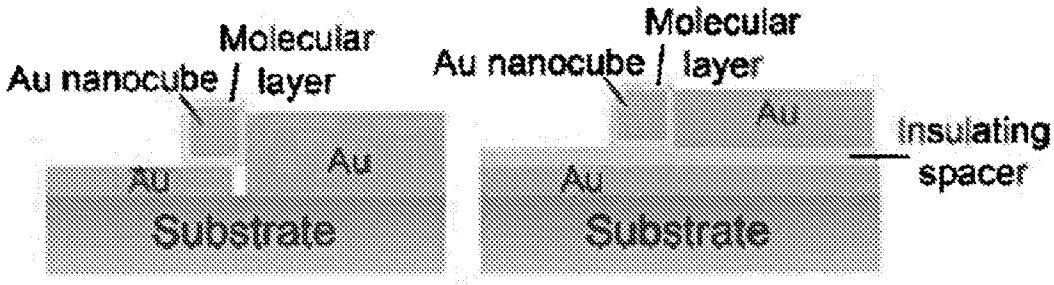

Molecular layer
Au nanocube
Au
Au
Substrate
Molecular layer
Au nanocube
Au
Insulating spacer
Au
Substrate

FIG. 20

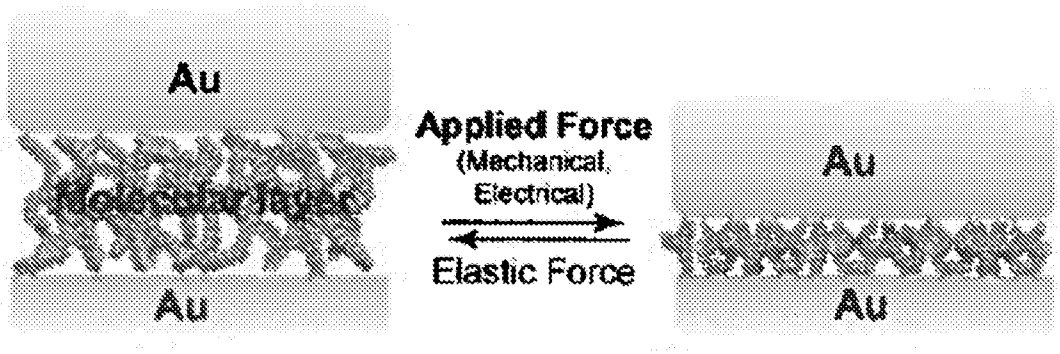

Au
Molecular layer
Au
Applied Force
(Mechanical,
Electrical)
Elastic Force
Au
Au

FIG. 21

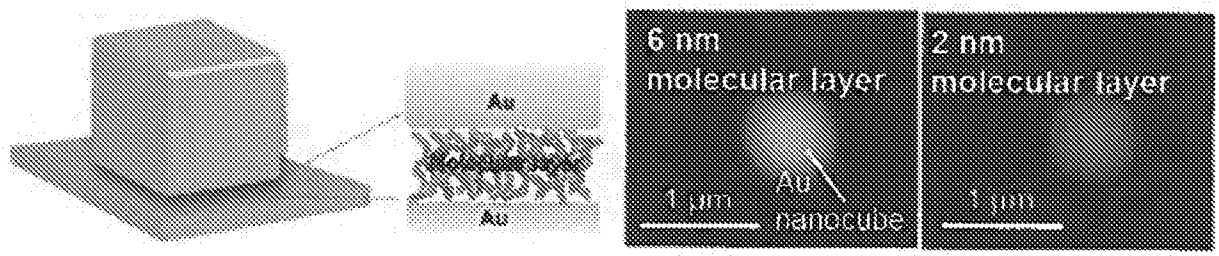

Au
Au
6 nm
molecular layer
1 μm
Au
nanocube
2 nm
molecular layer
1 μm

FIG. 22

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/061140

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 7-34
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

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International application No.
PCT/US2016/061140

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01H 13/12; G01L 1/24; H01H 11/04 (2016.01)
CPC - H01H 13/12; G01L 1/24; H01H 11/042; H01H 2003/007; H01H 2011/0075 (2016.11)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC - G01L 1/24; H01H 11/00; H01H 11/04; H01H 13/12
CPC - G01L 1/24; H01H 11/042; H01H 13/12; H01H 13/26; H01H 2003/007; H01H 2011/0075; H01L 29/84; H01L 29/86; H02M 7/32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 200/511; 307/119; 307/125; 335/48; 359/254; 359/291; 359/315; 359/320; 359/578 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google Scholar
Search terms used: deform, electrode, tunnel, float, surface roughness, floating, switch, plasmon, resonance, wavelength

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/0228805 A1 (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 13 August 2015 (13.08.2015) entire document	1, 5, 6
Y		2-4
Y	US 6,475,321 B1 (IKEDA et al) 05 November 2002 (05.11.2002) entire document	2
Y	US 2014/0211195 A1 (HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.) 31 July 2014 (31.07.2014) entire document	3, 4
A	US 2006/0119853 A1 (BAUMBERG et al) 08 June 2006 (08.06.2006) entire document	1-6
A	US 2012/0154793 A1 (PRYCE et al) 21 June 2012 (21.06.2012) entire document	1-6

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
29 December 2016

Date of mailing of the international search report
23 JAN 2017

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