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(54) **Title:** ELECTRICALLY TUNABLE METASURFACES INCORPORATING A PHASE CHANGE MATERIAL

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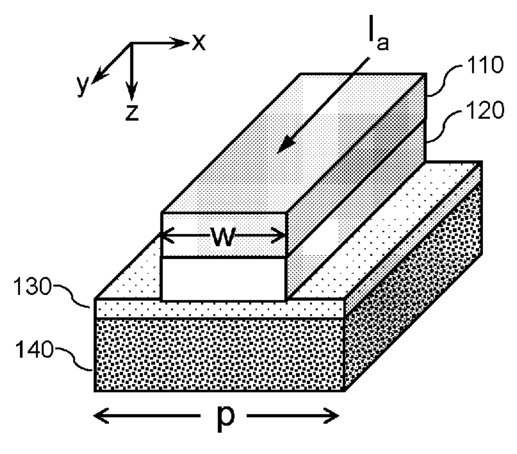

FIG. 1C

(57) **Abstract:** Electrically tunable metasurfaces including an array of subwavelength metasurface unit elements are presented. The unit elements include a stacked metal-insulator-metal structure within which an active phase change layer is included. A purely insulator, metal, or coexisting metal-insulator phase of the active layer can be electrically controlled to tune an amplitude and phase response of the metasurfaces. In combination with the subwavelengths dimensions of the unit elements, the phase and amplitude response can be controlled in a range from optical wavelengths to millimeter wavelength of incident light. Electrical control of the unit elements can be provided via resistive heating produced by flow of current though a top metal layer of the unit elements. Alternatively, electrical control of the unit elements can be provided via electrical field effect produced by applying a voltage differential between the top and bottom metal layers of the unit elements.

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ELECTRICALLY TUNABLE METASURFACES INCORPORATING A PHASE CHANGE MATERIAL

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to and the benefit of co-pending US provisional patent application Serial No. 62/792,010 entitled “Electrically Tunable Metasurfaces Incorporating a Phase Change Material”, filed on January 14, 2019, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT OF GOVERNMENT GRANT

[0002] The invention described herein was made in the performance of work under the Office of Science, U.S. Department of Energy (DOE) Office of Science Grant No. DE-FG02-07ER46405 (K.A.M. and H.A.A.).

TECHNICAL FIELD

[0003] The present disclosure relates to systems and methods for providing electrically tunable optical metasurfaces, including electrically tunable phase and amplitude, using a phase change material. Applications may include novel platforms capable of providing wavefront manipulation functionality for implementation of, for example, beam steering, focusing lens, polarization control, holographic imaging, absorbers, and color filtering in a dynamically reconfigurable manner.

BACKGROUND

[0004] Optical metasurfaces are judiciously designed arrays of subwavelength optical resonators, which interact with incident light and alter the properties of the scattered electromagnetic waves such as amplitude, phase, wavelength, and polarization (e.g., Refs. [1, 2]). Optical metasurfaces have drawn attention due to their promise in replacing conventional bulky optical components with low-profile nanophotonic analogs. Moreover, a single metasurface may realize an optical function, which otherwise can only be attained by combining multiple bulky optical components. While bulky optical components tailor the wavefront of the scattered light via phase accumulation, which occurs when electromagnetic waves propagate through the given medium, metasurfaces utilize subwavelength optical scatterers (e.g., metasurface unit cells, metasurface unit elements), which tailor the wavefront of the scattered light by introducing abrupt changes in the properties of the scattered light at subwavelength scale.

[0005] Metasurfaces have been designed to realize a number of optical components such as anomalous reflectors (e.g., per Refs. [4, 5], focusing lenses/mirrors (e.g., Refs. [6, 7]), polarization convertors (e.g., Refs. [3, 8, 9]) and holographic plates (e.g., Refs. [10−12]). However, these metasurfaces are passive, so their optical response cannot be dynamically changed after fabrication. The desire to dynamically control the key constitutive properties of light at subwavelength scale has given rise to a burgeoning field of active metasurfaces. While there are numerous reports of active amplitude control for scattered light, experimental demonstrations of dynamic phase control are rare.

[0006] Both phase and amplitude control are required to achieve many important applications for dynamically tunable metasurfaces such as, for example, chip-scale beam steering devices for light detection and ranging (LiDAR) systems, reconfigurable metalenses, and 3D holographic displays. The optical response of active metasurfaces can be dynamically changed upon application of external stimuli such as heat or electrical bias (voltage, current).

[0007] Previous research has created active metasurfaces by employing a number of physical phenomena such as thermo-optic effects in semiconductors (e.g., Refs. [13−15]); field effect in indium tin oxide (e.g., Refs. [16−20]), gallium arsenide (e.g., Ref. [21]), silicon (e.g., Ref. [22] and graphene (e.g., Refs. [23−28]); phase transitions in germanium antimony telluride (GST) (e.g., Refs. [29−34]) and vanadium dioxide (VO_2) (e.g., Refs. [35−44]); and reorientation of liquid crystal molecules (e.g., Refs. [45−48]), ionic transport (e.g., Ref. [49]), and mechanical deformations (e.g., Refs. [50−52]). A challenge for the field of active metasurfaces is the realization of comprehensive active control of both amplitude and phase of the scattered electromagnetic waves. However, most reports of active control have demonstrated amplitude modulation, whereas experimental demonstrations of dynamic control of the phase of scattered electromagnetic waves are much less common (e.g., Refs. [15, 18-20, 27, 29, 31-33, 39, 44, 47, 52]).

[0008] Continuous active control of phase variation of the scattered light throughout the spatial extent of a metasurface would enable complex wavefront engineering, enabling the manipulation of the properties of the scattered light. For example, prior research has reported a metasurface-based dynamic phase grating by temporally varying the spatial phase profile of the electromagnetic waves reflected from the metasurface (e.g., Ref. [19]). This enabled demonstration of electrical bias-actuated dynamic beam switching. Hence, from the point of view of future potential application, electrically tunable metasurfaces are especially interesting since they enable individual addressability to metasurface (unit) elements, holding promise to realize complex wavefront control.

[0009] Vanadium dioxide (VO2) is a well-known phase change material, which undergoes a reversible insulator-to-metal transition upon heating (e.g., Ref. [53]). The phase transition of VO_2 is accompanied by a large change in complex refractive index over a broad spectral range. The insulator-to-metal transition in VO_2 occurs at a temperature of Tc ~ 340 K (e.g., Ref. [54]) which is close to room temperature. This makes VO_2 a promising candidate for energy-efficient devices. While VO_2-based tunable metasurfaces (e.g., Refs. [35-44]) have been previously demonstrated, in the majority of these works, the insulator-to-metal transition in VO_2 was induced either by direct heating (e.g., Refs. [29-21, 35-39]) or optical pumping (e.g., Refs. [32, 33, 40]). A limited number of works have reported electrically tunable VO_2-based metasurfaces operating at near-infrared (e.g., Ref. [43], mid-infrared (e.g., Ref. [42]), or far-infrared (e.g., Ref. [41]) wavelengths. Although the electrical tuning mechanism is still induced by heating, the electrical controllability is essential to realize devices with complex functionalities such as, for example, phased array systems for beam steering applications, which require individual control of metasurface elements (e.g., Ref. [19]). These works, however, report only the intensity modulation/control of the scattered light and do not demonstrate phase modulation/control at optical frequencies (e.g., wavelength of 100 nm to 1 mm). While a prior work has shown an electrically tunable phase of electromagnetic waves transmitted through the VO_2-based metasurface, the operation wavelength is on the order of millimeters (e.g., Ref. [44]). The applications for the metasurface according to the present disclosure, such as LiDAR or holographic displays, require the metasurface operation wavelength to be in the near-infrared wavelength ranges (e.g., wavelength of 800 nm to 2000 nm). It is worth mentioning that besides VO_2, previous works have used amorphous-to-crystalline switching in GST to demonstrate active phase change metasurfaces (e.g., Refs. [29–34]). While a number of works on VO_2 (e.g., Refs. [39, 44]) or GST-based (e.g., Refs. [29, 31–33]) active metasurfaces have benefited from the phase difference of the scattered light, an actively controlled continuous phase shift of near-infrared electromagnetic waves scattered by VO_2 or GST-based active metasurfaces has not been demonstrated.

[0010] Teachings according to the present disclosure relate to electrically tunable metasurface unit elements that allow dynamic control of phase and amplitude of reflected light. Such unit elements may be arranged as part of dynamically tunable reflectarray metasurfaces (e.g., antenna with reflective metasurface unit elements) that can continuously modulate the phase and amplitude of the reflected light in a wavelength range that can include, for example, the near-infrared wavelength range (e.g., 800 nm to 2000 nm).

SUMMARY

[0011] A dynamically tunable (reflectarray) metasurface that continuously modulates the phase of reflected light, including in the near-infrared wavelength range (e.g., 800 nm to 2000 nm), under electrical control of an active layer comprising a phase transition material that transitions from a semiconducting state to a semimetallic state is presented.

[0012] According to an exemplary embodiment of the present disclosure, the active layer, which undergoes an insulator-to-metal transition upon resistive (i.e., Joule) heating, is arranged into a dielectric gap (between metal/conductive layers) of unit elements of the reflectarray metasurface.

[0013] According to an exemplary embodiment of the present disclosure, the active layer may be a layer of vanadium dioxide (VO_2) material. According to other exemplary embodiments, the active layer may be made of any of a number of chalcogenide compounds such as, for example, GeSbTes (e.g., a ternary compound of germanium, antimony, and tellurium).

[0014] The induced phase transition in the active layer of the metasurface according to the present disclosure perturbs a magnetic dipole resonance supported by the metasurface. By carefully controlling volume fractions of coexisting metallic and dielectric regions of the active layer, a continuous shift of a phase of the reflected light is provided, with a maximal achievable phase shift equal to, or larger than, 180 degrees and as high as 250 degrees for certain wavelengths of operation. Furthermore, reflectance modulation of 23.5% as well as a spectral shift of the resonance position by 175 nm can be observed. Accordingly, the metasurface phase modulation is fairly broadband, yielding in large phase shifts at multiple operation wavelengths, including in near-infrared wavelength ranges (e.g., 800 nm to 2000 nm).

[0015] According to one embodiment the present disclosure, an electrically tunable metasurface, is presented, the electrically tunable metasurface comprising: an array of subwavelength metasurface unit elements, each unit element comprising: a bottom conductive layer; an insulating layer overlying the bottom conductive layer; an active layer overlying the insulator layer; and a top conductive layer overlying the active layer, wherein the active layer comprises a phase change material having a phase controllable via resistive heating produced by a flow of a control current through the top conductive layer of the unit elements.

[0016] According to a second embodiment of the present disclosure, an electrically tunable metasurface is presented, the electrically tunable metasurface comprising: an array of subwavelength metasurface unit elements, each unit element comprising: a bottom conductive layer; an insulating layer overlying the bottom conductive layer; an active layer overlying the insulator layer; and a top conductive layer overlying the active layer, wherein the active layer comprises a phase change material having a phase controllable via an electric field produced by a voltage differential between the top conductive layer and the bottom conductive layer of the unit elements.

[0017] Further aspects of the disclosure are shown in the specification, drawings and claims of the present application.

BRIEF DESCRIPTION OF DRAWINGS

[0018] The accompanying drawings, which are incorporated into and constitute a part of this specification, illustrate one or more embodiments of the present disclosure and, together with the description of example embodiments, serve to explain the principles and implementations of the disclosure. Same reference designators refer to same features.

[0019] FIG. 1A shows a cross sectional view of an electrically tunable metasurface unit element incorporating a phase change material according to an embodiment of the present disclosure.

[0020] FIG. 1B shows a cross sectional view of two adjacent electrically tunable metasurface unit elements of FIG. 1A fabricated on a substrate.

[0021] FIG. 1C shows a perspective view of the electrically tunable metasurface unit element of FIG. 1A, including a control current flowing through a top metal layer of the unit element.

[0022] FIG. 1D shows spatial concentration of the magnetic field in the electrically tunable metasurface unit element of FIG. 1A when the phase change material is in insulating phase.

[0023] FIG. 1E shows spatial concentration of the magnetic field in the electrically tunable metasurface unit element of FIG. 1A when the phase change material is in metallic phase.

[0024] FIG. 2 shows a plan view of an electrically tunable metasurface according to an embodiment of the present disclosure comprising an array of a plurality of electrically tunable metasurface unit elements according to FIG. 1A coupled to a pair of contact pads for a same electrical control of the metasurface unit elements.

[0025] FIG. 3A shows a graph representing measured reflectance spectra for different applied control voltages of the electrically tunable metasurface shown in FIG. 2.

[0026] FIG. 3B shows a graph representing measured phase shift for different applied control voltages of the electrically tunable metasurface shown in FIG. 2.

[0027] FIG. 4 shows a plan view of an electrically tunable metasurface according to another embodiment of the present disclosure comprising an array of a plurality of electrically tunable metasurface unit elements according to FIG. 1A coupled to a plurality of (e.g., two) contact pads for different electrical controls of different groups of the metasurface unit elements.

[0028] FIG. 5 shows an electrically tunable metasurface according to another embodiment of the present disclosure comprising an array of a plurality of electrically tunable metasurface unit elements according to FIG. 1A that are controlled via an electric field.

DETAILED DESCRIPTION

[0029] FIG. 1A shows a cross sectional view (e.g., in (x, z) plan) of an electrically tunable metasurface unit element (100) incorporating a phase change material (e.g., part of layer 120) according to an embodiment of the present disclosure. As can be seen in FIG. 1A, such unit element (100) includes a stacked layer configuration according to a metal-insulator-metal (MIM) structure, including a top metal layer (110), a bottom metal layer (140) and a middle insulating layer (130). Furthermore, an active phase change layer (120) made of a phase change material whose optical properties can be changed upon application of an external stimulus, is provided between the top metal layer (110) and the middle insulating layer (130). In particular, the external stimulus may control volume fractions of coexisting metallic (conductor) and dielectric (insulator) regions of the active phase change layer (120), thereby control an effective insulator thickness of the MIM structure provided by the unit element (100).

[0030] With further reference to FIG. 1A, the MIM structure of the unit element (100) can support a magnetic dipole resonance under transverse magnetic (TM) excitation. It should be noted that other embodiments may be envisioned wherein the supported resonance is an electric dipole resonance or a higher order resonant mode instead of the magnetic dipole resonance.

[0031] According to an embodiment of the present disclosure, each of the (conductive) top metal layer (110) and the (conductive) bottom metal layer (140) of the unit element (100) shown in FIG. 1A is selected to support plasmon resonance. Accordingly, each of the layers (110) and (140) can be made of, or include, any one or a combination of: i) a metal, such as silver, copper, aluminum, gold; ii) or a semiconductor, such as gallium arsenide (GaAs), silicon (Si); iii) or a transparent conducting oxide (e.g., indium tin oxide (ITO), aluminum-doped zinc oxide (AZO), aluminum-doped zinc oxide (GZO), etc.); iv) or a transition metal nitride (e.g., titanium nitride (TiN), zirconium nitride (ZrN), etc.).

[0032] According to an embodiment of the present disclosure, the (non-conductive) insulating layer (130) of the unit element (100) shown in FIG. 1A can comprise one of, or a combination of, aluminum oxide, silicon oxide, titanium dioxide and silicon nitride. According to an embodiment of the present disclosure, material of the insulating layer (130) may support growth of the phase change material used in the active phase change layer (120) via deposition processes known to a person skilled in the art, such as, for example, an evaporative deposition (e-beam or thermal) process, sputtering or any suitable chemical vapor deposition (CVD) techniques. Accordingly, when the active phase change layer (120) is made of, for example, VO_2, such layer VO_2 may be grown onto the insulating layer (130).

[0033] According to an exemplary embodiment of the present disclosure, the layers (110), (120), (130) and (140) of the unit element (100) shown in FIG. 1A are respectively made of gold (Au), vanadium dioxide (VO_2), aluminum oxide (Al_2O_3), and gold (Au).

[0034] According to another exemplary embodiment of the present disclosure, the layers (110), (120), (130) and (140) of the unit element (100) shown in FIG. 1A are respectively made of gold (Au), vanadium dioxide (VO_2), silicon dioxide (SiO_2), and gold (Au). In such configuration, the insulating layer (130) can be made of a material (i.e., SiO_2) with low thermal conductivity to mitigate thermal crosstalk between adjacent unit elements (e.g., per FIG. 1B, FIG. 2 and FIG. 4). This allows individual/distinct control of the adjacent unit elements with reduced thermal crosstalk, wherein heat dissipation for the adjacent unit elements can be provided through a conductive base substrate (e.g., 150 of FIG. 1B) upon which the adjacent unit cells are fabricated.

[0035] FIG. 1B shows a cross sectional view of two of the electrically tunable metasurface unit elements (100) of FIG. 1A fabricated on a substrate (150). According to an embodiment of the present disclosure, the substrate (150) may be fabricated of, or include a, conductive material. As can be seen in FIG. 1B, the unit elements (100) may share a common bottom metal layer (140) and a common insulating layer (130) that are sequentially formed/staked on top of the substrate (150). In other words, the bottom metal (conductive) layer (140) and the insulating layer (130) of the unit elements (100) are part (or form) respective contiguous layers (140, 130 shown in FIG. 1B) that are common to the unit elements (100). In turn, layers (120) and (110) of each of the two unit elements (100) may be formed atop the common insulating layer (130). It should be noted that any known in the art suitable fabrication method can be employed to produce the subwavelength features of the unit elements (100), combined as necessary with known in the art film deposition and etching techniques, including, for example, Electron beam lithography; optical lithography such as, for example, ultraviolet (UV), deep ultraviolet (DUV), extreme ultraviolet (EUV); Ion beam lithography; and Soft lithography. It should also be noted that such fabrication method can be used to form a plurality of unit elements (100) to form a reflectarray metasurface with tunable control of phase and amplitude response as shown, for example, in FIG. 2 and FIG. 4 later described.

[0036] According to an exemplary embodiment of the present disclosure, a fabrication process of the unit elements (100) shown in FIG. 1B (and FIG. 2, FIG. 4) may include the following known in the art steps: i) depositing the bottom metal layer (140) on a substrate (150) having an adhesion layer (e.g. Ti or Cr). The bottom metal layer (140) can be grown by an appropriate deposition process, such as an evaporative deposition (e-beam or thermal) process or sputtering; ii) forming the insulating layer (130) on top of the bottom metal layer by any suitable techniques such as sputtering, evaporation, low pressure chemical vapor deposition (LPCVD), plasma enhanced chemical vapor deposition (PECVD) or atomic layer deposition (ALD); iii) growing the active layer (e.g., VO_2) (120) on the insulating layer (130) using any suitable technique, such as LPCVD, PECVD, atomic layer deposition (ALD), sputtering a sol-gel process or PLD. A corresponding pattern may be written on a positive electron beam resist using electron-beam lithography, and the pattern may be developed in a resist developer; iv) depositing the top metal layer (110) followed by a hard mask layer on the developed resist using electron beam deposition; v) forming the designed patterns via a lift-off process; vi) using the patterned top layer as a hard mask for dry etching of the active layer (120) and yielding self-aligned MIM metasurface elements of an antenna array (e.g., reflectarray); and vii) selectively removing the hard mask by a brief dry etching process that employs etchants which selectively etch the material of the active layer (120) (e.g., VO_2) and the hard mask respectively.

[0037] FIG. 1C shows a perspective view of the electrically tunable metasurface unit element (100) of FIG. 1A, including an externally provided control current (Ia) flowing through the strip shaped top metal layer (110) of the unit element (100). The phase transition material (e.g., VO_2) in the active layer (120) may be thermally induced via resistive (Joule) heating of the top metal layer (110) using the control current (Ia). This can allow precise control of the temperature of the phase transition material of the active layer (120). Because the phase transition material is incorporated directly into the MIM structure of the unit element (100), enhanced interaction between such active material and a strongly confined (magnetic) field within the structure can be obtained. When used as metasurface elements of an antenna array (e.g., per FIG. 2 and FIG. 4), strong light-matter interaction in the resonance cavity of the metasurface unit elements (100) may result in large phase shifts of reflected light induced by the significant change in the resonance of the unit elements (100). Furthermore, continuous phase shifts (e.g., 0 to 250 degrees) can be obtained by utilizing phase coexistence (i.e., insulator and metal) of the phase change material (e.g., VO_2) of the active layer (120) via gradual resistive (Joule) heating, which provides intermediate optical properties near the insulator-to-metal transition.

[0038] FIG. 1D shows spatial concentration of the magnetic field, Hy, in the electrically tunable metasurface unit element (100) of FIG. 1A when the phase change material (e.g., VO_2) of the active layer (120) is in insulating phase. When the phase change material is in the insulating phase, the incident plane wave excites a magnetic dipole resonance of the unit element (100) in the near-infrared, such as for example at a wavelength $\lambda = 1520$ nm. As seen in FIG. 1D, the magnetic field, Hy, is concentrated between the bottom metal layer (140) and the top metal layer (110) in a region formed by insulating material (or material phase) of the layers (120) and (130) and away from conductive regions formed by the metal layers (110, 140). Alternately, as shown in FIG. 1E, when the phase change material (e.g., VO_2) of the active layer (120) is in the metallic phase, the magnetic field, Hy, is mainly confined in the insulating layer (130) as the effective thickness of dielectric (insulator) provided by the layers (120, 130) decreases. The change in the near-field characteristics of the supported resonance mode in each of the two figures is accompanied by large changes in the amplitude and the phase of the reflected light as shown, for example, in FIG. 3A and FIG. 3B later described.

[0039] FIG. 2 shows a plan view (e.g., (x, y) plan) of an electrically tunable metasurface (200) according to an embodiment of the present disclosure comprising an array (210) of a plurality of electrically tunable metasurface unit elements (100) according to FIG. 1A coupled to a pair of contact pads (250, 255) for a same/uniform electrical control of the metasurface unit elements (100). By connecting an electrical bias supply (260), such as for example a variable voltage source or a variable current source, across the two contact pads (250, 255) as shown in FIG. 2, a control current Ia that flows through the top metal layer (110) of each of the unit elements (100) can be produced. Accordingly, local heat can be produced into the active layers (120) of each of the unit elements (100). Furthermore, by varying an output (voltage or current) of the electrical bias supply (260), controlled gradual heating of the active layers (120) can be provided, which in turn can dynamically control phase and amplitude response of the electrically tunable metasurface (200). It should be noted that being a plan view, FIG. 2 does not show the active layers (120) which can be seen, for example, in FIG. 1B, for a case of two adjacent unit elements (100) of the electrically tunable metasurface (200).

[0040] With continued reference to FIG. 2, the two contact pads (250) and (255) may be respectively coupled to two ends of each of the top metal layers (110) of the unit elements (100) via respective contact pad extensions (250a) and (255a). In other words, the contact pad extension (250a) provides connection between the contact pad (250) and one end of the strip shaped top metal layers (110), and the contact pad extension (255a) provides connection between the contact pad (255) and the other end of the strip shaped top metal layers (110). It should be noted that presence of the contact pad extensions (255a, 255a) may be optional as the contact pads (250, 255) may be designed for direct connection to the top metal layers. It should also be noted that shapes of the contact pads (250, 255) and the contact pad extensions (250a, 255a) may be any suitable shape for providing flow of the current Ia from the electrical bias supply (260) through the top metal layers (110).

[0041] With continued reference to FIG. 2, a person skilled in the art would realize that optical response of the electrically tunable metasurface (200) may be a function of a width *w*, period *p*, and thickness of the layers (110, 120, 130, 140) of the unit element (100) shown in FIG. 1A which are typically smaller (e.g., subwavelength) than an operating wavelength of the metasurface (200). In particular, the electrically tunable metasurface (200) can be made to operate at wavelengths ranging from optical wavelengths (e.g., wavelength of 100 nm to 1 mm) to millimeter wavelengths (e.g., wavelength of 1 mm to 10 mm) by designing the dimension of the unit element (100) according to methods/equations known in the art.

[0042] With further reference to FIG. 2, according to an exemplary embodiment of the present disclosure, for operation at a wavelength in a range of 1200 nm to 2000 nm, for each of the constituent unit elements (100), the width *w* may be equal to 210 nm, the period *p* may be equal to 400 nm, the thickness of the top metal layer (110) may be 40 nm, the thickness of the active layer (120) may be 40 nm, thickness of the insulating layer (130) may be 50 nm, and thickness of the bottom metal layer (140) may be 150 nm. According to an exemplary embodiment of the present disclosure, the total area of the array (210) may be about 100 μm x 100 μm which larger than a spot size of an incident beam of light during operation. For such configuration, a continuous phase shift of the reflected light ranging from 0 degrees to 180 degrees can be provided by the electrically tunable metasurface (200). In particular, a maximal phase shift of 250 degrees can be provided in a wavelength of operation that spans from 1515 nm to 1575 nm. A person skilled in the art would clearly understand that the exemplary dimensions/sizes provided herewith for operation in the wavelength range of 1200 nm to 2000 nm may be scaled up/down for operation at different wavelengths.

[0043] FIG. 3A shows a graph representing measured reflectance spectra at different operating wavelengths (e.g., 1250 nm to 1950 nm) for different applied control voltages (e.g., 0 V to 14 V) of the electrically tunable metasurface (200) shown in FIG. 2. In particular, as can be seen in FIG. 3A (indicated by arrow from 0 volts curve to 9 volts curve), for a wavelength of the incident light of about 1510 nm, the reflectance can change (be modulated) by about 20% when the applied control voltage changes from 0 volts, which corresponds to a purely insulating phase of the active layer (120), to 9 volts, which corresponds to a coexisting metal and insulator phase of the active layer (120).

[0044] FIG. 3B shows a graph representing measured phase shift for different applied control voltages (e.g., 0 V to 13 V) of the electrically tunable metasurface (200) shown in FIG. 2, based on an incident light with a wavelength of 1550 nm. A person skilled in the art would appreciate the continuously tunable phase shift provided by the electrically tunable metasurface (200) as a function of applied voltage via the electrical bias supply (260) shown in FIG. 2. As can be seen in the graph of FIG. 3B, there is a reversible voltage-dependent hysteresis loop in the phase shift response. As can be seen in FIG. 3B, by increasing the control voltage from 0 volts, corresponding to a purely insulating phase of the active layer (120), phase shift remains flat up to a control voltage of approximately 9 volts which corresponds to a threshold voltage for transition from the purely insulating phase of the active layer (120) to a coexisting metal and insulator phase of the active layer (120). Further increase of the control voltage produces pronounced variation of the phase shift according to a relatively steep slope up to a control voltage of about 11 volts which corresponds to a threshold voltage for transition to a purely metallic phase of the active layer (120), after which no further variation of the phase shift is observed. On the other hand, as can be seen in FIG. 3B, by decreasing the control voltage from 13 volts to 0 volts, a reverse sequence of transitions of the phases of the active layer (120) is observed at control voltages of about 9 volts and 8 volts, thereby producing the voltage-dependent hysteresis loop shown in the figure.

[0045] FIG. 4 shows a plan view (e.g., (x, y) plan) of an electrically tunable metasurface (400) according to an embodiment of the present disclosure comprising an array (210) of a plurality of electrically tunable metasurface unit elements (100) according to FIG. 1A coupled to different pairs of contact pads (250, 255) and (250’, 255’) for provision of different/non-uniform electrical control of the metasurface unit elements (100). In particular, as can be seen in FIG. 4, each of the two pairs of contact pads (250, 255) and (250’, 255’) provides electrical control to two different (non-overlapping) groups of the metasurface unit elements (100). Accordingly, an optical response of a first group of the metasurface unit elements (100) whose top metal layers (110) are electrically coupled to a first electrical bias supply (260) can be controlled independently from an optical response of a second group of the metasurface unit elements (100) whose top metal layers (110) are electrically coupled to a second electrical bias supply (260'). Accordingly, the first and the second electrical bias supply (260) and (260') can provide flow of a respective control current Ia and I'a through the top metal layers (110) of the first and second groups of metasurface unit elements (100).

[0046] A person skilled in the art would clearly understand that the configuration shown in FIG. 4 can be expanded to any number of distinct/separate/non-overlapping groups of metasurface unit elements (100), each such group comprising one or more such unit elements (100) arranged in a sequence (e.g., adjacent to one another) or interspersed (e.g., non-adjacent) within the array (210). It should also be noted that a person skilled in the art would clearly understand that other aspects related to principle of operation of the electrically tunable metasurface (400) can be taken from the description above with reference to, for example, FIG. 1B and FIG. 2. Furthermore, although separate electrical bias supplies (e.g., 260, 260') coupled to different groups of unit elements (100) are shown in FIG. 4, a person skilled in the art would know of many alternative design implementations for providing different control currents (e.g., Ia, I'a) to the different groups of unit elements (100) which do not necessarily require different electrical bias supply units. Some such alternative designs may include a single electrical supply unit for provision of a reference voltage/current to an electrical circuit which may generate therefrom the different control currents.

[0047] It should be noted that according to an embodiment of the present disclosure, the resistive (Joule) heating of the metasurface unit elements (100) via electrical current conductance through the top metal layers (110) as described above may be substituted, as shown in FIG. 5, with electrical field effect by applying an electric field (e.g., shown as arrows in FIG. 5, controlled by a voltage source 560) between the top metal layer (110) and the bottom metal layer (140). In such configuration, the stacked metal-insulator-metal structure of the metasurface unit elements (100) operate as a capacitor with an electrical field generated between the two metal plates (top and bottom metal layers 110, 140) that is proportional to the voltage differential applied, via the (variable) voltage source (560) between the two plates.

[0048] With continued reference to FIG. 5, by increasing/decreasing the voltage differential, the electric field can be controlled, which in turn controls a phase of the active layer (120) to purely insulating, purely metal or coexisting metal and insulator, thereby controlling the optical response (e.g., amplitude/reflectance and phase shift) of the metasurface unit elements (100) as described above with reference to FIGs 3A and 3B. A practical implementation of such configuration may be derived from FIG. 2 by coupling the contact pad (250) and corresponding optional contact pad extension (250a) to any of the two sides/ends of the top metal layers (110), and coupling the contact pad (255) and corresponding optional contact pad extension (255a) to any region of the bottom metal layer (not necessarily end regions as shown in FIG. 2). Another practical implementation of such configuration may be derived from FIG. 4 by coupling the contact pads (250, 250') and corresponding optional contact pad extension (250a, 250'a) to any of the two sides/ends of the two (or more) different groups of top metal layers (110), and coupling the contact pads (255, 255') and corresponding optional contact pad extension (255a, 255'a) to any region of the bottom metal layer (not necessarily end regions as shown in FIG. 4).

[0049] A number of embodiments of the disclosure have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the present disclosure. Accordingly, other embodiments are within the scope of the following claims.

[0050] The examples set forth above are provided to those of ordinary skill in the art as a complete disclosure and description of how to make and use the embodiments of the disclosure and are not intended to limit the scope of what the inventor/inventors regard as their disclosure.

[0051] Modifications of the above-described modes for carrying out the methods and systems herein disclosed that are obvious to persons of skill in the art are intended to be within the scope of the following claims. All patents and publications mentioned in the specification are indicative of the levels of skill of those skilled in the art to which the disclosure pertains. All references cited in this disclosure are incorporated by reference to the same extent as if each reference had been incorporated by reference in its entirety individually.

[0052] It is to be understood that the disclosure is not limited to particular methods or systems, which can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise. The term "plurality" includes two or more referents unless the content clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the disclosure pertains.

[0053] The references in the present application, shown in the reference list below, are incorporated herein by reference in their entirety.

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CLAIMS

1. An electrically tunable metasurface, comprising:

an array of subwavelength metasurface unit elements, each unit element comprising:

a bottom conductive layer;

an insulating layer overlying the bottom conductive layer;

an active layer overlying the insulator layer; and

a top conductive layer overlying the active layer,

wherein

the active layer comprises a phase change material having a phase controllable via resistive heating produced by a flow of a control current through the top conductive layer of the unit elements.

2. The electrically tunable metasurface of claim 1, wherein the phase change material is vanadium dioxide (VO_2).

3. The electrically tunable metasurface of claim 1, wherein the phase change material is germanium antimony telluride (GST).

4. The electrically tunable metasurface of claim 2 or claim 3, wherein:

each of the bottom conductive layer and the top conductive layer comprises at least one of: a) a metal; b) a semiconductor; c) a transparent conducting oxide; and d) a transition metal nitride.

5. The electrically tunable metasurface of claim 4, wherein:

the metal comprises one or a combination of: a1) silver, a2) copper, a3) aluminum, and a4) gold.

6. The electrically tunable metasurface of claim 4, wherein:

the semiconductor comprises one or a combination of: b1) gallium arsenide (GaAs), and b2) silicon.

7. The electrically tunable metasurface of claim 4, wherein:

the transparent conducting oxide comprises one or a combination of: c1) indium tin oxide (ITO), c2) aluminum-doped zinc oxide (AZO), and c3) aluminum-doped zinc oxide (GZO).

8. The electrically tunable metasurface of claim 4, wherein:

the transition metal oxide comprises one or a combination of: d1) titanium nitride (TiN), and d2) zirconium nitride (ZrN).

9. The electrically tunable metasurface of claim 2 or claim 3, wherein:

the active layer is grown onto the insulating layer via a deposition process.

10. The electrically tunable metasurface of claim 9, wherein:

the bottom conductive layer is gold (Au), the insulating layer is aluminum oxide (Al_2O_3), and the top conductive layer is gold (Au).

11. The electrically tunable metasurface of claim 9, wherein:

the bottom conductive layer is gold (Au), the insulating layer is silicon dioxide (SiO_2), and the top conductive layer is gold (Au).

12. The electrically tunable metasurface of any one of claims 1-12, wherein:

the bottom conductive layer and the insulating layer are part of respective contiguous layers that are common to the unit elements, and

the active layer and the top conductive layer of the unit elements are formed according to a periodic pattern of the array.

13. The electrically tunable metasurface of claim 12, wherein:

the periodic pattern comprises a shape of a strip with i) a length that extends over an entire length of the array, and ii) a width that is provided by a same width of the active layer and the top conductive layer.

14. The electrically tunable metasurface of claim 13, wherein:
a period of the periodic pattern is 400 nm,
the same width of the active layer and the top conductive layer is 210 nm,
a thickness of the bottom conductive layer is 150 nm,
a thickness of the insulating layer is 50 nm,
a thickness of the active layer is 40 nm, and
a thickness of the top conductive layer is 40 nm.

15. The electrically tunable metasurface of claim 14, wherein:
the array has a substantially square shape with a total area of about 100 μm x 100 μm.

16. The electrically tunable metasurface of any one of claims 1 or 13-15, wherein for an incident light having a wavelength in a range of 1200 nm to 2000 nm, the electrically tunable metasurface is configured to provide a continuous phase shift in a range of 0 degrees to 180 degrees responsive to a variation of the control current.

17. The electrically tunable metasurface of claim 16, further comprising an electrical bias supply that is electrically coupled to the top conductive layer and is configured to generate the flow of the control current.

18. A wavefront manipulation system, comprising:
the electrically tunable metasurface of any one of claims 1-17,
wherein the wavefront manipulation system is configured to implement functionality of one of: a) beam steering, b) focusing lens, c) polarization control, d) holographic imaging, e) absorber, and f) color filtering.

19. An electrically tunable metasurface, comprising:

an array of subwavelength metasurface unit elements, each unit element comprising:

a bottom conductive layer;

an insulating layer overlying the bottom conductive layer;

an active layer overlying the insulator layer; and

a top conductive layer overlying the active layer,

wherein

the active layer comprises a phase change material having a phase controllable via an electric field produced by a voltage differential between the top conductive layer and the bottom conductive layer of the unit elements.

20. The electrically tunable metasurface of claim 19, wherein the phase change material is vanadium dioxide (VO_2).

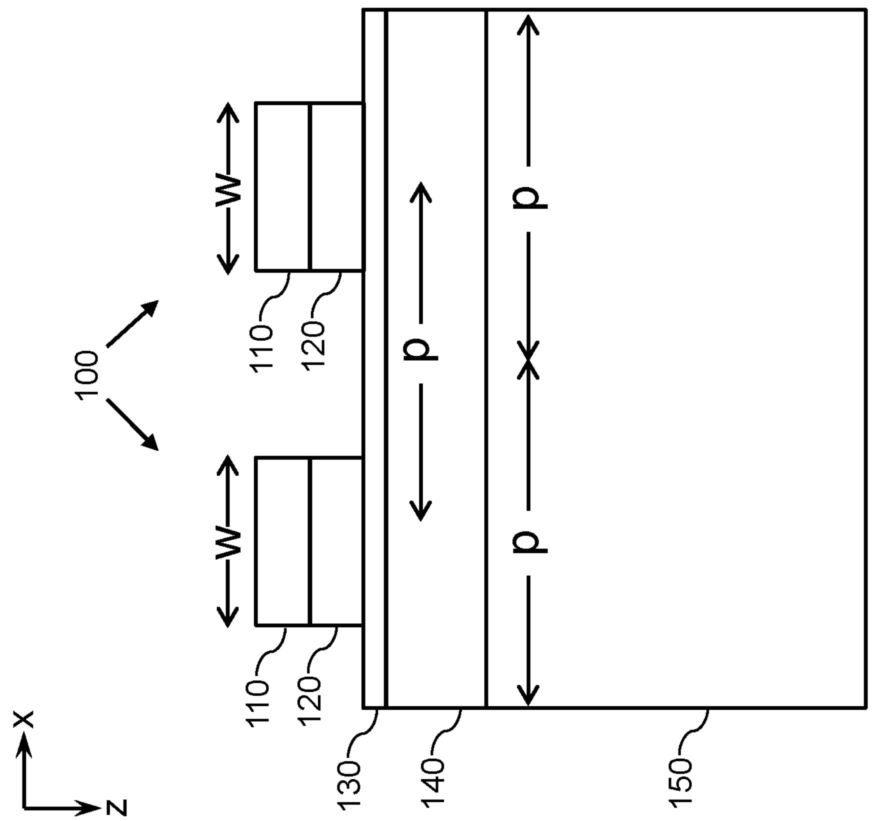

FIG. 1B

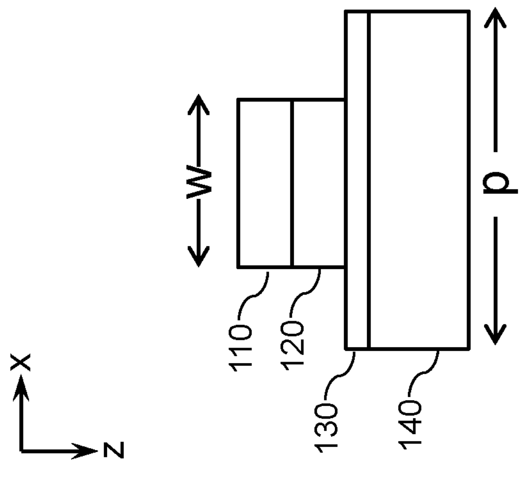

FIG. 1A

100

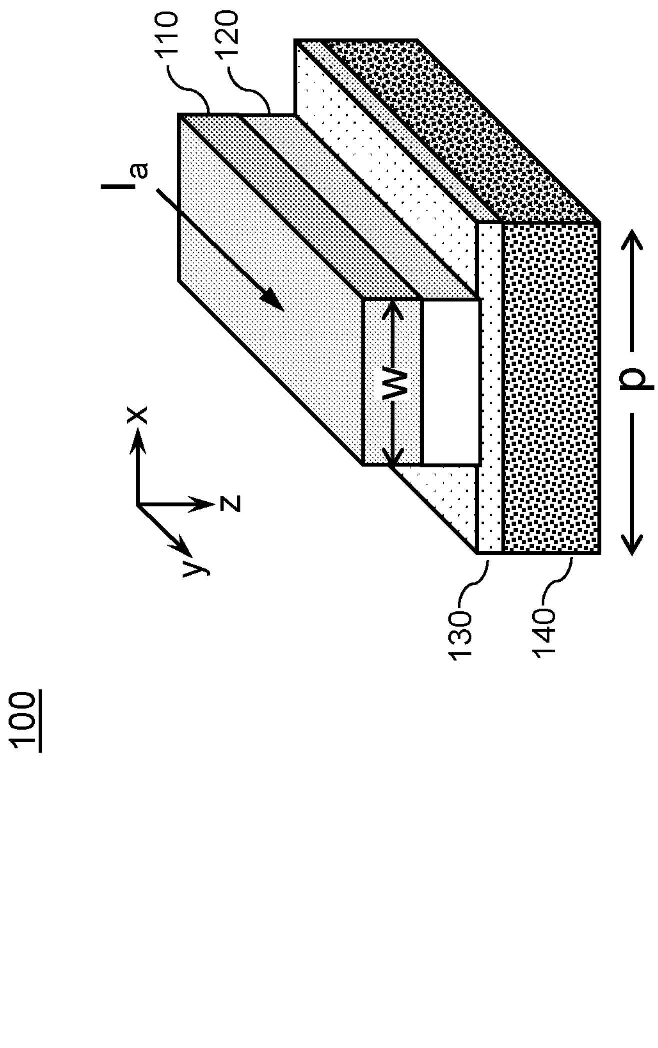

FIG. 1C

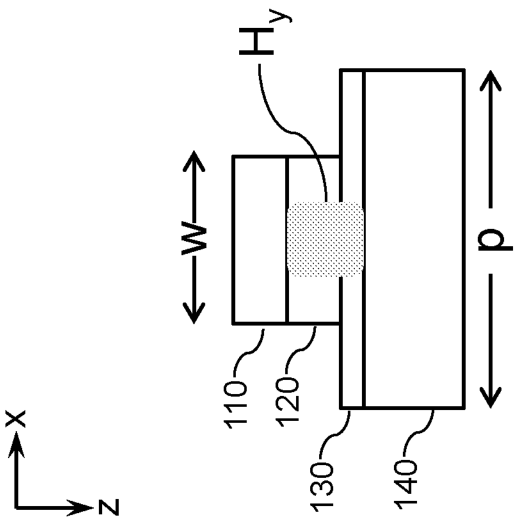

FIG. 1D

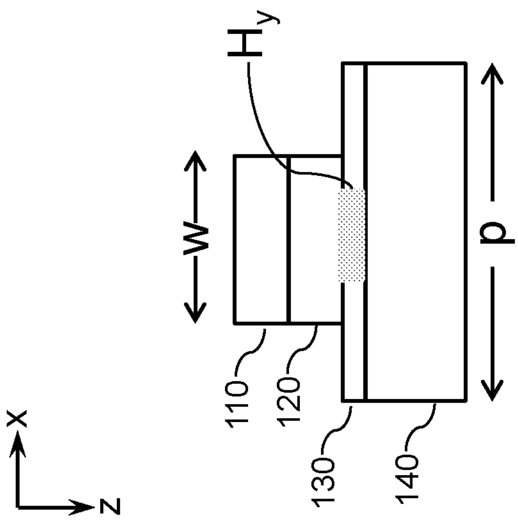

FIG. 1E

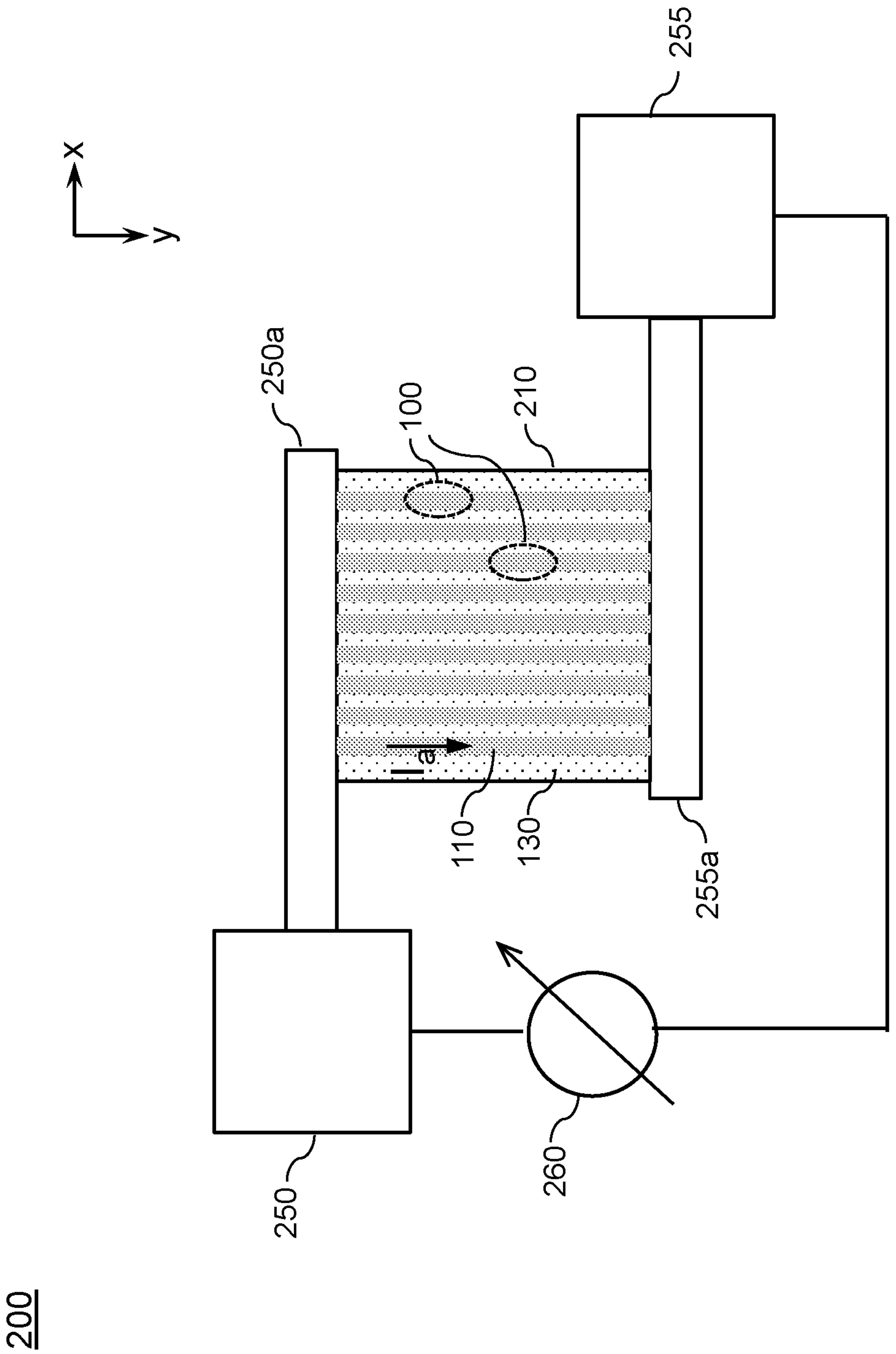

FIG. 2

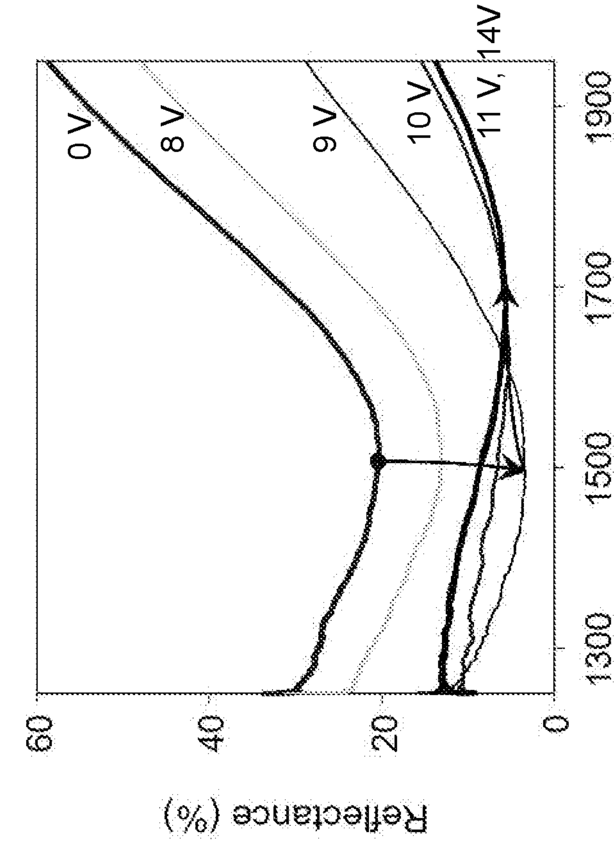
Reflectance (%)
60
40
20
0
1300
1500
1700
1900
Wavelength (nm)
0 V
8 V
9 V
10 V
11 V, 14V

FIG. 3A

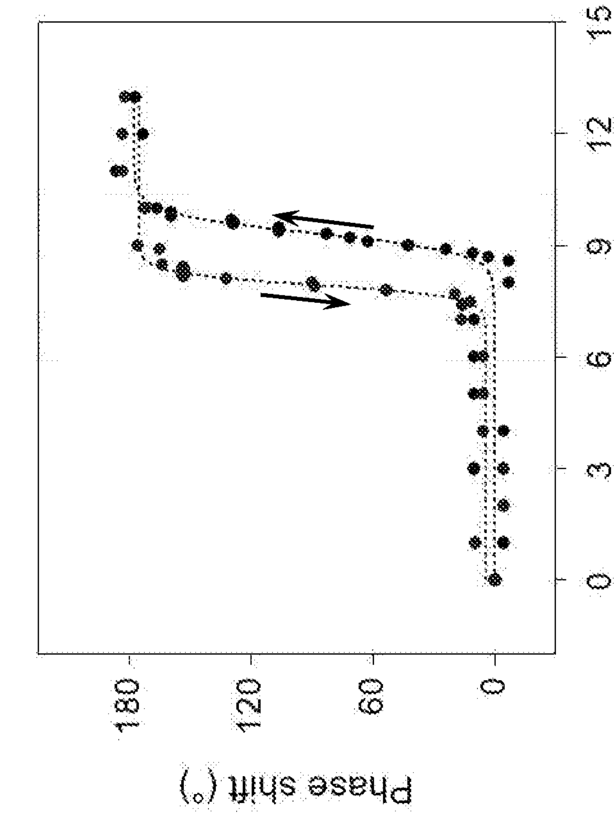
Phase shift (°)
180
120
60
0
0
3
6
9
12
15
Voltage (V)

FIG. 3B

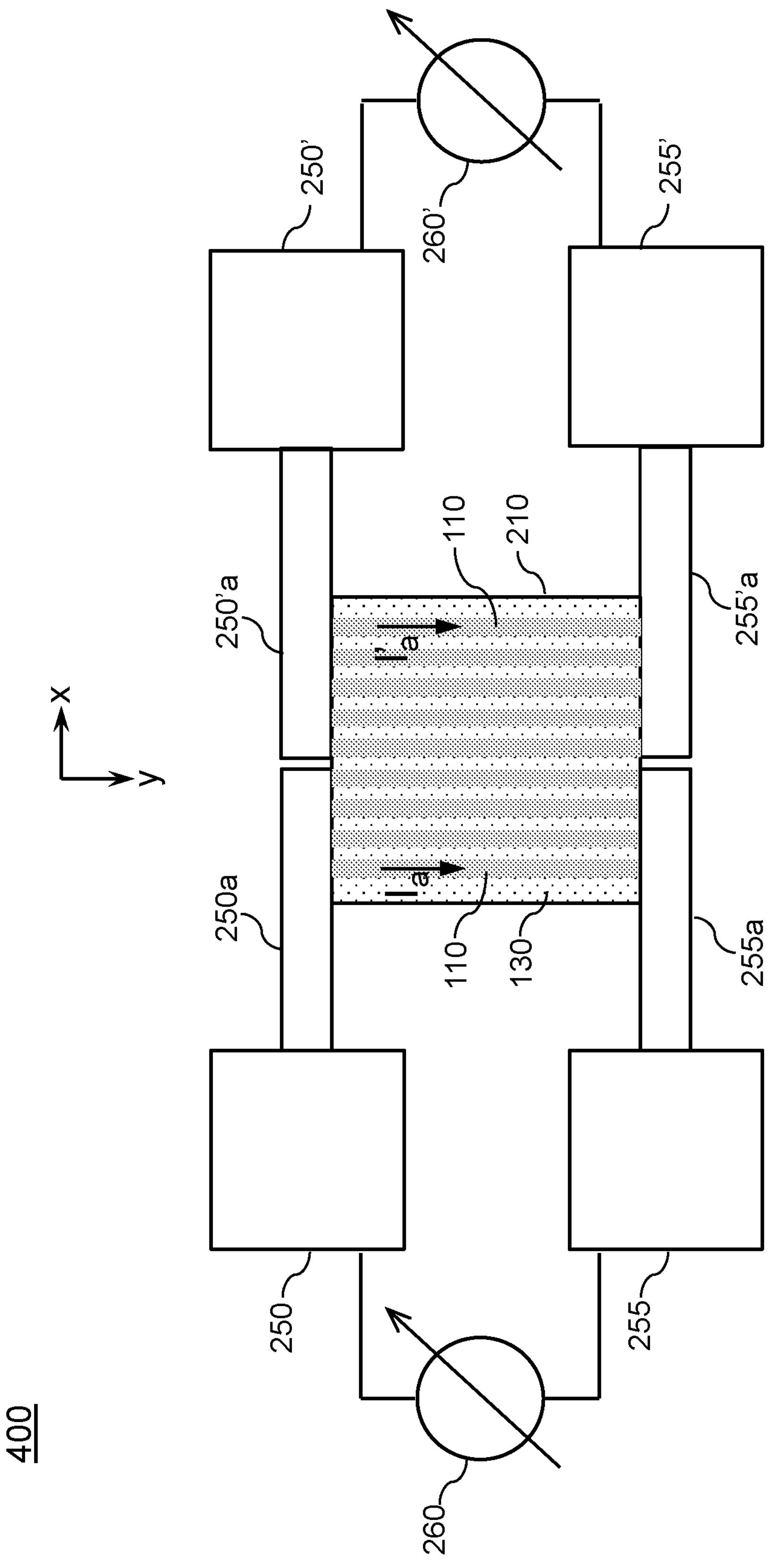
400
250'
255'
260'
250'a
255'a
110
210
x
y
I'_a
I_a
250a
255a
110
130
250
255
260

FIG. 4

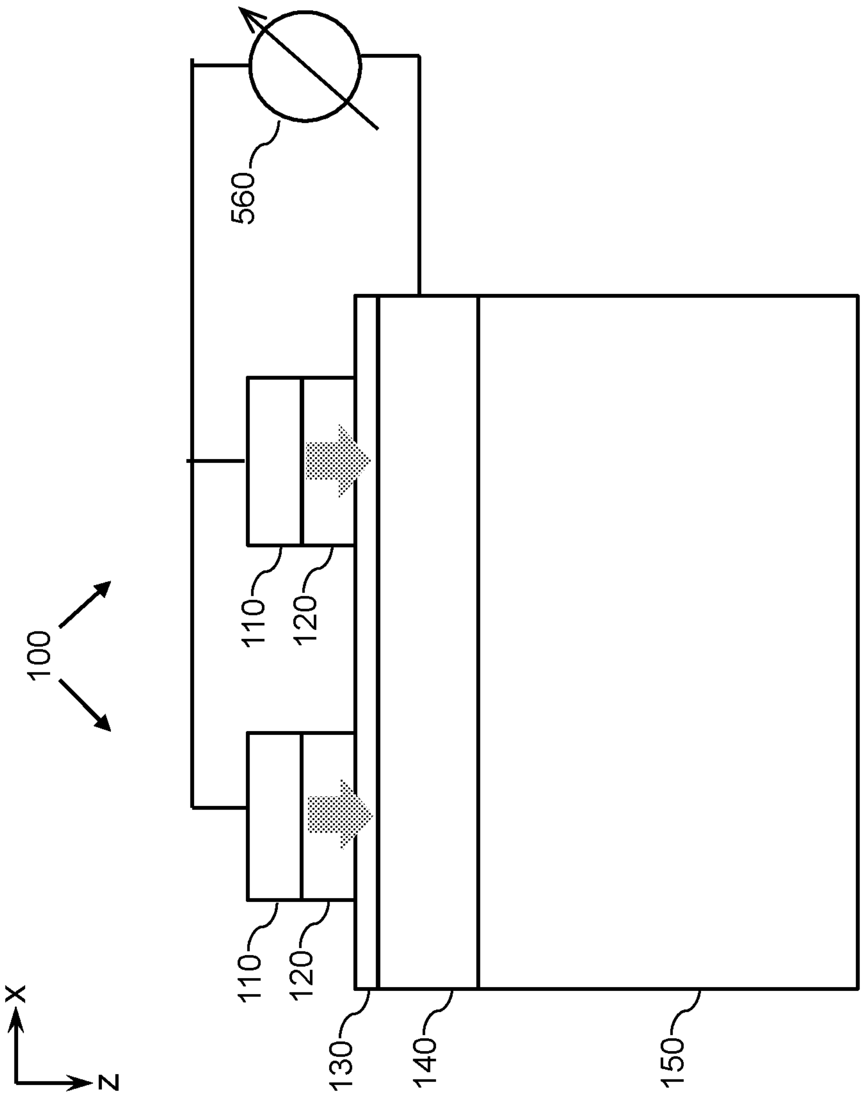

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/013220

A. CLASSIFICATION OF SUBJECT MATTER

G02B 1/00(2006.01)i

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)
G02B 1/00; G01J 3/12; G02B 26/02; G02B 5/00; G02B 5/28; G02F 1/00; G02F 1/19; G02F 2/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: metasurface, conductive, insulating, active, phase and change

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016-0223723 A1 (SAMSUNG ELECTRONICS CO., LTD. et al.) 04 August 2016 paragraphs [0053]-[0069], [0078]-[0082], [0096], [0106]-[0109] and figures 1-3, 8-10, 18	1-20
A	US 2017-0276848 A1 (NATIONAL TECHNOLOGY & ENGINEERING SOLUTIONS OF SANDIA, LLC) 28 September 2017 paragraphs [0036]-[0042] and figures 2-3, 10A-13B	1-20
A	US 2018-0321518 A1 (CALIFORNIA INSTITUTE OF TECHNOLOGY) 08 November 2018 paragraphs [0006]-[0026] and figures 5A-5C	1-20
A	WO 2013-068516 A1 (DANMARKS TEKNISKE UNIVERSITET) 16 May 2013 page 3, line 10-page 7, line 12 and figure 3	1-20
A	KR 10-2018-0099326 A (KWANGWOON UNIVERSITY INDUSTRY-ACADEMIC COLLABORATION FOUNDATION) 05 September 2018 paragraphs [0030]-[0047] and figure 1	1-20

☐ 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
"D" document cited by the applicant in the international application
"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	Date of mailing of the international search report
11 May 2020 (11.05.2020)	**11 May 2020 (11.05.2020)**

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