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(54) METHODS FOR FABRICATING AND USING NANOWIRES

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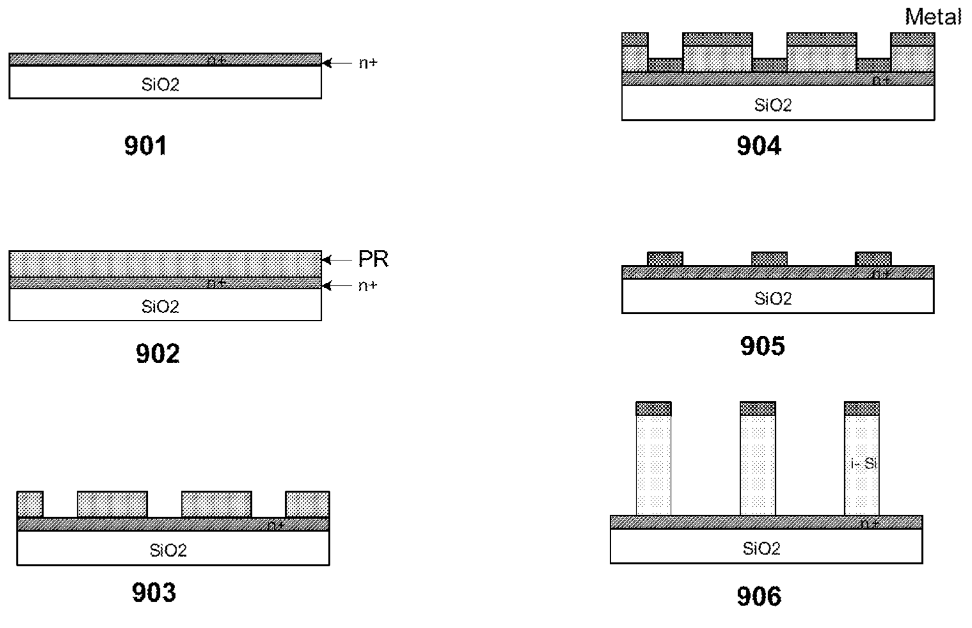
(57) ABSTRACT

Methods, apparatuses, systems, and devices relating to fabricating one or more nanowires are disclosed. One method for fabricating a nanowire includes: selecting a particular wavelength of electromagnetic radiation for absorption for a nanowire; determining a diameter corresponding to the particular wavelength; and fabricating a nanowire having the determined diameter. According to another embodiment, one or more nanowires may be fabricated in an array, each having the same or different determined diameters. An image sensor and method of imaging using such an array are also disclosed.

900



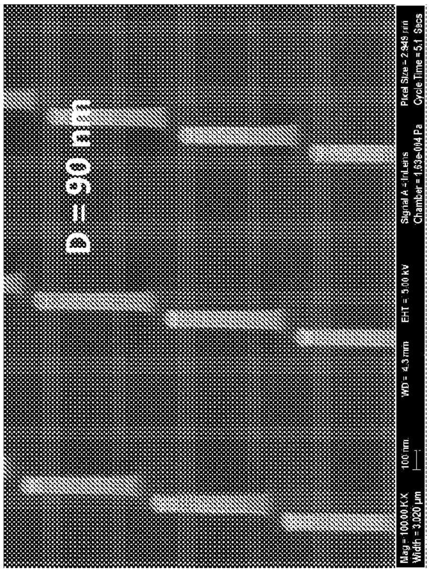


FIG. 1A

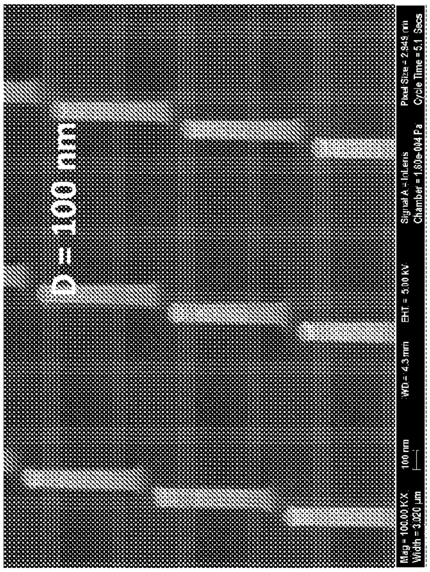


FIG. 1B

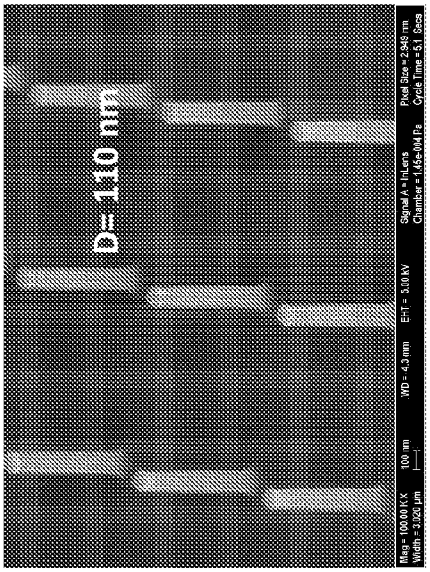


FIG. 1C

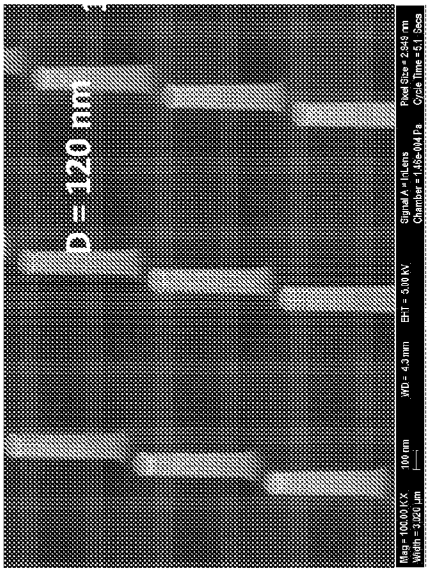


FIG. 1D

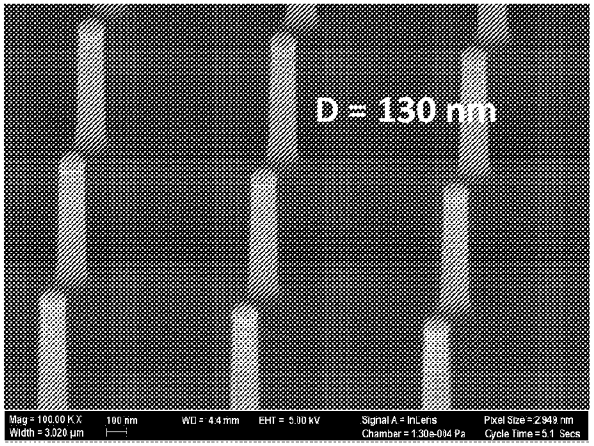


FIG. 1E

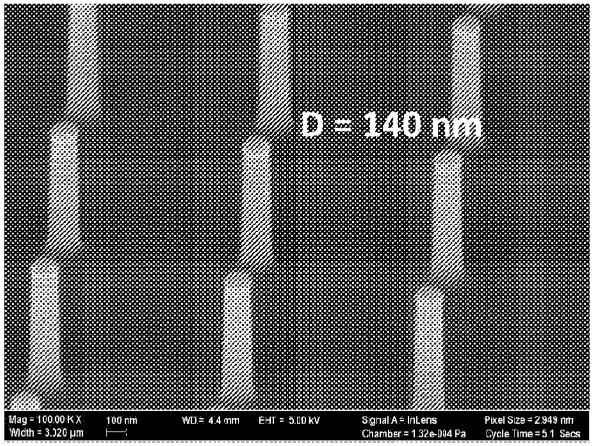


FIG. 1F

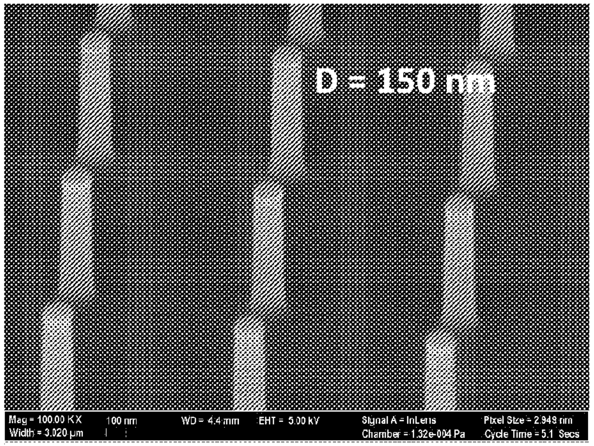


FIG. 1G

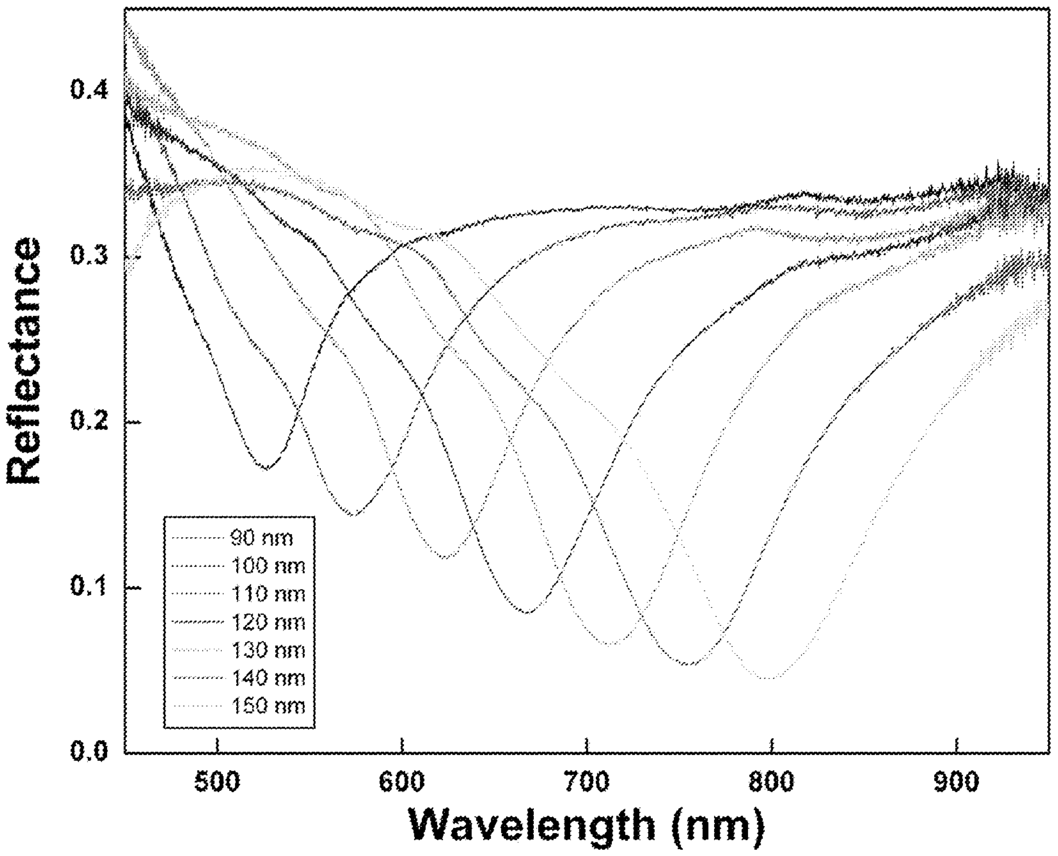

Reflectance
0.4
0.3
0.2
0.1
0.0
500
600
700
800
900
Wavelength (nm)
90 nm
100 nm
110 nm
120 nm
130 nm
140 nm
150 nm

FIG. 2

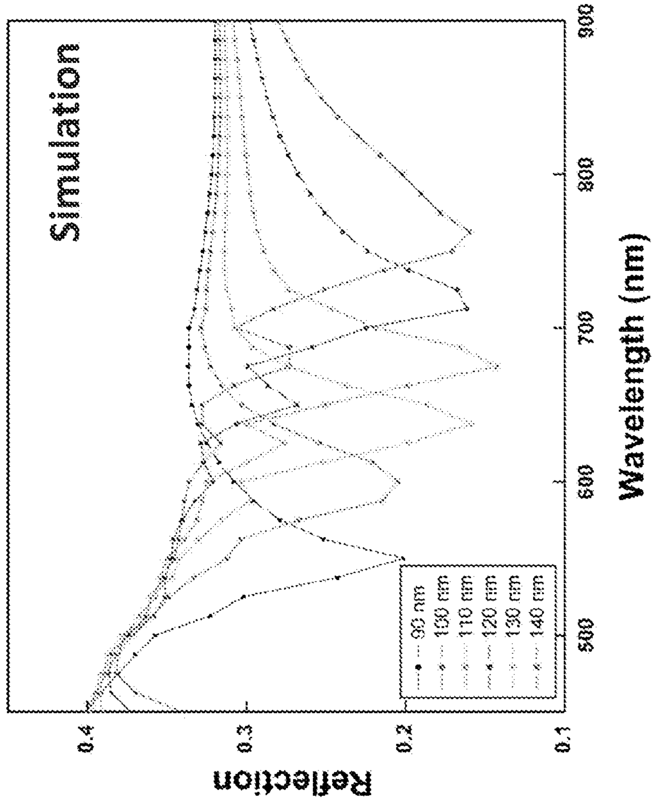

Simulation
Reflection
0.1
0.2
0.3
0.4
Wavelength (nm)
500
600
700
800
900
90 nm
100 nm
110 nm
120 nm
130 nm
140 nm

FIG. 3B

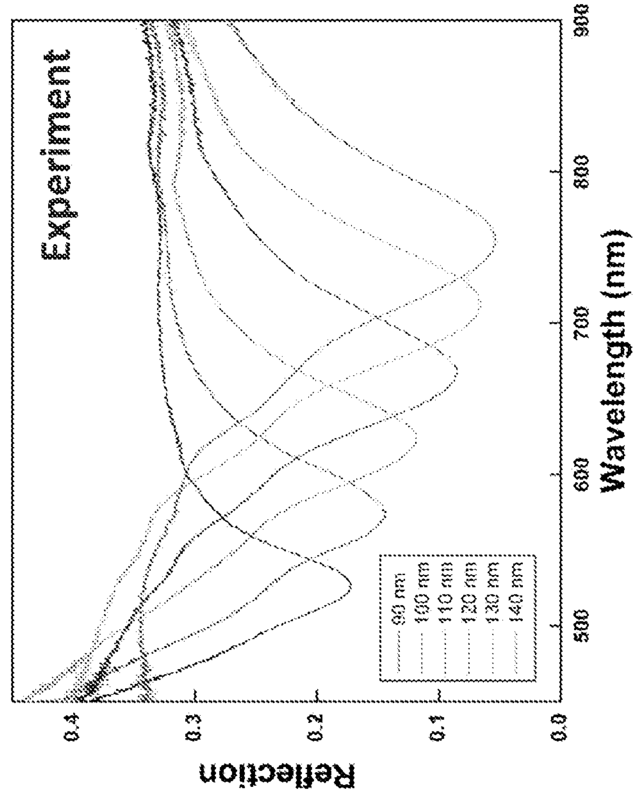

Experiment
Reflection
0.0
0.1
0.2
0.3
0.4
Wavelength (nm)
500
600
700
800
900
90 nm
100 nm
110 nm
120 nm
130 nm
140 nm

FIG. 3A

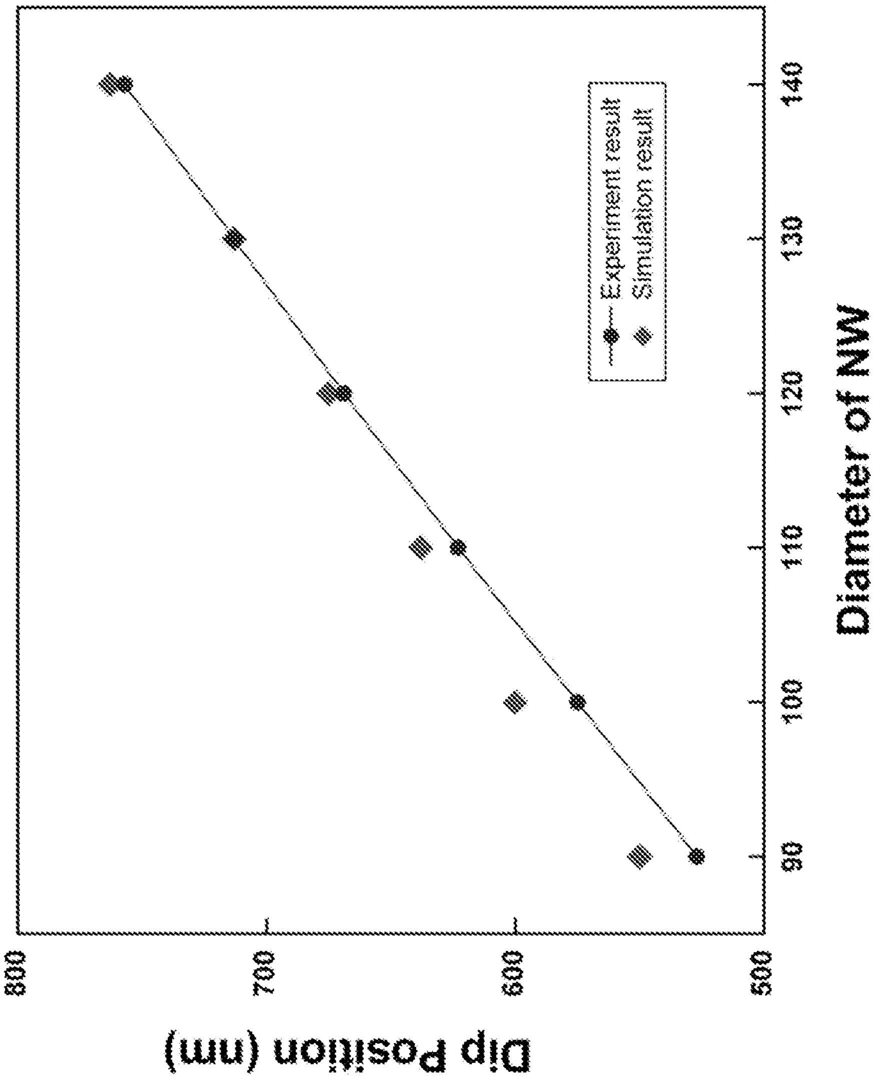

Dip Position (nm)
800
700
600
500
90
100
110
120
130
140
Diameter of NW
Experiment result
Simulation result

FIG. 3C

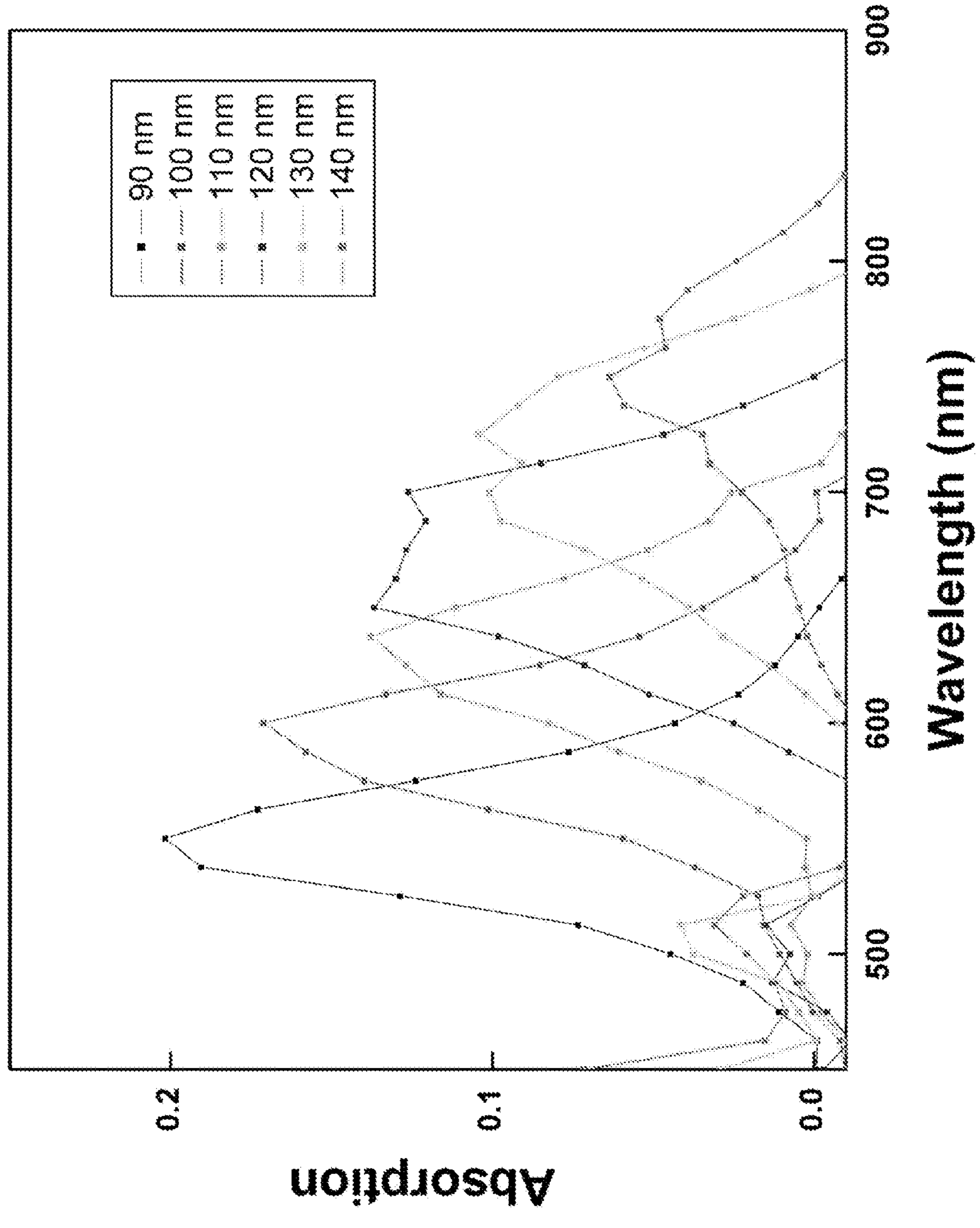

Absorption
0.0
0.1
0.2
500
600
700
800
900
Wavelength (nm)
90 nm
100 nm
110 nm
120 nm
130 nm
140 nm

FIG. 4

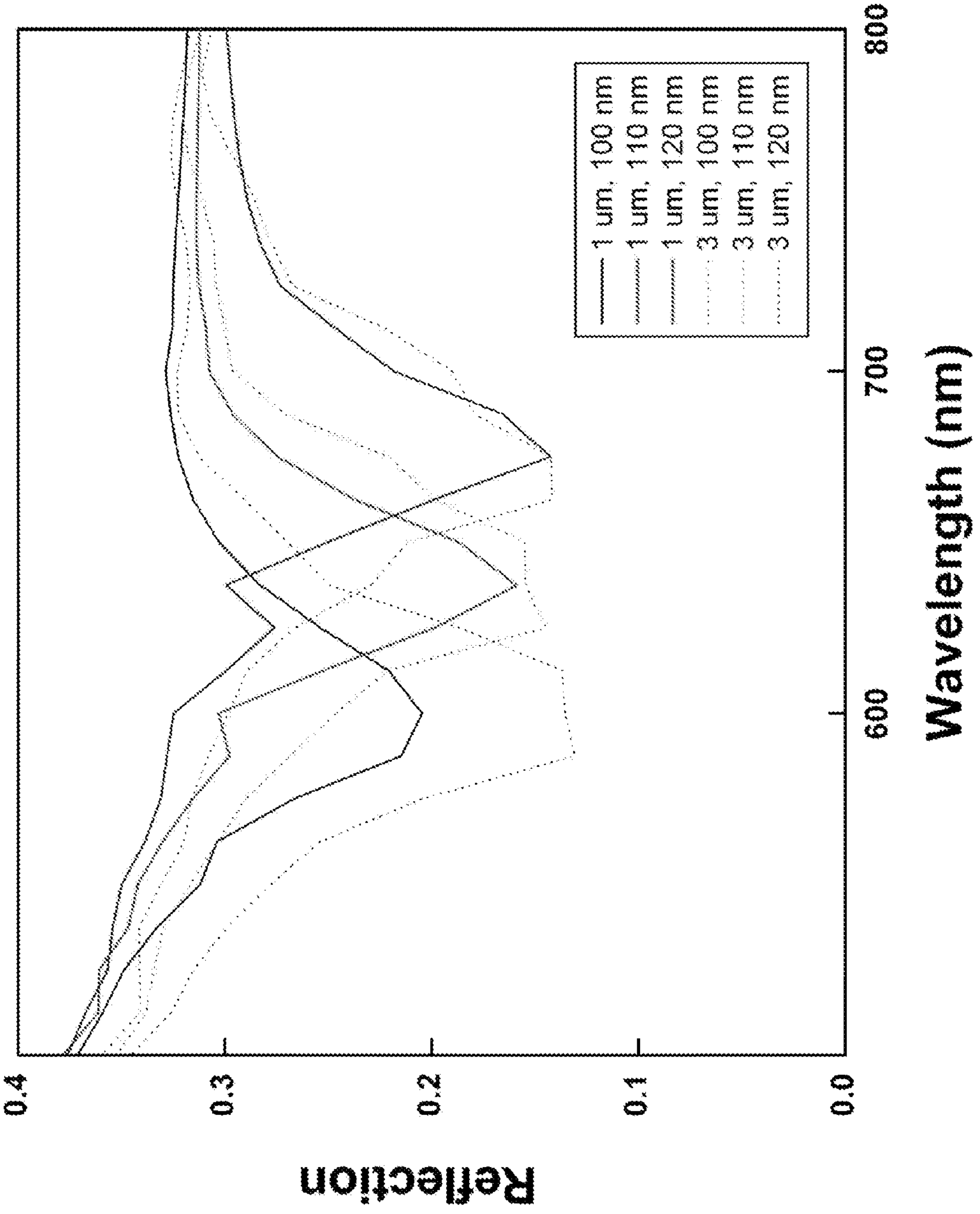

Reflection
0.4
0.3
0.2
0.1
0.0
600
700
800
Wavelength (nm)
1 um, 100 nm
1 um, 110 nm
1 um, 120 nm
3 um, 100 nm
3 um, 110 nm
3 um, 120 nm

FIG. 5

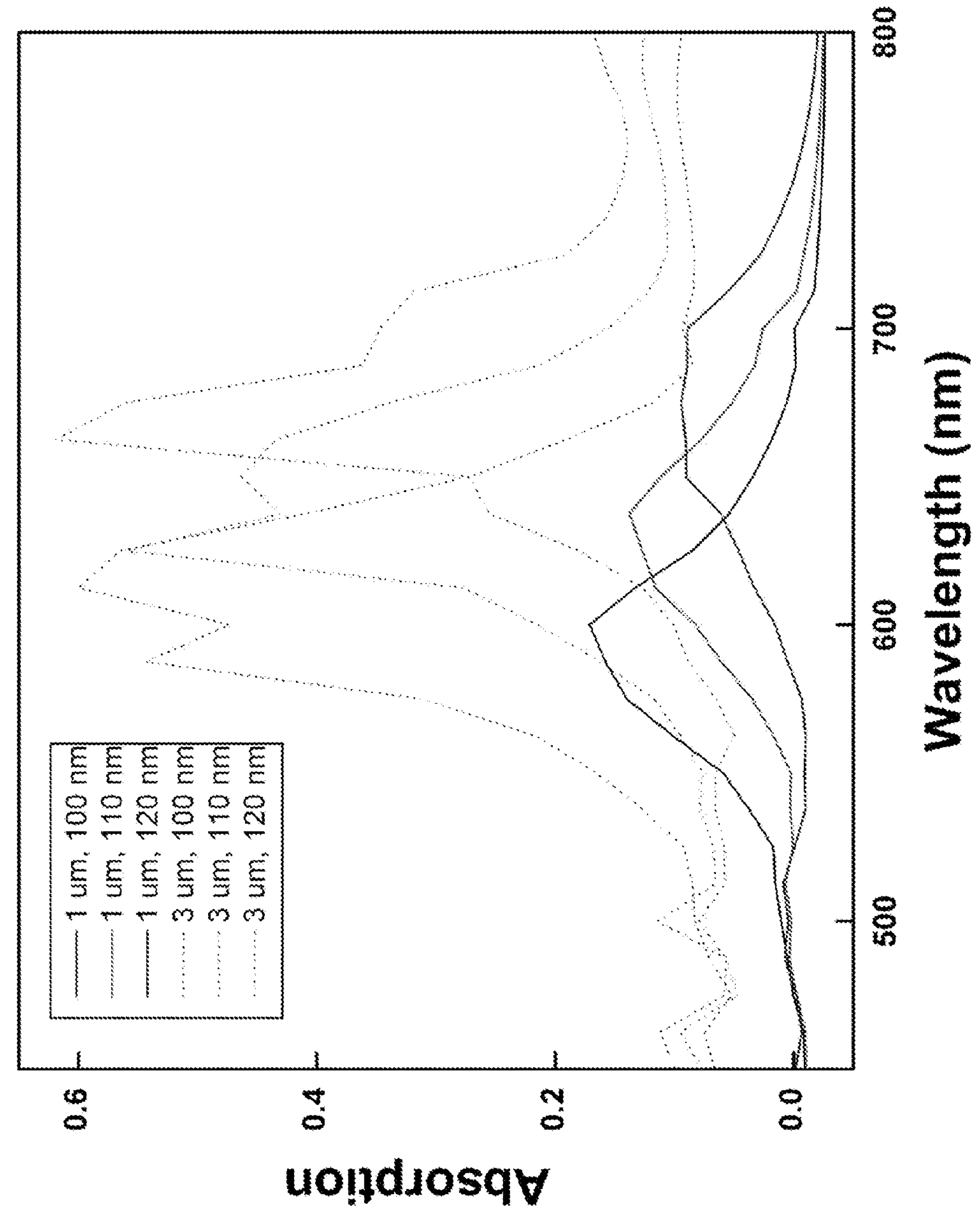

Absorption
0.6
0.4
0.2
0.0
500
600
700
800
Wavelength (nm)
1 um, 100 nm
1 um, 110 nm
1 um, 120 nm
3 um, 100 nm
3 um, 110 nm
3 um, 120 nm

FIG. 6

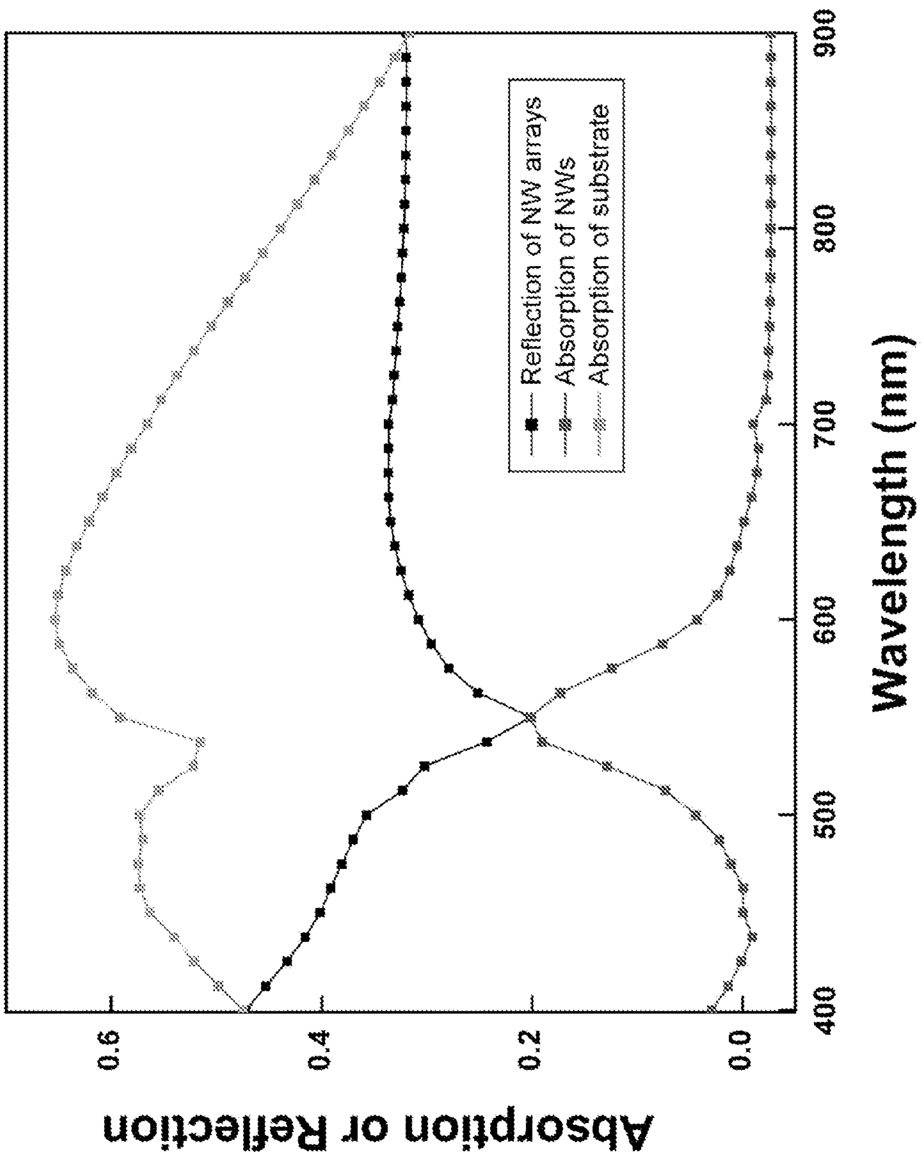

Absorption or Reflection
0.0
0.2
0.4
0.6
400
500
600
700
800
900
Wavelength (nm)
Reflection of NW arrays
Absorption of NWs
Absorption of substrate

FIG. 7

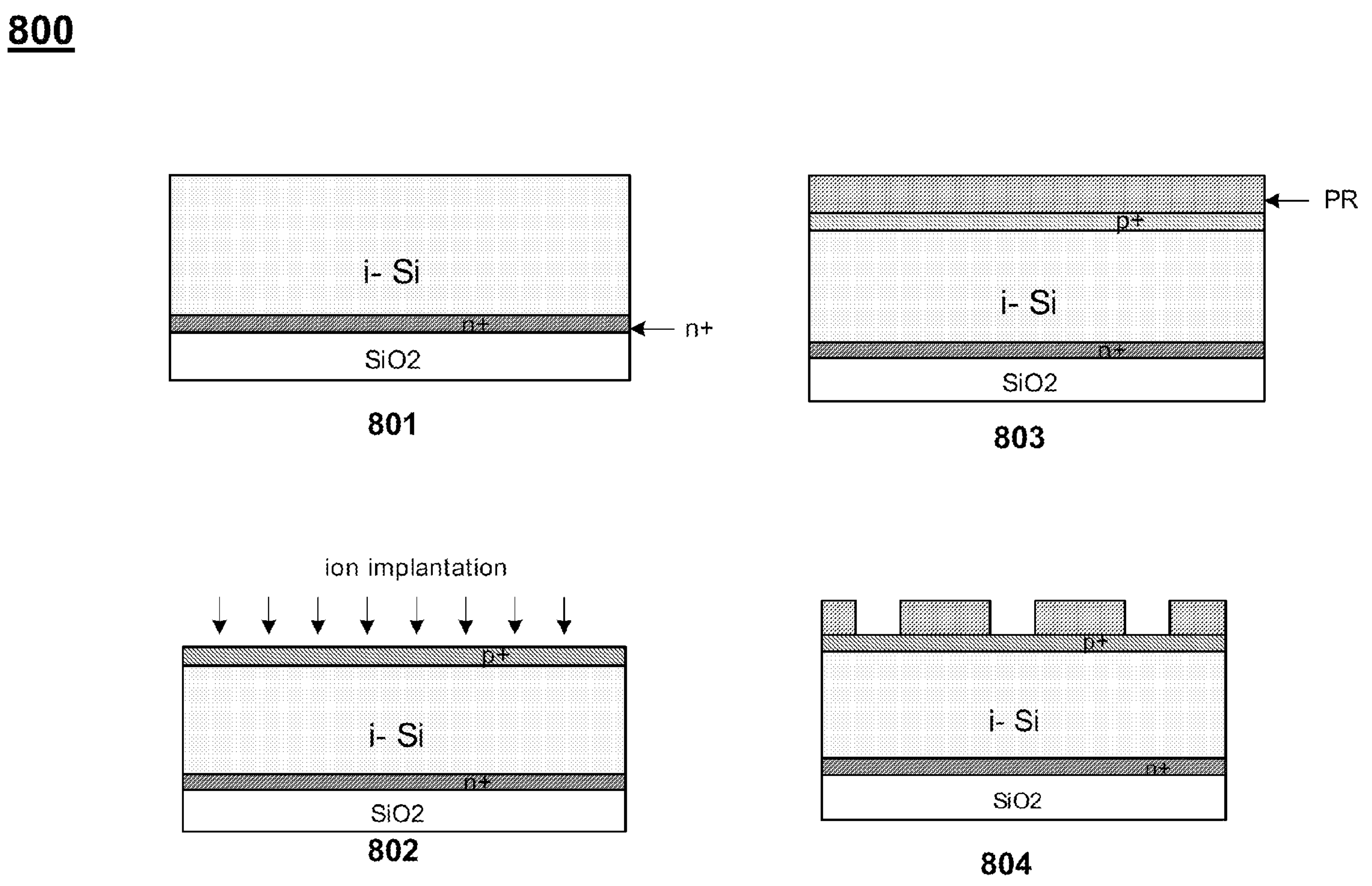

800
i- Si
n+
n+
SiO2
801
i- Si
p+
PR
n+
SiO2
803
ion implantation
p+
i- Si
n+
SiO2
802
p+
i- Si
n+
SiO2
804

FIG. 8

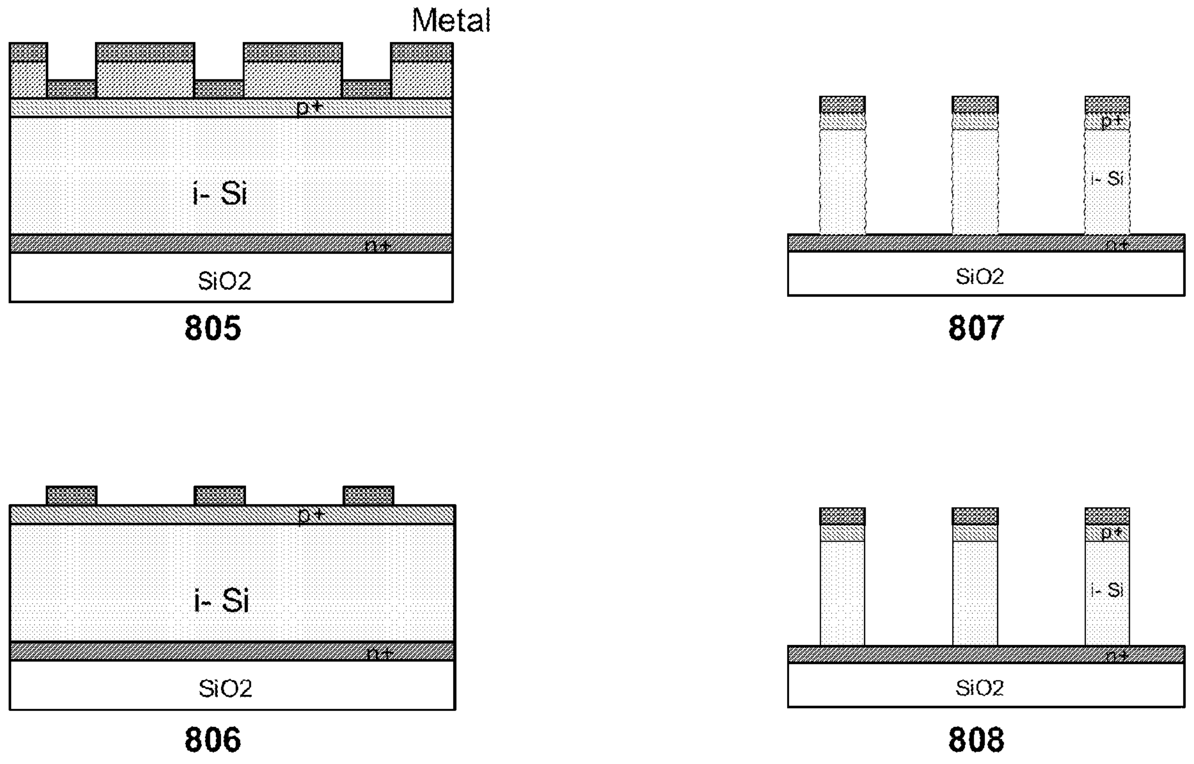

Metal
p+
i- Si
n+
SiO2
805
p+
i- Si
n+
SiO2
807
p+
i- Si
n+
SiO2
806
p+
i- Si
n+
SiO2
808

FIG. 8 (Cont.)

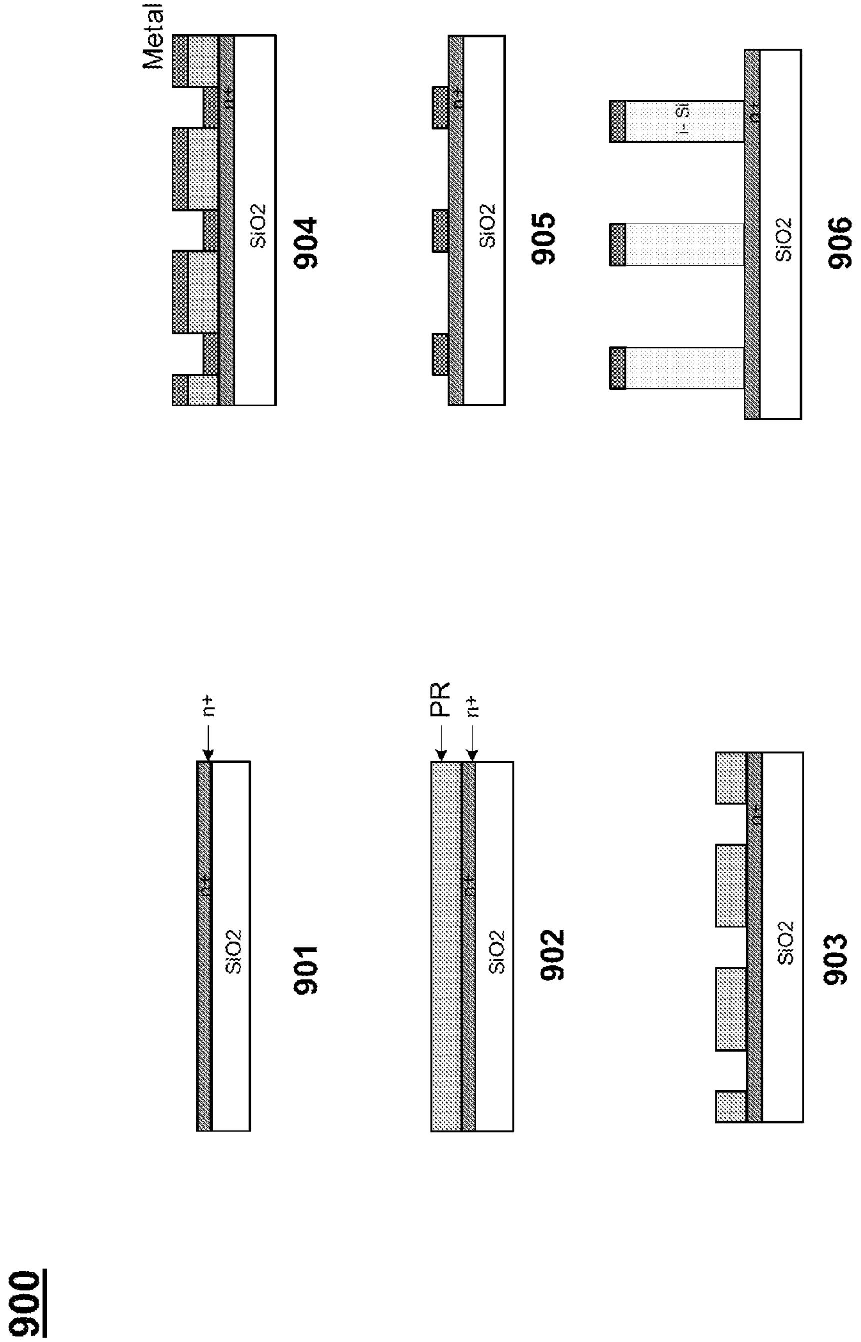

900
901
n+
SiO2
902
PR
n+
SiO2
903
n+
SiO2
904
Metal
n+
SiO2
905
n+
SiO2
906
i- Si
n+
SiO2

FIG. 9

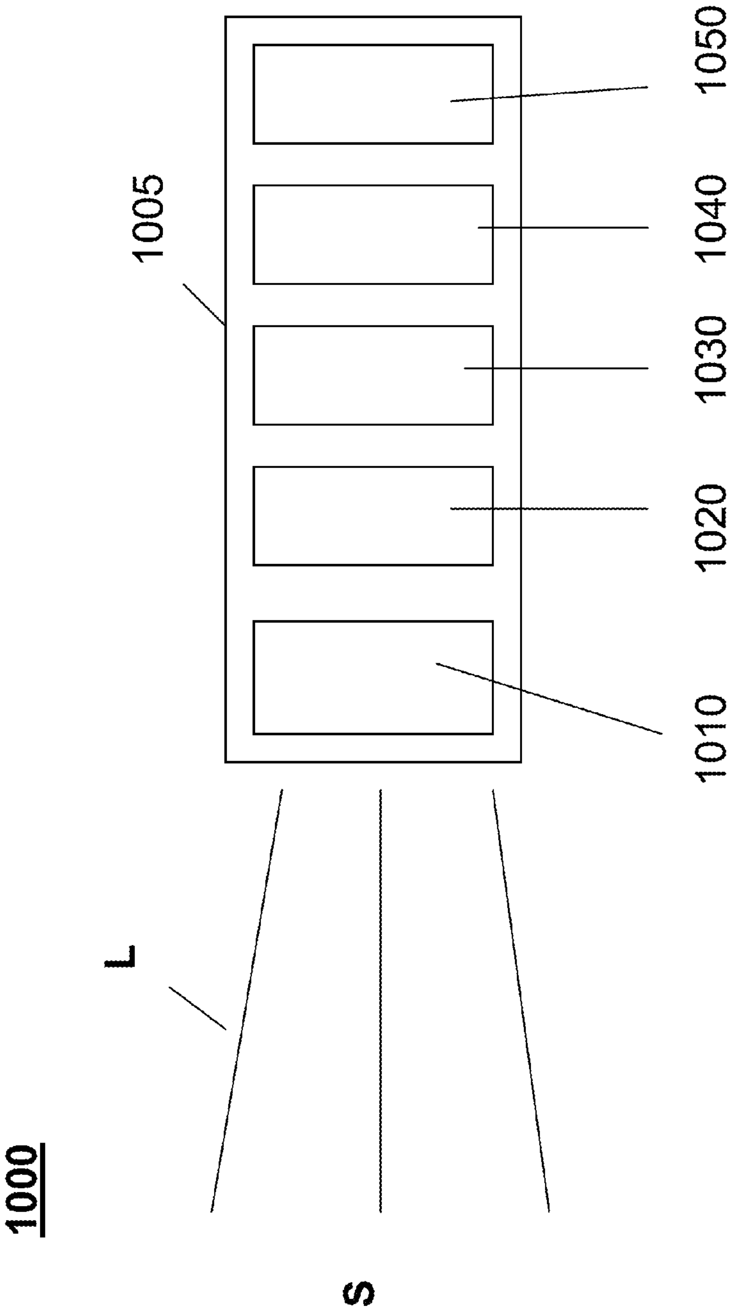


FIG. 10

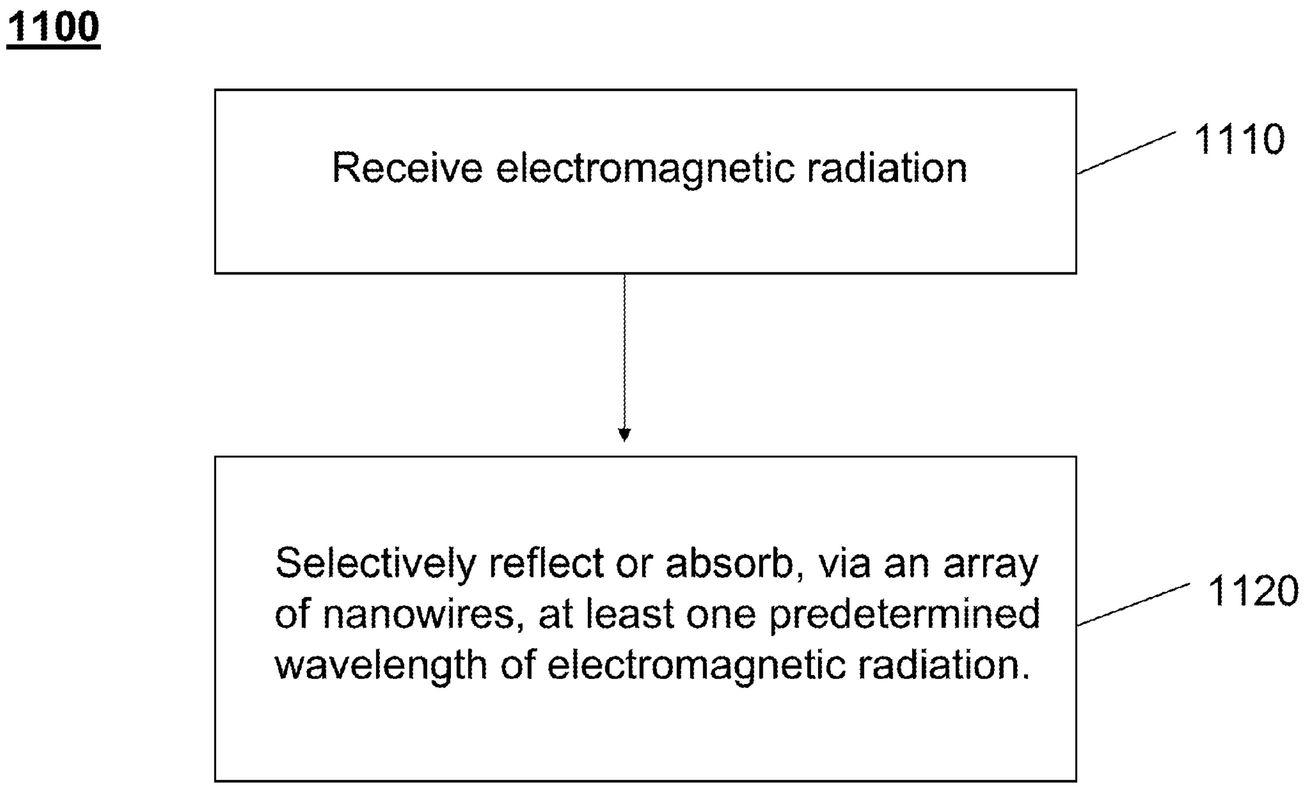

1100
Receive electromagnetic radiation
1110
Selectively reflect or absorb, via an array of nanowires, at least one predetermined wavelength of electromagnetic radiation.
1120

FIG. 11

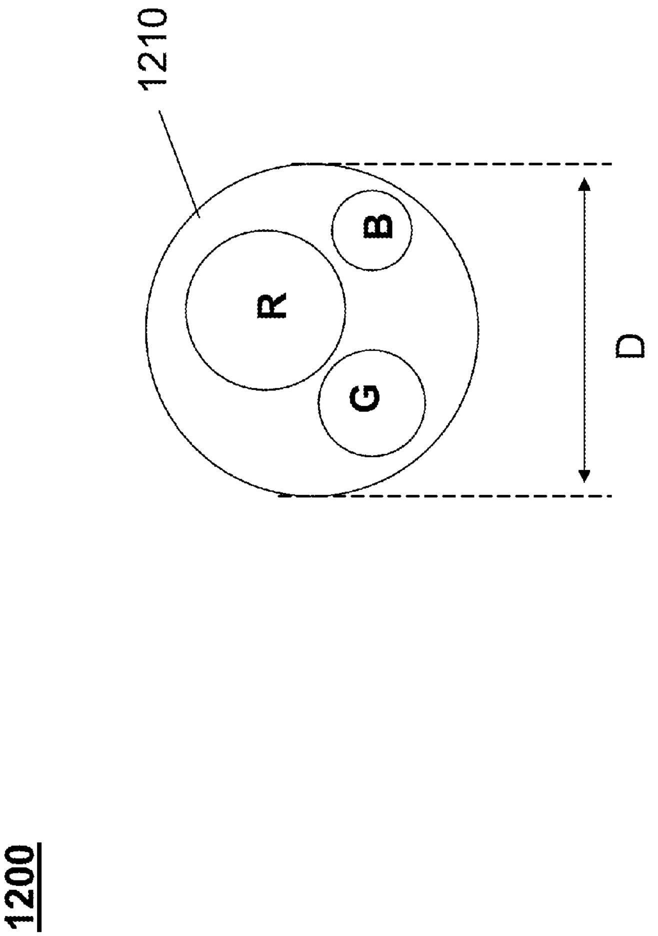


FIG. 12

METHODS FOR FABRICATING AND USING NANOWIRES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 12/966,514, filed Dec. 13, 2010 and claims the benefit of U.S. Provisional Application No. 61/357,429, filed on Jun. 22, 2010, which is hereby incorporated by reference as if fully set forth herein.

[0002] This application is related to the disclosures of U.S. patent application Ser. No. 12/204,686, filed Sep. 4, 2008 (now U.S. Pat. No. 7,646,943, issued Jan. 12, 2010), Ser. No. 12/648,942, filed Dec. 29, 2009 (now U.S. Pat. No. 8,229,255, issued Jul. 24, 2012), Ser. No. 13/556,041, filed Jul. 23, 2012, Ser. No. 15/057,153, filed Mar. 1, 2016, Ser. No. 12/270,233, filed Nov. 13, 2008 (now U.S. Pat. No. 8,274,039, issued Sep. 25, 2012), Ser. No. 13/925,429, filed Jun. 24, 2013 (now U.S. Pat. No. 9,304,035, issued Apr. 5, 2016), Ser. No. 15/090,155, filed Apr. 4, 2016, Ser. No. 13/570,027, filed Aug. 8, 2012 (now U.S. Pat. No. 8,471,190, issued Jun. 25, 2013), Ser. No. 12/472,264, filed May 26, 2009 (now U.S. Pat. No. 8,269,985, issued Sep. 18, 2012), Ser. No. 13/621,607, filed Sep. 17, 2012 (now U.S. Pat. No. 8,514,411, issued Aug. 20, 2013), Ser. No. 13/971,523, filed Aug. 20, 2013 (now U.S. Pat. No. 8,810,808, issued Aug. 19, 2014), Ser. No. 14/459,398 filed Aug. 14, 2014, Ser. No. 12/472,271, filed May 26, 2009 (now abandoned), Ser. No. 12/478,598, filed Jun. 4, 2009 (now U.S. Pat. No. 8,546,742, issued Oct. 1, 2013), Ser. No. 14/021,672, filed Sep. 9, 2013 (now U.S. Pat. No. 9,177,985, issued Nov. 3, 2015), Ser. No. 12/573,582, filed Oct. 5, 2009 (now U.S. Pat. No. 8,791,470, issued Jul. 29, 2014), Ser. No. 14/274,448, filed May 9, 2014, Ser. No. 12/575,221, filed Oct. 7, 2009 (now U.S. Pat. No. 8,384,007, issued Feb. 26, 2013), Ser. No. 12/633,323, filed Dec. 8, 2009 (now U.S. Pat. No. 8,735,797, issued May 27, 2014), Ser. No. 14/068,864, filed Oct. 31, 2013 (now U.S. Pat. No. 9,263,613, issued Feb. 16, 2016), Ser. No. 14/281,108, filed May 19, 2014 (now U.S. Pat. No. 9,123,841, issued Sep. 1, 2015), Ser. No. 13/494,661, filed Jun. 12, 2012 (now U.S. Pat. No. 8,754,359, issued Jun. 17, 2014), Ser. No. 12/633,318, filed Dec. 8, 2009 (now U.S. Pat. No. 8,519,379, issued Aug. 27, 2013), Ser. No. 13/975,553, filed Aug. 26, 2013 (now U.S. Pat. No. 8,710,488, issued Apr. 29, 2014), Ser. No. 12/633,313, filed Dec. 8, 2009, Ser. No. 12/633,305, filed Dec. 8, 2009 (now U.S. Pat. No. 8,299,472, issued Oct. 30, 2012), Ser. No. 13/543,556, filed Jul. 6, 2012 (now U.S. Pat. No. 8,766,272, issued Jul. 1, 2014), Ser. No. 14/293,164, filed Jun. 2, 2014, Ser. No. 12/621,497, filed Nov. 19, 2009 (now abandoned), Ser. No. 12/633,297, filed Dec. 8, 2009 (now U.S. Pat. No. 8,889,455, issued Nov. 18, 2014), Ser. No. 14/501,983 filed Sep. 30, 2014, 12/982,269, filed Dec. 30, 2010 (now U.S. Pat. No. 9,299,866, issued Mar. 29, 2016), Ser. No. 15/082,514, filed Mar. 28, 2016, 12/966,573, filed Dec. 13, 2010 (now U.S. Pat. No. 8,866,065, issued Oct. 21, 2014), Ser. No. 14/503,598, filed Oct. 1, 2014, Ser. No. 12/967,880, filed Dec. 14, 2010 (now U.S. Pat. No. 8,748,799, issued Jun. 10, 2014), Ser. No. 14/291,888, filed May 30, 2014, Ser. No. 12/974,499, filed Dec. 21, 2010 (now U.S. Pat. No. 8,507,840, issued Aug. 13, 2013), Ser. No. 12/966,535, filed Dec. 13, 2010 (now U.S. Pat. No. 8,890,271, issued Nov. 18, 2014) Ser. No. 12/910,664, filed Oct. 22, 2010 (now U.S. Pat. No. 9,000,353, issued Apr. 17, 2015), Ser. No. 14/632,739, filed Feb. 26, 2015, Ser. No. 12/945,492, filed Nov. 12, 2010, Ser. No. 13/047,392, filed Mar. 14, 2011 (now U.S. Pat. No. 8,835,831, issued Sep. 16, 2014), Ser. No. 14/450,812, filed Aug. 4, 2014, Ser. No. 13/048,635, filed Mar. 15, 2011 (now U.S. Pat. No. 8,835,905, issued Sep. 16, 2014), Ser. No. 14/487,375, filed Sep. 16, 2014 (now U.S. Pat. No. 9,054,008, issued Jun. 9, 2015), Ser. No. 14/705,380, filed May 6, 2015, Ser. No. 13/106,851, filed May 12, 2011 (now U.S. Pat. No. 9,082,673, issued Jul. 14, 2015) Ser. No. 14/704,143, filed May 5, 2015, Ser. No. 13/288,131, filed Nov. 3, 2011, Ser. No. 14/334,848, filed Jul. 18, 2014, Ser. No. 14/032,166, filed Sep. 19, 2013, Ser. No. 13/543,307, filed Jul. 6, 2012, Ser. No. 13/963,847, filed Aug. 9, 2013, Ser. No. 15/093,928, filed Apr. 8, 2016, Ser. No. 13/693,207, filed Dec. 4, 2012, 61/869,727, filed Aug. 25, 2013, Ser. No. 14/322,503, filed July. 2, 2014, Ser. No. 14/311,954, filed Jun. 23, 2014, Ser. No. 14/563,781, filed Dec. 8, 2014, 61/968,816, filed Mar. 21, 2014, Ser. No. 14/516,402, filed Oct. 16, 2014, Ser. No. 14/516,162, filed Oct. 16, 2014, 62/161,485, filed May 14, 2015 and 62/307,018, filed Mar. 11, 2016 are each hereby incorporated by reference in their entirety.

FIELD

[0003] This application generally relates to semiconductor sensing devices and manufacturing, and in particular, selected spectral absorption of nanowires.

BACKGROUND

[0004] An image sensor may be fabricated to have a large number of identical sensor elements (pixels), generally more than 1 million, in a (Cartesian) square grid. The pixels may be photodiodes, or other photosensitive elements, that are adapted to convert electromagnetic radiation into electrical signals. Recent advances in semiconductor technologies have enabled the fabrication of nanoscale semiconductor components such as nanowires.

[0005] Nanowires have been introduced into solid state image devices to confine and transmit electromagnetic radiation impinging thereupon to the photosensitive elements. These nanowires can be fabricated from bulk silicon which appears gray in color, although researchers have patterned the surface of silicon so it "looks" black and does not reflect any visible light.

[0006] However, nanowires configured to selectively absorb (or to lower the reflectance of) light at a predetermined wavelength have not been fabricated.

SUMMARY

[0007] According to an embodiment, a method for fabricating a nanowire comprises: selecting a particular wavelength of electromagnetic radiation for absorption for a nanowire; determining a diameter corresponding to the particular wavelength; and fabricating a nanowire having the determined diameter.

[0008] According to an embodiment, there may be a nearly linear relationship between the nanowire diameter and the wavelength of electromagnetic radiation absorbed by the nanowire. However, it will be appreciated that other relationships may exists, based on the nanowire materials, fabrication techniques, cross-sectional shape, and/or other parameters. Based on the diameter of the nanowire, the particular wavelength of light absorbed may be within the UV, VIS or IR spectra.

[0009] According to an embodiment, the nanowire may be fabricated to have a diameter between about 90 and 150 nm for absorbing a wavelength of visible light. Of course, the nanowire diameters may need to be smaller for absorbing wavelengths of UV light or larger for absorbing wavelengths of IR light. While this disclosure primarily describes nanowires having a circular cross-sectional shape, it will appreciated that other cross-sectional shapes are also possible (e.g., those that function as a waveguide).

[0010] According to an embodiment, the length of the nanowire may be, for example, between about 1 and 10 μm (or perhaps even longer). The longer the nanowire is, the greater the volume may be available for absorption of electromagnetic energy.

[0011] According to an embodiment, the nanowire may be fabricated by a dry etching process, or a vapor-liquid-solid (VLS) method from a silicon or indium arsenide wafer. It will be appreciated, though, that other materials and fabrication techniques may also be used. During fabrication of the nanowire, a mask having the diameter of the nanowire may be used to form the nanowire having substantially the same diameter.

[0012] According to an embodiment, a plurality of nanowires may be fabricated into an array, each having the same or different determined diameters. The size of the array may be about 100 μm×100 μm or larger. And the nanowires can be spaced at a pitch of about 1 μm or less in the x- and y- directions (Cartesian). In one implementation, the array may include about 10,000 or more nanowires.

[0013] According to an embodiment, the spacing (pitch) of the nanowires may affect the amount of absorption. For instance, near total absorption may be realized by adjusting the spacing.

[0014] According to an embodiment, an image sensor comprises: a plurality of pixels, each of the pixels including at least one nanowire, wherein each of the nanowires has a diameter that corresponds to a predetermined wavelength of electromagnetic radiation for absorption by the sensor. The pixels may include one or more nanowires having the same or different determined diameters. The latter configuration may be effective for detecting absorbing multiple wavelengths of electromagnetic radiation (light). For instance, a red-green-blue (RGB) pixel for an image sensor may be fabricated having three nanowires having different diameters configured to absorb red, green and blue light, respectively.

[0015] According to an embodiment, the image sensor may include various elements, such as, foreoptics configured to receive the electromagnetic radiation and focus or collimate the received radiation onto the one or more pixels, a readout circuit configured to receive output from the one or more pixels, a processor configured to receive the output from the readout circuit and generate an image, and a display device configured to display the image generated by the processor. In some implementations, the image sensor may be configured as a spectrophotometer or as a photovoltaic cell.

[0016] According to an embodiment, a method of imaging comprises: receiving electromagnetic radiation; selectively absorbing, via one or more nanowires, at least one predetermined wavelength of electromagnetic radiation, wherein each of the nanowires has a diameter corresponding to at least one predetermined wavelength of electromagnetic radiation for absorption. The method may be used for performing multispectral imaging or hyperspectral imaging.

[0017] Other features of one or more embodiments of this disclosure will seem apparent from the following detailed description, and accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Embodiments of the present disclosure will now be disclosed, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference symbols indicate corresponding parts, in which:

[0019] FIGS. **1A-1G** are scanning electron microscope (SEM) images showing nanowire arrays of various diameters, according to an embodiment.

[0020] FIG. **2** shows a plot of reflection for silicon nanowires having different diameters, but having the same pitch, according to an embodiment.

[0021] FIGS. **3A-3C** show experimental and simulation results for reflection of silicon nanowire arrays, according to an embodiment

[0022] FIG. **4** shows a plot of absorption spectra of silicon nanowire arrays, according to an embodiment.

[0023] FIG. **5** shows a plot of reflection spectra of silicon nanowire arrays, according to an embodiment.

[0024] FIG. **6** shows a plot of absorption spectra of silicon nanowire arrays, according to an embodiment.

[0025] FIG. **7** shows a plot of absorption and reflection spectra of silicon nanowire arrays, according to an embodiment.

[0026] FIG. **8** shows an exemplary dry etch method for fabricating an array of vertical nanowires, according to an embodiment.

[0027] FIG. **9** shows an exemplary vapor liquid solid method for fabricating an array of vertical nanowires, according to an embodiment.

[0028] FIG. **10** shows a schematic of an image sensor, according to an embodiment.

[0029] FIG. **11** shows a method for selectively imaging, according to an embodiment.

[0030] FIG. **12** shows an exemplary pixel of an image sensor formed of three nanowires having different diameters configured to absorb red, green, and blue light, respectively, according to an embodiment.

DETAILED DESCRIPTION

[0031] In the following detailed description, reference is made to the accompanying drawings, which form a part thereof. In the drawings, similar symbols typically identify similar components, unless the context dictates otherwise. The illustrative embodiments described in the detail description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

[0032] This disclosure is drawn to, among other things, methods, apparatuses, systems, and devices relating to the fabrication of one or more nanowires. Each of the nanowires may be fabricated to absorb (or to significantly lower reflectance of) a specific wavelength of electromagnetic radiation (light). This absorbed light includes a wavelength of light in one of the ultraviolet (UV), visible (VIS) or infrared (IR) spectra.

[0033] Silicon-based nanowires may be used for VIS applications. Vertically aligned crystalline silicon (Si) nanowire arrays may be fabricated, in various one embodiments, for example, by a dry etching process (as shown in FIG. **8** and further discussed below), or a Vapor Liquid Solid (VLS) growth method (as shown in FIG. **9** and further discussed below), with a silicon wafer as the starting material.

[0034] Of course, it will be appreciated that other materials and/or fabrication techniques may also be used for fabricating the nanowires in keeping with the scope of the invention. For instance, nanowires fabricated from an indium arsenide (InAs) wafer or related materials could be used for IR applications.

[0035] Each nanowire can include a photodiode detector element that may form a pixel in an image sensor. For example, a silicon-on-insulator (SOI)-type wafer or silicon-on-glass (SG) wafer may be used as the substrate material for which one or more nanowires may be formed upon. Depending on its configuration, the nanowire may be fabricated, such that: (i) the substrate may have an intrinsic epitaxial (epi) layer and a thin n+ layer at the oxide interface; (ii) the substrate may have a lightly doped n epi layer and a thin n+ layer at the oxide interface. (iii) the substrate may have lightly doped p epi layer and a thin p+ layer at the oxide interface, or (iv) the substrate may have an intrinsic epi layer and a thin p+ layer at the oxide interface.

[0036] P+ or n+ ion implantation may be employed to form a shallow junction at the top layer of the SOI or SG wafer. As a result, the vertical structure of p-i-n, p-n, n-i-p, n-p diode is formed respectively, depending on the substrate doping profile. In some instances, one or more transistors may be formed on the wafer for controlling the photocharge transfer from the nanowire to a readout circuit (ROC) and/or other electronics.

[0037] According to an aspect of the disclosure, the inventors have discovered a unique correlation between the nanowire diameter and its absorption (or reflectance) characteristics. For instance, the reflection spectra of fabricated silicon nanowire arrays each show a spectral dip for reflectance (or peak for absorption) at a specific wavelength position dependent on the nanowire diameter.

[0038] While the experiments performed by the inventors used nanowires fabricated having a circular cross-section, it is believed that the cross-section shape of the nanowire could be any polygonal shape, in keeping with the scope of the invention. The nanowire may be any "waveguide" shape, although the shape might have some impact on wavelength absorption.

[0039] Also, with different nanowire spacing (pitch), absorption intensity selectivity can be realized. For instance, by adjusting the spacing of adjacent nanowire, near total absorption may be realized.

[0040] The nanowire diameter may be determined by the diameter of a mask used in the process by which the nanowires are fabricated. In one implementation, the mask be formed of aluminum (Al). Of course, it will be appreciated that other mask materials can also be used.

[0041] A filtering effect can be employed in image sensor devices based on nanowire diameters. For instance, one or more nanowire arrays may be used to selectively absorb electromagnetic radiation (light) at a particular wavelength. While the incident light may be white (or other colors), absorption is "selected" by the size and/or arrangement of the nanowires. For example, the individual nanowires of the array may be fabricated to absorb light of one or more particular colors in the VIS spectrum, such as, for example, violet (400 nm), blue (475 nm), cyan (485 nm), green (510 nm), yellow (570 nm), orange (590 nm), and red (650 nm). Other absorbed colors are also possible, including black.

[0042] Similarly, individual nanowires of the array may be fabricated to absorb light in at least one wavelength of various bands of the IR spectrum, such as, for example, near-infrared (NIR), short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR), long-wavelength infrared (LWIR) or far infrared (FIR).

[0043] In one implementation, a plurality of nanowire arrays may also be configured for multispectral imaging or hyperspectral imaging, which detect electromagnetic (light) over multiple discrete spectral bands and/or spectra (e.g., VIS, NIR, SWIR, MWIR, LWIR, FIR, etc). The nanowire arrays may be configured for spectral-selective imaging which detect one or more specific wavelength of electromagnetic radiation (light). In one embodiment, an image sensor may be fabricated from an array of nanowires with one or more nanowires forming each pixel of the sensor.

[0044] FIGS. **1A-1G** are scanning electron microscope (SEM) images showing nanowire arrays of various diameters, according to an embodiment.

[0045] Vertical nanowire or nanopillar arrays may be fabricated, for example, by a dry etch method. Although, it will be appreciated that the nanowires may similarly fabricated using a VLS growing method, or other fabrication techniques. The nanowires may be formed in a Cartesian (x-y) matrix structure so that each nanowire can be controlled or individually addressed.

[0046] As shown, the nanowire arrays may be fabricated to have a very uniform circular cross-sectional shape, for instance, of about 1 to 3 μm in length or more. Using the VLS growing method, nanowires 10 μm in length can be grown. Longer nanowires may be able to absorb more radiation as they have a larger volume for the same given diameter. In addition, it may be possible to confine more radiation for absorption, for instance, using a cladding material deposited around the nanowires.

[0047] Each of the arrays shown includes nanowires formed from silicon having the same diameters ranging from about 90 to 150 nm. This diameter range may be effective for absorbing various wavelengths (colors) of visible light. Of course, the nanowire diameters may need to be smaller for absorbing wavelengths of UV light or larger for absorbing wavelengths of IR light.

[0048] The size of each of the array may be about 100 μm×100 μm, having 10,000 nanowires at a pitch (spacing) of about 1 μm or less in the x- and y- directions (in a Cartesian plane). Of course, the nanowire arrays may be fabricated in larger sizes, for instance, having a million or more nanowires. The nanowires may be spaced apart at different (larger) intervals and/or forming different shapes, as well.

[0049] FIG. **2** shows a plot of reflectance spectra for nanowires having different diameters, but having the same pitch, according to an embodiment.

[0050] The measured reflectance spectra were obtained using a collimated light method to measure reflectance of light from the nanowire array. The reflectance was normalize with respect to a silver (Ag) mirror. For each nanowire diameter, there is a significant dip in reflectance at a particular wavelength. This reflectance dip corresponds to absorption of light at that particular wavelength.

[0051] The bandwidth of the reflectance dip (or peak in absorption) is approximately 50-100 nm at the particular wavelength.

[0052] FIGS. **3**A-**3**C show experimental and simulated results for reflection of Si nanowire arrays, according to an embodiment.

[0053] FIG. **3**A shows similar experimental results shown in FIG. **2**, but the measured reflectance spectra were obtained using a Raman spectroscopy setup configured to measure reflectance of light focused onto the nanowire array. The reflectance was normalized with respect to a silver (Ag) mirror. For each nanowire diameter, there is a significant dip in reflectance at a particular wavelength. This reflectance dip corresponds to absorption of light at that particular wavelength.

[0054] FIG. **3**B shows simulated results. The computer-simulated results were obtained by finite difference time domain (FDTD) simulations.

[0055] In this case, two different mathematical techniques for solving Maxwell's equations were employed. The first employs a technique of numerically solving for the optical modes (eignenvalues and eigenmodes) of the nanowire array. The second numerical technique employed the FDTD approach wherein a simulated illuminant is propagated through the nanowire array. The FDTD technique is a grid-based numerical modeling method in which time-dependant Maxwell's equations (in partial differential form) are discretized using central-difference approximation to the space and time partial derivations. The resulting finite-difference equations for the electric field vector components are solved at a given instance in time, and then the magnetic field vector components are solved in the next instance of time. This processing is repeated over and over until a steady-state behavior is evolved.

[0056] There is a strong correlation between the dip position for reflectance and the diameter of the nanowires for both the experimental and simulated results. Although, for small diameter nanowire (e.g., less than about 200 nm), the simulation appears to indicate a single mode confinement.

[0057] FIG. **3**C more clearly shows the correlation between the dip positions and nanowire diameter for the experimental results and the simulation results. There is a nearly linear correlation between nanowire diameter and the wavelength for the spectral dip position for reflectance (or the peak for absorption) for the nanowire.

[0058] Experimental data appears to confirm that for certain nanowire spacing the relationship is linear, especially for silicon nanowires. However, without being bound by theory, the inventors do not rule out the possibility of non-linear effects that are small in magnitude and/or that might have a larger impact using different materials or under different fabrication conditions. Simulation, for example, shows that for larger diameter nanowires (greater than about 200 nm), if the spacing is too close, that there may be multimode coupling. As such, the relationship might not be linear.

[0059] FIG. **4** shows a plot of absorption spectra of Si nanowire arrays, according to an embodiment. There is clearly a peak absorption for each nanowire diameter, which corresponds to the spectral dip of reflection shown in FIG. **2**.

[0060] FIG. **5** shows a plot of reflection spectra of Si nanowire arrays, according to an embodiment. This plot shows reflectance spectrum for nanowires of a length of 3 μm, while in FIGS. **2** and **4**, the reflectance spectra shown are for nanowires having a length of 1 μm.

[0061] Both nanowires of 1 and 3 μm lengths, generally showed a spectral dip in reflectance at the same wavelength for the same nanowire diameter. Although, for at least the smaller nanowire diameter of 100 nm, the 3 μm length nanowire experienced a much larger dip in reflectance than the 1 μm length nanowire. The larger length nanowires have a greater volume, which in turn results in higher radiation absorption.

[0062] FIG. **6** shows a plot of absorption spectra of Si nanowire arrays, according to an embodiment. This plots show a comparison of the absorption spectrum for nanowires which are 1 μm and 3 μm in length.

[0063] Both nanowires of 1 and 3 μm lengths, generally showed an increase in absorption at the same wavelength for the same diameter. However, the nanowires of 3 μm length all showed a significant increase over the nanowires of 1 μm in length.

[0064] FIG. **7** shows a plot of absorption and reflection spectra of Si nanowire arrays, according to an embodiment. This plot shows absorption and reflectance spectrum for nanowire arrays having nanowires of 1 μm in length. As is apparent, the absorption and reflection are inversely correlated, with a dip in reflectance corresponding to a peak in absorption at the same wavelength. The substrate also shows a similar phenomenon at the same wavelength. The dip in substrate absorption is actually due to the nanowire absorption at that wavelength (peak). This is atypical behavior for an ordinary silicon wafer.

[0065] FIG. **8** shows an exemplary dry etch method **800** for fabricating an array of vertical nanowires, according to an embodiment.

[0066] In step **801**, a starting material is provided which may include a SOI (silicon on insulator) substrate with an intrinsic epi layer and n+ type layer at the oxide interface. In one instance, the thickness of the i- layer and n+-layer may be 5 μm and 0.5 μm, respectively. In an alternative implementation, the starting substrate may have a lightly doped n-type epi-layer instead of the intrinsic epi-layer layer.

[0067] Next, in step **802**, a shallow p+ type layer is formed by an ion implantation with p-type dopant and minimum energy. Photoresist (PR) is deposited on the p+ layer in step **803** for the preparation of lithography. And, in step **804**, the PR is patterned, for instance, by employing the electron beam (or e-beam) lithography technique.

[0068] Metal deposition commences in step **805**, for example, by either evaporation or sputtering method. One metal that may be used in the fabrication, for example, is aluminum. A lift-off etch method is then employed in step **806** for removing the PR and any unwanted metal on it.

[0069] In step **807**, a dry etch is performed using the metal pattern as a etch mask. For applying the dry etch on the silicon material, etching gases such as, for instance, octafluorocyclobutane (C_4F_8) and sulfur hexafluoride (SF_6) can be used. An array of circular pillars (nanowires) are formed by the etch process. The diameter of the etch mask determines the diameter of the pillars which form each nanowire. In one implementation, the etch mask may be formed of aluminum.

[0070] Since the surfaces of the etched pillars may be rough, a surface treatment may be needed to make surfaces smooth. Thus, in step **808**, the pillar surfaces may be dipped briefly in an etchant, such as, potassium hydroxide (KOH) and a cleaning performed afterwards.

[0071] In some embodiments, a readout circuit may further be fabricated in connection with to the n+ layer, to control and individually address each nanowire in the array. The readout circuit may include a plurality of switching transistors, with one or more switching transistors provided for selectively controlling or addressing each nanowire.

[0072] FIG. **9** shows an exemplary VLS method **900** for fabricating an array of vertical nanowires, according to an embodiment.

[0073] In step **901**, a starting material is provided which may include a SOI or SG substrate with an n+ type layer on top of the SiO_2. Next, in step **902**, PR is deposited for the preparation of the lithography. The PR may patterned in step **903**, for instance, by employing the electron beam lithography technique. Metal deposition commences in step **904** by either evaporation or sputtering method. Metals that may be used in the fabrication are gold or aluminum. In step **905**, a lift-off etch method is employed for removing the PR and any unwanted metal on it.

[0074] Continuing to step **906**, intrinsic type nanowires are grown employing a VLS method. In an alternative embodiment, lightly doped n-type nanowires can be grown instead of the intrinsic nanowires. The diameter of the metal mask (applied in step **904**) determines the diameter of the pillars which form each nanowire grown ins step **906**. In a subsequent step (not shown), a CMP technique may be employed to planarize the top surface and remove the metal.

[0075] In some embodiments, a readout circuit may further be fabricated in connection with to the n+ layer, to control and individually address each nanowire in the array. The readout circuit may include a plurality of switching transistors, with one or more switching transistors provided for selectively controlling or addressing each nanowire.

[0076] FIG. **10** shows a schematic of an image sensor **1000** in accordance with an embodiment.

[0077] The image sensor **1000** generally includes foreoptics **1010**, an array of pixels **1020**, a readout circuit (ROC) **1030**, a processor **1040** and a display device **1050**. A housing **1005** may incorporate one of more the foregoing elements of the sensor **1000**, and protects the elements from excessive/ambient light, the environment (e.g., moisture, dust, etc.), mechanical damage (e.g., vibration, shock), etc.

[0078] Electromagnetic radiation (light) L from a scene S emanates toward the image sensor **1000**. For clarity, only light L from the scene S impinging upon the sensor **1000** is depicted (although it will be appreciated that light L from the scene S radiates in all directions).

[0079] The foreoptics **1010** may be configured to receive the electromagnetic radiation (light) L from the scene S and focus or collimate the received radiation onto the array of pixels **1020**. for instance, foreoptics **1010** may include, for instance, one or more of: a lens, an optical filter, a polarizer, a diffuser, a collimator, etc.

[0080] The array of pixels **1020** may be fabricated from an array of one or more nanowires, as disclosed above (see FIG. **8** or **9**). Each of the pixels may include one or more nanowires having a diameter that corresponds to a predetermined wavelength of electromagnetic radiation (light) L for absorption by the sensor **1000**. At least one of the nanowires in the array may have a different determined diameter than another of the nanowire in the array. This enables multiple wavelength absorption (and detection).

[0081] The ROC **1030** may be connected to the array of pixels **1020** and is configured to receive output from the pixels **1020**. The ROC **1030** may include one or more switching transistors connected to the nanowires for selectively controlling or addressing each pixel of the array **1020**.

[0082] The processor **1040** is configured to receive output from the ROC **1030** and generate an image for viewing on the display device **1050**. The processor **1040** may, in some instances, be configured to provide data scaling, zooming/magnification, data compression, color discrimination, filtering, or other imaging processing, as desired.

[0083] In one embodiment, the processor **1040** may include hardware, such as Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), digital signal processors (DSPs), or other integrated formats. However, those skilled in the art will recognize that the processor **1040** may, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer programs having computer-executable instructions or code running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and/or firmware would be well within the skill of one skilled in the art in light of this disclosure. In addition, those skilled in the art will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment of the subject matter described herein applies regardless of the particular type of computer-readable medium used to actually carry out the distribution.

[0084] The display device **1050** may include any device configured for displaying image data. Exemplary displays may include a cathode ray tube (CRT), plasma, liquid crystal display (LCD), light emitting diode (LED) display, pen chart, etc. In some instance, the display device **1050** may, alternatively or additionally, include a printer or other device for capturing the displayed image. In addition, the image data may be output to an electronic memory (not shown) for storage.

[0085] In some implementations, the image sensor **1000** may be configured as a spectrophotometer to measure intensity of reflection or absorption at one more wavelengths.

[0086] In other implementations, the image sensor **1000** could be configured as a photovoltaic device. By adjusting the spacing of the nanowires, it may be possibly to nearly control all various wavelengths of a spectrum, without any reflection.

[0087] FIG. **11** shows a method **1100** for selectively imaging, according to an embodiment.

[0088] In step **1110**, electromagnetic radiation (light) may be received, for instance, using the image sensor **1000** (FIG. **10**). Next, in step **1120**, the array **1020** of the image sensor **1000** may selectively absorb at least one predetermined wavelength of electromagnetic radiation (light). Method **1100** may be used for multispectral imaging or hyperspectral imaging applications.

[0089] Depending on the construction of the nanowire array, multiple wavelengths of electromagnetic radiation (light) may be absorbed and/or detected by selectively providing nanowires of different diameters. A three-nanowire pixel element may be fabricated. Of course, pixels having additional nanowires are also possible.

[0090] FIG. **12** shows an exemplary pixel **1200** formed of three nanowires R, G, B having different diameters configured to absorb red, green, and blue light, according to an embodiment. For instance, the R, G, B nanowires can have diameters configured to absorb wavelengths of about 650 nm, 510 nm, and 475 nm, respectively (see, e.g., FIG. **3**C).

[0091] An array can be fabricated from a plurality of pixels **1200**. In one implementation, the effective diameter D of the pixel **1200** may be 1 μm or less. A cladding **1210** may, in some instance, surround the pixel **1200** to increase absorption of the nanowires.

[0092] The foregoing detailed description has set forth various embodiments of the devices and/or processes by the use of diagrams, flowcharts, and/or examples. Insofar as such diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof.

[0093] Those skilled in the art will recognize that it is common within the art to describe devices and/or processes in the fashion set forth herein, and thereafter use engineering practices to integrate such described devices and/or processes into data processing systems. That is, at least a portion of the devices and/or processes described herein can be integrated into a data processing system via a reasonable amount of experimentation.

[0094] The herein described subject matter sometimes illustrates different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermediate components.

[0095] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

[0096] All references, including but not limited to patents, patent applications, and non-patent literature are hereby incorporated by reference herein in their entirety.

[0097] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed:

1. A nanowire on a substrate, comprising the nanowire and the substrate, wherein:

the nanowire has a determined diameter;

wherein the determined diameter corresponds to a particular wavelength of electromagnetic radiation for absorption of the nanowire;

wherein the nanowire is essentially vertical to the substrate;.

wherein the nanowire with the determined diameter has an absorption peak of electromagnetic radiation at the particular wavelength.

2. The nanowire according to claim **1**, wherein the diameter of the nanowire is between about 90 and 150 nm for absorbing electromagnetic radiation in the visible spectrum.

3. The nanowire according to claim **2**, wherein the length of the nanowire is between about 1 and 10 μm.

4. The nanowire according to claim **3**, wherein the bandwidth of the particular wavelength of absorption is approximately 50-100 nm.

5. The nanowire according to claim **4**, further comprising a cladding material deposited around the nanowire.

6. A device comprising a plurality of pixels, each of the pixels including at least one nanowire of claim **1**.

7. The device according to claim **6**, wherein at least one of the nanowires in the array has the same or a different determined diameter than another of the nanowires in the array.

8. The device according to claim **7**, wherein the at least one of the nanowires in the array has a different determined diameter than another of the nanowire in the array.

9. The device according to claim **8**, wherein each pixel has a plurality of nanowires, and at least one of the nanowires in the pixel has a different determined diameter than another of the nanowires in the pixel.

10. The device according to claim **9**, wherein there are three nanowires in each pixel.

11. The device according to claim **10**, wherein the three nanowires are configured to absorb red, green and blue light, respectively, in the visible spectrum.

12. The device according to claim **6**, further comprising foreoptics configured to receive the electromagnetic radiation and focus or collimate the receive radiation onto the one or more pixels.

13. The device according to claim **6**, further comprising a readout circuit configured to receive output from the one or more pixels.

14. The device according to claim **13**, further comprising a processor configured to receive an output from the readout circuit and generate an image.

15. The device according to claim **14**, further comprising a display device configured to display the image generated by the processor.

16. The device according to claim **6**, wherein the device is configured as a spectrophotometer or as a photovoltaic device.

17. The device according to claim **6**, wherein the device is configured as an image sensor.

18. A method of imaging comprising receiving electromagnetic radiation; and selectively absorbing, via the device of claim **6**, the particular wavelength of the electromagnetic radiation.

19. The method according to claim **18**, further comprising performing multispectral imaging or hyperspectral imaging.

20. The method according to claim **18**, further comprising detecting multiple wavelengths of electromagnetic energy using nanowires having different diameters.

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