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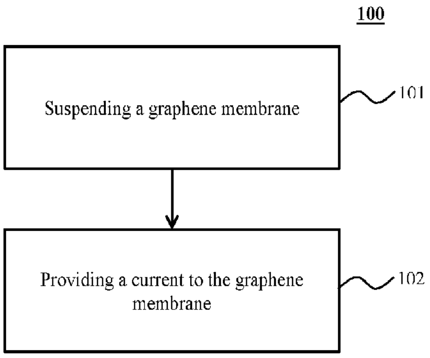

FIGURE 1

(57) Abstract: Methods and systems for emitting light from electrically biased graphene are provided. An exemplary method of generating a light emission from graphene includes suspending a graphene membrane using at least one mechanical clamp and providing a current to the graphene membrane to establish a source-drain bias voltage along the graphene membrane.

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LIGHT EMISSION FROM ELECTRICALLY BIASED GRAPHENE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to United States Provisional Application Nos. 62/096,643 filed December 24, 2014, 62/127,576 filed March 3, 2015, and 62/129,526 filed March 6, 2015, the contents of which are hereby incorporated by reference in their entireties.

NOTICE OF GOVERNMENT SUPPORT

[0002] This invention was made with government support under Contract Number FA9550-09-1-0705 awarded by the Air Force Office of Scientific Research. The government has certain rights in the invention.

BACKGROUND

[0003] Graphene is a two-dimensional (2D) carbon film one atom thick. Graphene can have certain useful properties such as charge carrier mobility, current capacity, thermal conductivity, mechanical stiffness and strength, optical transparency, high melting temperature (~ 5000 K) and high-temperature stability.

[0004] Certain methods for wafer-scale graphene growth have been used in connection with electrodes and optoelectronic applications. For example, graphene-based photonic elements, where a number of graphene optoelectronic devices such as photodetector, optical modulators and plasmonic devices utilize graphene's strong light-matter interaction, can provide ultrafast carrier response over a broad spectral range.

[0005] In gapless graphene, radiative electron-hole recombination processes are not necessarily efficient at least in part due to the rapid energy relaxation that occurs through electron-electron and electron-phonon interactions. However, the above-noted properties of graphene can make it useful for thermal light emission. Thermal radiation from electrically biased graphene supported on a substrate can be limited to the infrared range, and can be inefficient as only a small fraction of the applied energy – about a part in one million – is converted into light radiation. Such limitations can be attributed to heat dissipation through the underlying substrate and a significant hot electron relaxation from extrinsic scattering effects such as charged impurities and surface polar optical phonon interaction, both of which can limit operating temperatures and brightness.

[0006] Thus, there remains a need for improved techniques for emitting light from graphene.

SUMMARY

[0007] The disclosed subject matter provides methods and systems for emitting light from electrically biased graphene.

[0008] In certain embodiments, an exemplary method for generating a light emission from graphene includes suspending a graphene membrane using a circular mechanical clamp and providing a current to the graphene membrane to establish a source-drain bias voltage along the graphene membrane.

[0009] In certain embodiments, the graphene membrane can contain from about one to about ten layers of carbon atoms. The graphene membrane can have a width from about 0.5 μm to about 3 μm. The graphene membrane can be prepared by mechanical exfoliation or chemical vapor deposition (CVD). The source-drain bias voltage can be from about 1 V to about 4 V. The light emission can include photons having energy from about 0.1 eV to about 3 eV. In certain embodiments, the light emission can include photons having an energy from about 1.2 eV to about 3 eV.

[0010] In certain embodiments, the graphene membrane can be suspended over trench having a trench depth. The method can further include modulating the trench depth to alter the intensity of the light emission.

[0011] In certain embodiments, an exemplary method for generating a light emission from graphene includes encapsulating a graphene membrane using a dielectric material and providing a current to the graphene membrane to establish a source-drain bias voltage along the graphene membrane.

[0012] In certain embodiments, the dielectric material can include hexagonal boron nitride. The source-drain bias voltage can be from about 6 V to about 45 V.

BRIEF DESCRIPTION OF THE FIGURES

[0013] **Figure 1.** A method of generating a light emission from graphene according to one exemplary embodiment of the disclosed subject matter.

[0014] **Figure 2.** A method of generating a light emission from graphene according to another exemplary embodiment of the disclosed subject matter.

[0015] **Figure 3.** A system for generating a light emission from graphene according to one exemplary embodiment of the disclosed subject matter.

[0016] **Figure 4.** An alternative clamping arrangement for systems according to the disclosed subject matter.

[0017] **Figure 5.** A system for generating a light emission from graphene according to another exemplary embodiment of the disclosed subject matter.

[0018] **Figure 6.** A schematic illustration of a process for fabricating suspended graphene membranes in a circular mechanical clamp.

[0019] **Figure 7.** Plots of (A) a current-voltage (I-V) curve; (B) simulated thermal conductivity; and (C) a temperature profile corresponding to electron temperature for monolayer graphene.

[0020] **Figure 8.** An example setup for measuring Raman spectra and light emissions for suspended graphene.

[0021] **Figure 9.** Spectra of visible light emissions from (A) monolayer graphene and (B) tri-layer graphene at various source-drain bias voltages.

[0022] **Figure 10.** A plot of intensity versus source-drain bias voltage for one example graphene membrane.

[0023] **Figure 11.** (A) Plot of simulated intensity as a function of trench depth and photon energy; and (B) a spectra of visible light emissions at various trench depths.

[0024] **Figure 12.** Current-voltage (I-V) curves and images of visible light emissions from encapsulated graphene membranes (A) in a vacuum and (B) under ambient conditions.

DETAILED DESCRIPTION

[0025] The presently disclosed subject matter provides techniques for generating a light emission from graphene. In certain embodiments, the disclosed subject matter provides methods and systems for emitting light from a graphene membrane by providing a current to the graphene membrane.

[0026] Figure 1 is a schematic illustration of an exemplary method for generating a light emission. In certain embodiments, a method 100 includes suspending a graphene membrane 101. For example, the graphene membrane can be suspended using at least one mechanical clamp.

[0027] The method 100 can further include providing a current to the graphene membrane 102. In certain embodiments, electrical current can be introduced at one end of the graphene membrane, and a source-drain bias voltage can be established across the graphene membrane. For example, an electric field can be applied to the graphene membrane. The electric field can have a strength of about 0.01 V/μm to about 10 V/μm, *e.g.*, from about 0.05 V/μm to about 5 V/μm, from about 0.1 V/μm to about 3 V/μm, or from about 0.2 V/μm to about 1 V/μm. In certain embodiment, the electric field has a strength from about 0.4 V/μm to about 0.5 V/μm.

[0028] As used herein, the term “about” or “approximately” means within an acceptable error range for the particular value as determined by one of ordinary skill in the art, which will depend in part on how the value is measured or determined, *i.e.*, the limitations of the measurement system. For example, “about” can mean a range of up to 20%, up to 10%, up to 5%, and or up to 1% of a given value.

[0029] The source-drain bias voltage (V_{SD}) can be correlated to electric field strength (F). For example, the relationship can be represented by Formula 1, where L is the length of the graphene membrane.

$$F = V_{SD} / L \tag{1}$$

[0030] In certain embodiments, the source-drain bias voltage can be from about 0.1 V to about 10 V, from about 0.5 V to about 5 V or from about 1 V to about 4 V. In certain embodiments, the source-drain bias voltage can be repeatedly swept up and down, with the maximum voltage increasing each cycle until the desired source-drain bias voltage is established.

[0031] Additionally, providing a current can cause the graphene membrane to heat to temperatures greater than about 1200 K, *e.g.*, greater than about 1400 K, greater than about 1600 K, greater than about 1800 K, or greater than about 2000 K. Under these conditions, the thermal conductivity of graphene can decrease. As a result of the decreased thermal conductivity, heat and electrons can pool at the center of the graphene membrane. The electrons can reach temperatures greater than about 2200 K, *e.g.*, greater than about 2400 K, greater than about 2600 K, or greater than about 2800 K.

[0032] Umklapp phonon-phonon scattering can decrease the thermal conductivity of graphene at high temperatures (*e.g.*, greater than about 1500 K). In a suspended graphene membrane, there is no heat dissipation to a substrate so the lattice temperature of the acoustic phonons (T_{ap}) can be much higher compared to temperatures in a supported graphene membrane. As a result, the temperatures of optical phonons (T_{op}) and electrons (T_e) are also increased. T_{op} (which can be assumed to be equal to T_e because optical phonons and electrons are in equilibrium) is related to T_{ap} as represented by Formula 2.

$$T_{op} = T_{ap} + \alpha(T_{ap} - T_0) \qquad (2)$$

[0033] In Formula 2, α is a constant determined by the current and source-drain bias voltage and T_0 is the environmental temperature. Carrier mobility (μ) and thermal conductivity (κ) are inversely related to T_e and T_{ap}, as shown in Formulas 3 and 4.

$$\mu(T_e) = \mu_0(T_0/ T_e)^{\beta} \qquad (3)$$

$$\kappa(T_{ap}) = \kappa_0(T_0/ T_{ap})^{\gamma} \qquad (4)$$

[0034] As shown by Formulas 2-4, carrier mobility and thermal conductivity will decrease as T_{ap} increases. Therefore, carrier mobility and thermal conductivity are reduced when the graphene membrane is suspended and heat dissipation is reduced, compared to when the graphene membrane is supported on a substrate.

[0035] Under these conditions, the graphene membrane can emit photons. Because the hot electrons are centralized in the graphene membrane, the emitted photons can be localized at a point in the center of the graphene membrane. The photons can have an energy from about 0.1 eV to about 3 eV, *i.e.*, can emit light on the infrared or visible spectrum. In certain embodiments, the photons can have an energy from about 1.2 eV to about 3 eV, *i.e.*, can emit light on the visible spectrum.

[0036] Figure 2 is a schematic illustration of another exemplary method for generating a light emission. The method 200 can include encapsulating a graphene membrane in a dielectric material 201. For example, the dielectric material can be hexagonal boron nitride.

[0037] The method 200 can further include providing a current to the graphene membrane 202. In certain embodiments, electrical current can be introduced at one end of the graphene membrane, and a source-drain bias voltage can be established across the graphene membrane. The source-drain bias voltage can be from about 1 V to about 50 V, *e.g.*, from about 6 V to about 45 V.

[0038] Figure 3 provides a schematic illustration of an exemplary system for generating a light emission. In certain embodiments, a system 300 includes a graphene membrane 301 and mechanical clamp 302.

[0039] The graphene membrane can have a certain number of layers of carbon atoms. For example, the graphene membrane can have from about 1 to about 100 layers. In certain embodiments, the graphene membrane can be monolayer, *i.e.*, a single layer of carbon atoms. In other certain embodiments, the graphene membrane can have from about 2 to about 10 layers.

[0040] In certain embodiments, the graphene membrane can have a width from about 0.5 µm to about 15 µm, *e.g.*, from about 1 µm to about 10 µm, or from about 2 µm to about 7 µm. The graphene membrane can have a length from about 1 µm to about 40 µm, *e.g.*, from about 2 µm to about 30 µm, or from about 3 µm to about 20 µm.

[0041] In certain embodiments, the graphene membrane can be prepared by mechanical exfoliation. Alternatively, the graphene membrane can be prepared by chemical vapor deposition (CVD). Alternatively, the graphene membrane can be prepared by physical vapor deposition (PVD).

[0042] The graphene membrane can be suspended using one or more mechanical clamps. For example, the graphene membrane can be suspended within a circular or elliptical mechanical clamp (*see* Figure 3). A circular or elliptical mechanical clamp can provide a geometry that increases the mechanical stability of the graphene by enforcing structural rigidity onto the graphene membrane. Additionally, a circular or elliptical mechanical clamp can provide a bypass for the current at high strength electric fields. In certain embodiments, a circular mechanical clamp can have a diameter of about 2 μm. An elliptical mechanical clamp can have a length of about 4 μm and a width of about 2.5 μm. In alternative embodiments, the graphene membrane can be suspended between two mechanical clamps, where each clamp holds an opposite end of the graphene membrane (*see* Figure 4).

[0043] In certain embodiments, the mechanical clamp can be made of a polymeric or dielectric material. In particular embodiments, the mechanical clamp is made using SU-8 photoresist. Alternatively, the mechanical clamp can be made of a semiconducting or metallic material. The clamp(s) can include one or more electrodes. By way of example, the electrodes can be made of a conductive material, such as gold (Au), silver (Ag), copper (Cu), or chromium (Cr).

[0044] In certain embodiments, the graphene membrane can be suspended over a substrate. For example, the graphene membrane can be suspended over a trench within a substrate. For example, the substrate can be a material having electrical properties, *e.g.*, silicon or silicon dioxide. The trench can have a depth from about 80 nm to about 1200 nm.

[0045] In certain embodiments, the trench depth can affect the spectrum of the light emitted from the graphene. For example, light can be reflected from the substrate and create constructive or destructive interference with the light emitted from the graphene membrane. As an example, the destructive interference can be approximated by Formula 5, where D represents the trench depth.

$$\Delta(D) = (1242.4\ \text{nm} / 2D)\ \text{eV} \qquad (5)$$

[0046] Using Formula 5, radiation having a particular wavelength can be selectively enhanced by altering the trench depth of the substrate. For example, radiation intensity can be increased by up to about 100% by using constructive interference. Alternatively or additionally, radiation intensity can be decreased by up to about 40% by using destructive interference. Selectively enhancing radiation has potential utility in the field of optoelectronics.

[0047] In certain embodiments, two or more suspended graphene membranes can be arranged in an array, such that the graphene membranes are independently programmable.

[0048] A person having ordinary skill in the art will recognize that alternative arrangements of graphene membranes can be used to achieve this result. For example, graphene membranes can be encapsulated in a dielectric material. In certain embodiments, the graphene membrane can be encapsulated in hexagonal boron nitride (hBN). For example, the graphene membrane can be encapsulated with 2D or 3D hBN.

[0049] It should be noted that encapsulated graphene membranes can emit light under ambient conditions, unlike suspended graphene membranes which must be operated below a burn temperature or in a vacuum or inert gas. Encapsulation can allow the graphene membranes to emit light under ambient conditions, and at temperatures as high as 3000 K. For the purpose of illustration, Figure 5 provides a schematic illustration of an exemplary system for generating a light emission from an 2D encapsulated graphene membrane. The graphene membrane 502 can be sandwiched between two layers, *e.g.*, an encapsulation layer 501 and a substrate 503. This structure can provide a seal to prevent the graphene membrane from burning at high temperatures. Additionally, the encapsulation layers can provide a path for heat, to allow fast cooling of the graphene membrane. Because encapsulated graphene membranes can emit light under ambient conditions and are thin and transparent, they can be integrated with a photonic circuit or other optical component, such as an optical cavity, photonic crystal, or flexible and transparent substrate.

[0050] The methods and systems of the presently disclosed subject matter can provide advantages over certain existing technologies, including decreased heat dissipation, and thus efficient conversion of electrical energy to light radiation. For example, compared to certain prior technologies, there is decreased heat dissipation between suspended graphene and a substrate. Additionally, the decreased thermal conductivity at high temperatures reduces the amount of heat dissipation within the graphene membrane. This increased conversion of electrical energy can result in light emissions on the visible spectrum. An additional advantage includes mechanical and thermal stability of the graphene membrane over repeated light emissions.

[0051] EXAMPLES

[0052] The presently disclosed subject matter will be better understood by reference to the following Examples. These Examples are provided as merely illustrative of the disclosed methods and systems, and should be considered as a limitation in any way.

[0053] Example 1: Preparing suspended graphene membranes using mechanically exfoliated graphene.

[0054] This Example describes one exemplary method of making an atomically thin suspended graphene membranes with mechanically exfoliated graphene.

[0055] Kish graphene was transferred onto an SiO_2/Si substrate. PMMA (polymethyl methacrylate, 950 K, C4) was spin-coated onto the graphene at 4500 rpm, followed by a baking process at 180 °C for 5 minutes. The PMMA was formed into an etch mask by exposing PMMA on unwanted areas of graphene using electron beam lithography. The graphene was patterned by O_2 etching using the PMMA mask. The PMMA was removed using acetone to reveal the patterned graphene array including multiple graphene membranes.

[0056] To attach the graphene membranes to the mechanical clamps, PMMA was again spin-coated onto the graphene membranes using the same procedure. The PMMA with graphene was separated from the SiO_2/Si substrate in 10 wt-% potassium hydroxide (KOH) solution. The PMMA with graphene was rinsed with water and dried at room temperature under nitrogen. The graphene was aligned onto a substrate having pre-formed trenches (with depths from 300 to 1000 nm) and each end of the graphene membrane was adhered to gold (Au) electrodes on the substrate. The PMMA was removed by an acetone wash and isopropanol rinse. The suspended graphene membranes were dried in a critical point drying process.

[0057] **Example 2: Preparing suspended graphene membranes using chemical vapor deposition (CVD) graphene.**

[0058] This Example describes an exemplary method of making an atomically thin suspended graphene membranes with chemical vapor deposition (CVD) graphene.

[0059] CVD graphene was transferred onto an SiO_2/Si substrate and patterned as described in Example 1. Electrodes were patterned by electron beam lithography and metals (Cr/Au at 20/80 nm) were deposited onto the electrodes. SiO_2 was removed from the graphene using buffered oxide etchants (BOE) or hydrofluoric acid (HF) and rinsed with D.I. water. The suspended graphene membranes were dried in a critical point drying process.

[0060] **Example 3: Preparing graphene membranes with circular mechanical clamps.**

[0061] This Example describes one method of fabricating clamped graphene membranes using a circular mechanical clamp.

[0062] Figure 6 depicts a flow chart showing one exemplary method of fabricating circularly-clamped graphene membranes. A local gate can be layered onto a silicon substrate and coated with SiO_2 using plasma-enhanced chemical vapor deposition (PECVD) 601. Graphene can be transferred onto a top surface and patterned 602, *e.g.*, using the methods described in Examples 1 and 2. Electrodes can be applied to either end of the graphene 603. The top surface of the electrodes can be coated with SU-8 photoresist 604. Then, buffered oxide etchants (BOE) can be used to remove some of the SiO_2, to reveal a suspended graphene membrane 605. Using this method, the SU-8 photoresist can form a circular clamp to provide mechanical support for the graphene membrane.

[0063] **Example 4: Thermal simulation of monolayer and tri-layer graphene membranes.**

[0064] Thermal conductivity and photon energy can depend on the number of layers in a suspended graphene membrane. Additionally, as discussed with reference to Formulas 2-4, thermal conductivity can decrease as the lattice temperature increases.

[0065] In the case of monolayer graphene, and with reference to Formula 3, the minimum carrier mobility (μ) can be taken as 10000 $cm^2V^{-1}s^{-1}$ and β can be 1.7. With reference to Formula 4, thermal conductivity (κ_0) can be taken as 2700 $Wm^{-1}K^{-1}$ and γ can be 1.92. Additionally, it is assumed that T_0 is 300 K. Using these assumptions, the source-drain bias voltage (V_{SD}) for different simulations of monolayer graphene membranes can be calculated, as shown in Table 1.

Table 1. Source-drain bias voltage in suspended monolayer graphene membranes.

V_{SD} (V)	μ ($cm^2V^{-1}s^{-1}$)	Width (μm)	T_{op} (K)	T_{ap} (K)
2.7	10000, 10250	0.784, 0.765	2634, 3039	1979, 2270
2.6	10000, 11500	0.796, 0.705	1802, 3016	1380, 2254
2.5	10000, 12700	0.87, 0.705	1381, 2951	1077, 2200
2.3	10000, 12700	1.15, 0.92	975, 1474	785, 1144
2.0	10000, 12700	1.63, 1.28	665, 838	562, 687
1.6	10000, 12700	1.93, 1.52	471, 525	423, 462

[0066] Furthermore, Figure 7A provides the current (I_D)-voltage (V_{SD}) curve for monolayer graphene. Figure 7B simulates the thermal conductivity of monolayer graphene based on the current-voltage curve and Formulas 3 and 4. Figure 7C provides a temperature profile of the optical phonon temperature (which is assumed to be equal to the electron temperature) of monolayer graphene across the length of the graphene membrane, and for various source-drain bias voltages. As shown in Figures 7B and 7C, where the temperature is greatest (*i.e.*, at the center of the graphene membrane), the thermal conductivity is lowest.

[0067] In the case of tri-layer graphene, and with reference to Formula 3, the minimum carrier mobility (μ) can be taken as 2200 $cm^2V^{-1}s^{-1}$ and β can be 1.155. With reference to Formula 4, thermal conductivity (κ_0) can be taken as 1900 $Wm^{-1}K^{-1}$ and γ can be 1. Additionally, it is assumed that T_0 is 300 K. Using these assumptions, the source-drain bias voltage (V_{SD}) for different simulations of tri-layer graphene membranes can be calculated, as shown in Table 2.

Table 2. Source-drain bias voltage in suspended tri-layer graphene membranes.

V_{SD} (V)	μ ($cm^2V^{-1}s^{-1}$)	Width (μm)	T_{op} (K)	T_{ap} (K)
3.65	2220, 2500	1.73, 1.63	2425, 2866	1934, 2275
3.6	2220, 2500	1.78, 1.67	2284, 2741	1826, 2177
3.55	2220, 2500	1.82, 1.71	2240, 2650	1792, 2106
3.5	2220, 2500	1.89, 1.78	2157, 2508	1729, 1999
3.45	2220, 2500	2.02, 1.89	2017, 2412	1620, 1924
3.4	2220, 2500	2.17, 2.05	1989, 2333	1600, 1865
3.35	2220, 2500	2.62, 2.46	1902, 2212	1533, 1771
3.3	2220, 2500	2.8, 2.64	1852, 2124	1494, 1704
3.25	2220, 2500	2.9, 2.72	1744, 2049	1410, 1645
3	2220, 2500	3, 2.82	1447, 1645	1182, 1334

[0068] These data show simulate maximum and minimum widths and thermal conductivities for monolayer and tri-layer suspended graphene membranes across multiple source-drain bias voltages.

[0069] **Example 5: Measuring intensity of emitted light.**

[0070] In this Example, the intensity of light emitted from suspended graphene is observed and measured.

[0071] Figure 8 provides one example setup for measuring Raman spectra and light emissions from a graphene sample 801. Both the Raman spectra and light emissions can be measured using the a laser 802, *e.g.*, the 514.5 nm line of an Ar ion laser or the 441.6 nm line of a He-Cd laser with a power of 500 μW. The laser beam can be focused on the sample, *e.g.*, using an objective lens 803 (*e.g.*, 50x, NA 0.42, WD 20.3 mm). A spectrometer 804 (*e.g.*, Jobin-Yvon Triax 320, 1200 groove/mm) and charge-coupled device array (*e.g.*, Andor iDus DU420A BR-DD) can be used to record the spectra. Figures 9A-B provide spectra of visible light emissions from (A) monolayer graphene and (B) tri-layer graphene at various source-drain bias voltages.

[0072] Additionally, the intensity can be plotted against the source-drain bias voltage to determine a critical voltage for maximum intensity. In one particular example, as shown in Figure 10, as the source-drain bias voltage increased, so did the intensity, until a critical voltage of 5 V. Additionally, it was observed that the emitted light was wavelength-selective, *i.e.*, had zero intensity at certain wavelengths on the visible light spectrum.

[0073] **Example 6: Modulating trench depth on the substrate.**

[0074] This Example illustrates modulating trench depth, where the graphene membrane is suspended over a substrate containing trenches.

[0075] With reference to Formula 5, trench depth can be modulated to alter the intensity of radiation reflected off the substrate. In Figure 11A, the simulated intensity of radiation is presented as a function of trench depth and photon energy. The electron temperature is assumed to be constant at 2850 K. In Figure 11A, the solid lines show constructive interference and the dashed lines show destructive interference. Figure 11B shows the spectra of the emitted light at various trench depths. Depending on the trench depth, the intensity of the light is highest at different photon energies (*i.e.*, different wavelengths). These data illustrate how trench depth can be used to modulate the intensity of the emitted light from graphene.

[0076] **Example 7: Visible light emissions from encapsulated graphene under ambient conditions.**

[0077] This Example demonstrates visible light emissions from graphene encapsulated in hexagonal boron nitride (hBN) under ambient conditions.

[0078] A current was applied to a graphene membrane encapsulated in hBN within a vacuum. At a source-drain bias voltage of 46 V, a visible light emission was observed. Figure 12A shows an image of the visible light emission and the current-voltage curve for the encapsulated graphene membrane in a vacuum.

[0079] Under ambient conditions, a current was also applied to a second graphene membrane encapsulated in hBN. At a source-drain bias voltage of 30 V, a visible light emission was observed. Figure 12B shows an image of the visible light emission and the current-voltage curve for the encapsulated graphene membrane under ambient conditions.

[0080] These data show that an encapsulated graphene membrane can emit visible light under ambient conditions.

* * *

[0081] In addition to the various embodiments depicted and claimed, the disclosed subject matter is also directed to other embodiments having other combinations of the features disclosed and claimed herein. As such, the particular features presented herein can be combined with each other in other manners within the scope of the disclosed subject matter such that the disclosed subject matter includes any suitable combination of the features disclosed herein. The foregoing description of specific embodiments of the disclosed subject matter has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosed subject matter to those embodiments disclosed.

[0082] It will be apparent to those skilled in the art that various modifications and variations can be made in the methods and systems of the disclosed subject matter without departing from the spirit or scope of the disclosed subject matter. Thus, it is intended that the disclosed subject matter include modifications and variations that are within the scope of the appended claims and their equivalents.

WHAT IS CLAIMED IS:

1. A method for generating a light emission from graphene, comprising:
    a. suspending a graphene membrane using a circular mechanical clamp; and
    b. providing a current to the graphene membrane to establish a source-drain bias voltage along the graphene membrane.
2. The method of claim 1, wherein the graphene membrane comprises from about one to about ten layers of carbon atoms.
3. The method of claim 1, wherein the graphene membrane has a width from about 0.5 μm to about 3 μm.
4. The method of claim 1, wherein the graphene membrane is prepared by one of mechanical exfoliation and chemical vapor deposition.
5. The method of claim 1, wherein the source-drain bias voltage is from about 1 V to about 4 V.
6. The method of claim 1, wherein the light emission comprises photons having an energy from about 0.1 eV to about 3 eV.
7. The method of claim 1, wherein the light emission comprises photons having an energy from about 1.2 eV to about 3 eV.
8. The method of claim 1, wherein the graphene membrane is suspended over trench having a trench depth and the method further comprises modulating the trench depth to alter an intensity of the light emission.
9. A method for generating a light emission from graphene, comprising:
    a. encapsulating a graphene membrane using a dielectric material; and
    b. providing a current to the graphene membrane to establish a source-drain bias voltage along the graphene membrane.
10. The method of claim 9, wherein the dielectric material comprises hexagonal boron

nitride (hBN).

11. The method of claim 9, wherein the source-drain bias voltage is from about 6 V to about 45 V.

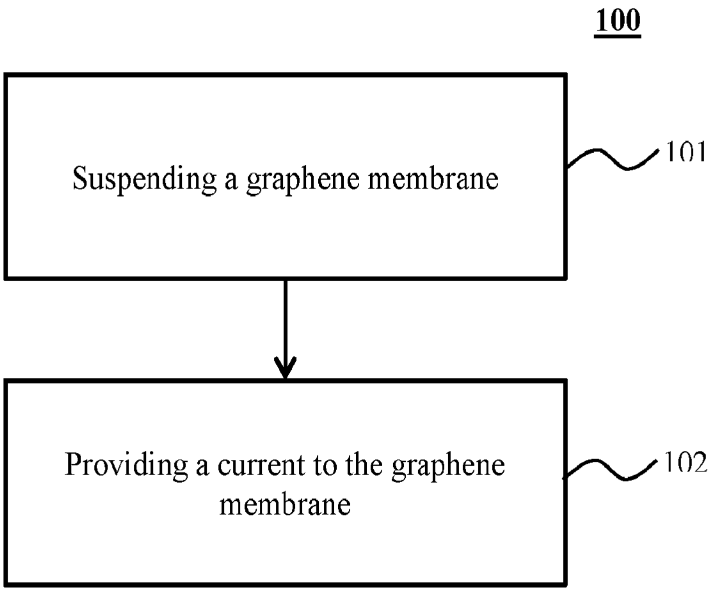

100
Suspending a graphene membrane
101
Providing a current to the graphene membrane
102

FIGURE 1

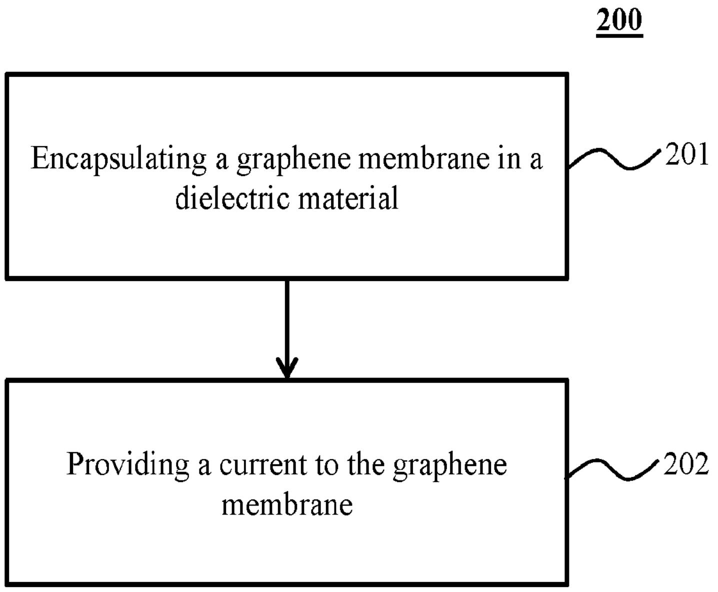
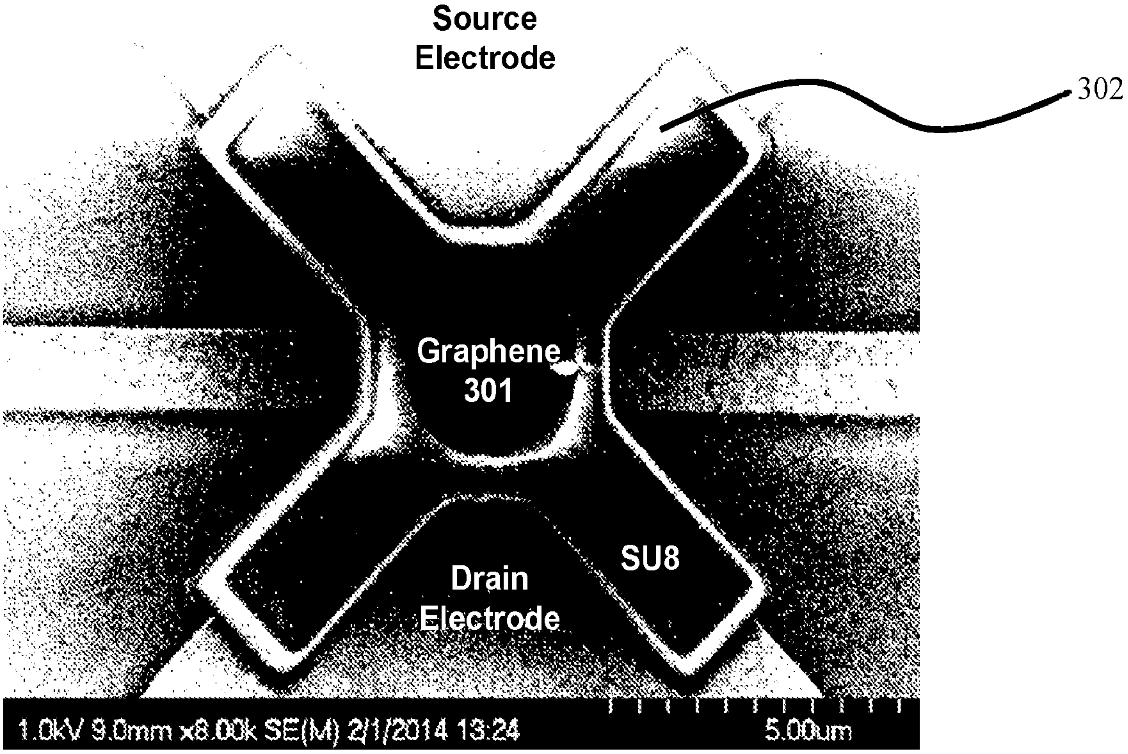

200
Encapsulating a graphene membrane in a dielectric material
201
Providing a current to the graphene membrane
202

FIGURE 2

FIGURE 3


Source
Electrode
302
Graphene
301
SU8
Drain
Electrode
1.0kV 9.0mm x8.00k SE(M) 2/1/2014 13:24
5.00um

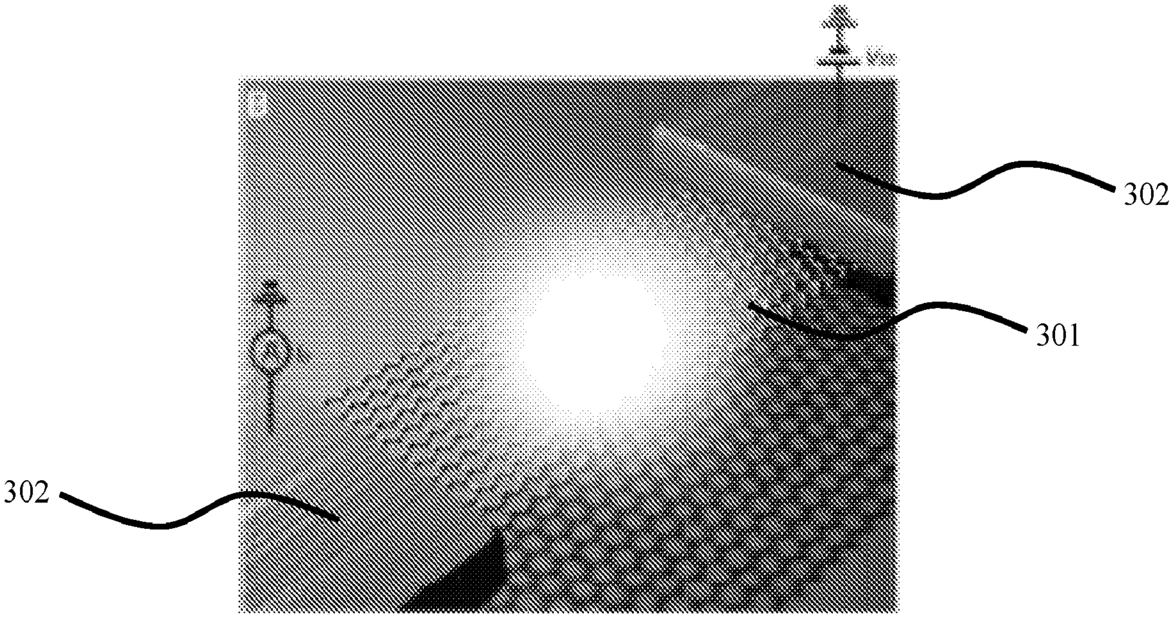


FIGURE 4

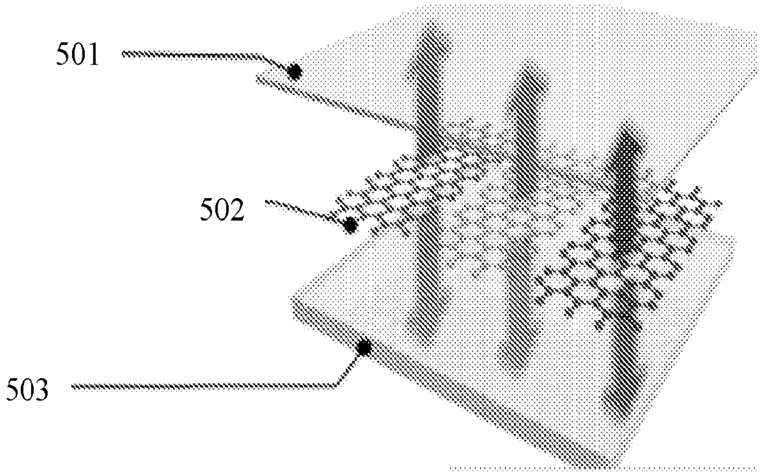
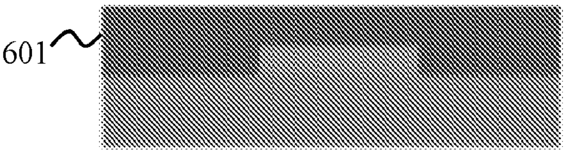
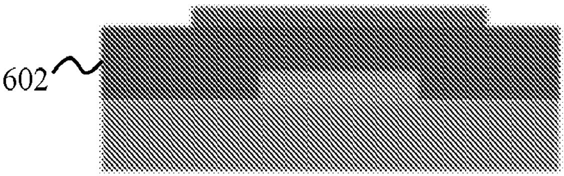


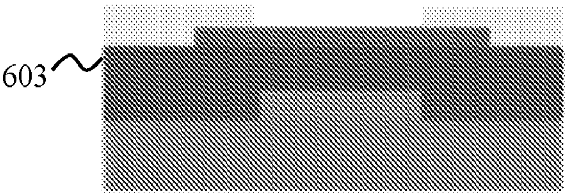
FIGURE 5



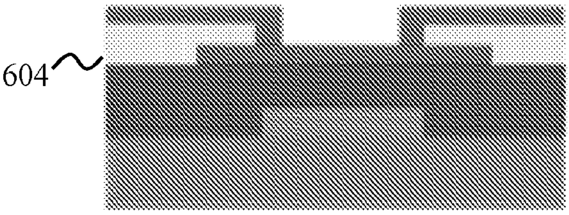
(a) Local Gate with SiO_2 Cladding & CMP



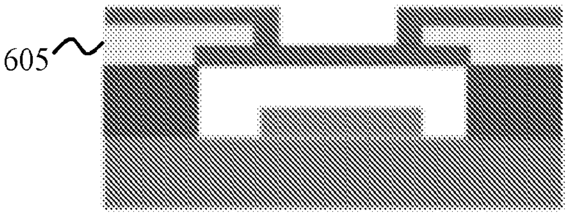
(b) Graphene Transfer & Patterning



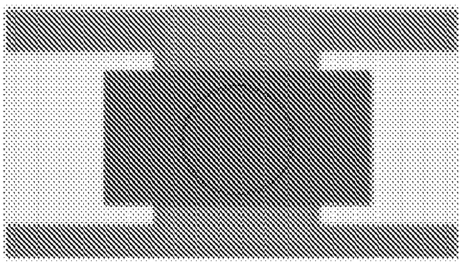
(c) Source & Drain Electrodes



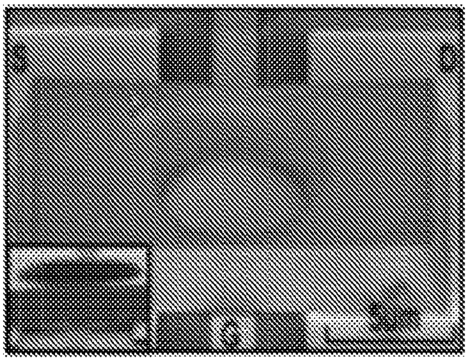
(d) Circular Clamping Using SU-8



(e.1) BOE Release



(e.2) BOE Release *top-view*



(f) False Color SEM

▨ PECVD SiO_2

▨ SU-8

▨ Local Gate

▨ Graphene

▨ Silicon

▨ Source/Drain

FIGURE 6

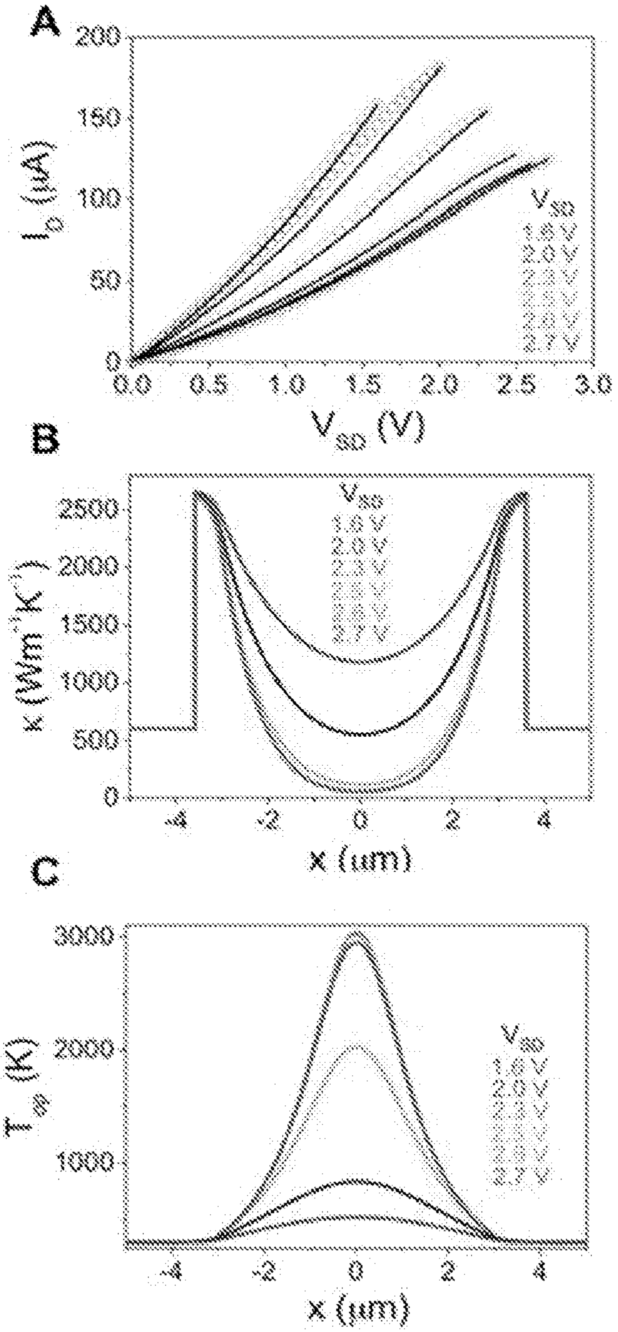

A
200
150
100
50
0
I_D (μA)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
V_{SD} (V)
V_{SD}
1.6 V
2.0 V
2.3 V
2.5 V
2.6 V
2.7 V
B
2500
2000
1500
1000
500
0
κ (Wm^{-1}K^{-1})
-4 -2 0 2 4
x (μm)
V_{SD}
1.6 V
2.0 V
2.3 V
2.5 V
2.6 V
2.7 V
C
3000
2000
1000
T_{ep} (K)
-4 -2 0 2 4
x (μm)
V_{SD}
1.6 V
2.0 V
2.3 V
2.5 V
2.6 V
2.7 V

FIGURE 7

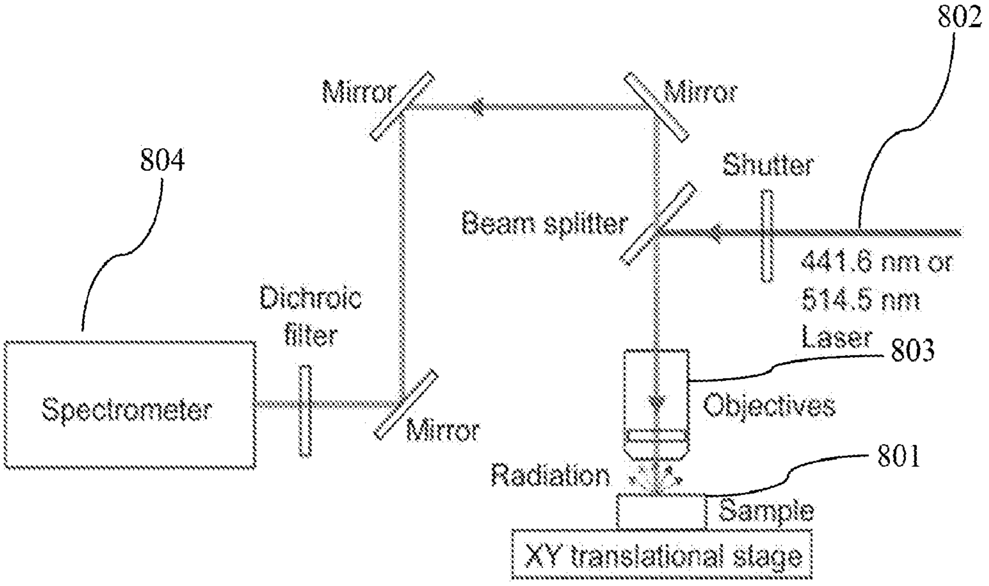
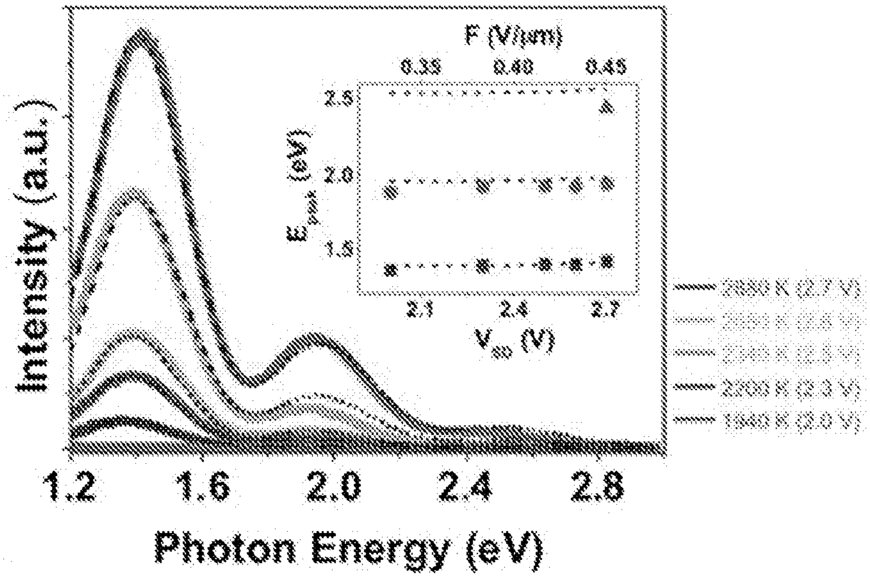

802
Mirror
Mirror
804
Shutter
Beam splitter
441.6 nm or
514.5 nm
Laser
Dichroic
filter
803
Spectrometer
Objectives
Mirror
801
Radiation
Sample
XY translational stage

FIGURE 8

FIGURE 9A



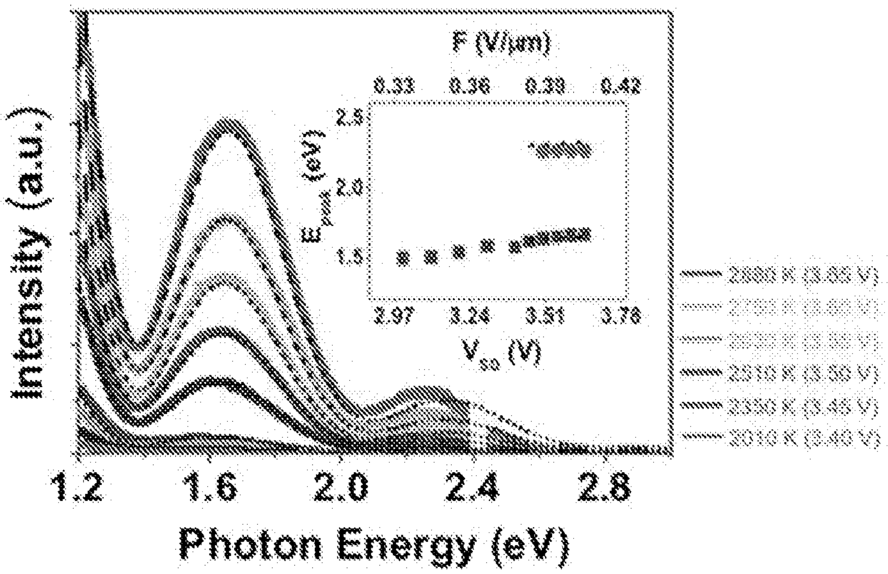


FIGURE 9B

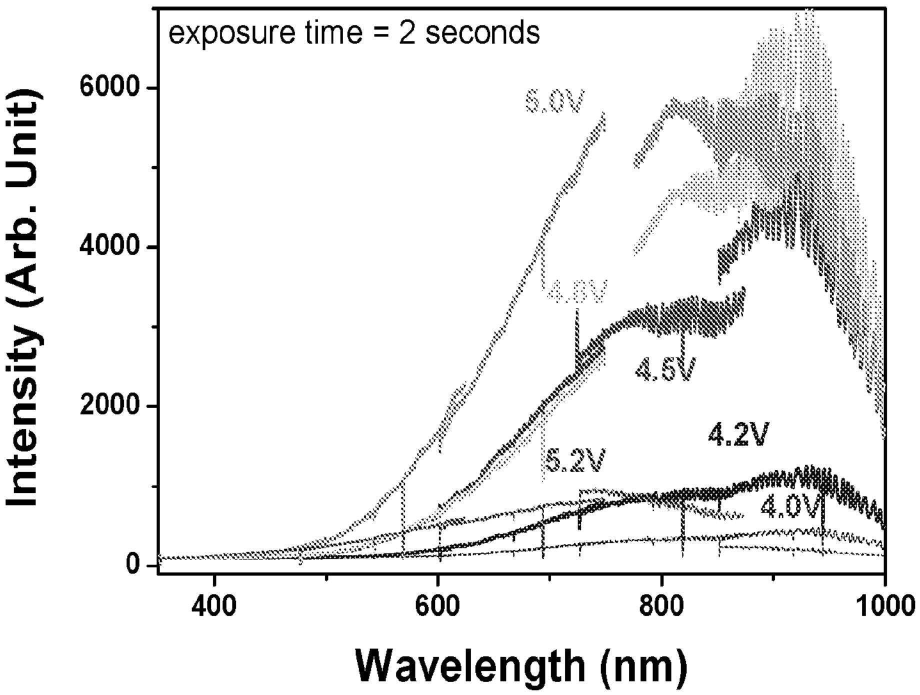
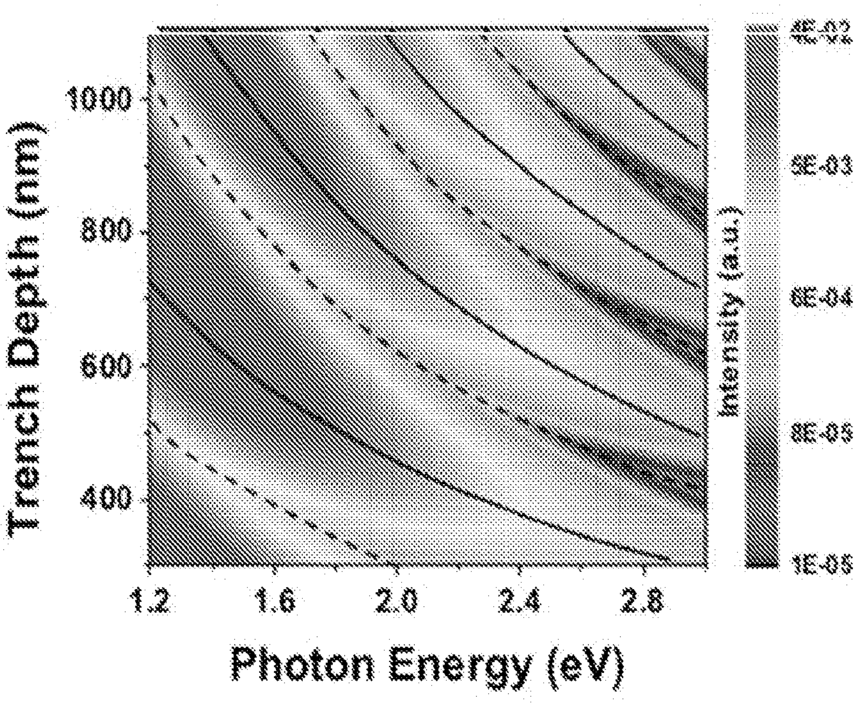

exposure time = 2 seconds
Intensity (Arb. Unit)
Wavelength (nm)
0
2000
4000
6000
400
600
800
1000
5.0V
4.8V
4.5V
5.2V
4.2V
4.0V

FIGURE 10

FIGURE 11A


Trench Depth (nm)
1000
800
600
400
1.2
1.6
2.0
2.4
2.8
Photon Energy (eV)
Intensity (a.u.)
4E-02
5E-03
6E-04
8E-05
1E-05

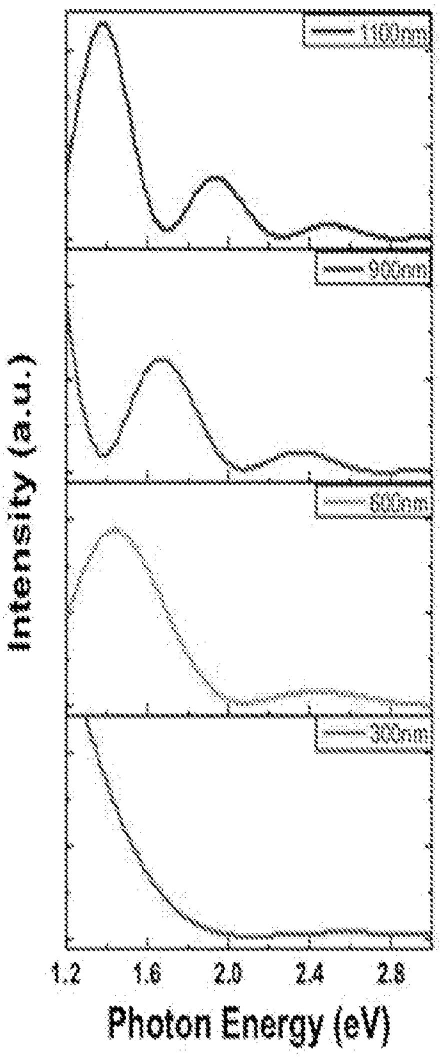
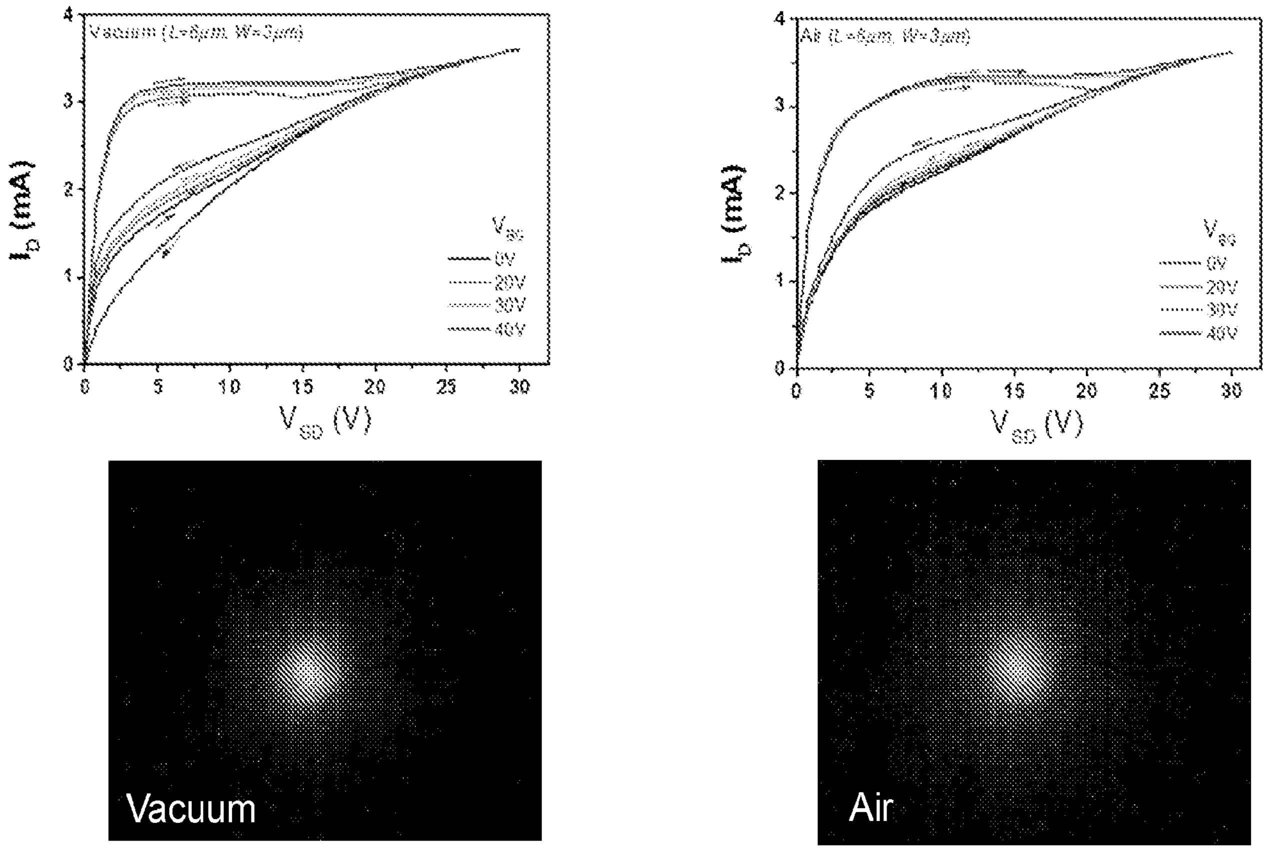

1100nm
900nm
600nm
300nm
Intensity (a.u.)
1.2
1.6
2.0
2.4
2.8
Photon Energy (eV)

FIGURE 11B

FIGURE 12


Vacuum (L=6μm, W=3μm)
I_D (mA)
V_SD (V)
V_SG
0V
20V
30V
40V
0
1
2
3
4
0
5
10
15
20
25
30
Vacuum
Air (L=6μm, W=3μm)
I_D (mA)
V_SD (V)
V_SG
0V
20V
30V
40V
Air

A

B