gases present in the processing chamber can be provided as will be evident to one familiar with CVD systems.

[0034] The method further includes subjecting the substrate to a flow of a carbon precursor for a predetermined period of time (218). As an example, the carbon precursor can be one of several gaseous species, including methane, acetylene, cyclohexane, toluene, PMMA, polystyrene, benzene, a combination thereof, or the like. After growth, the substrate is cooled and removed from the growth chamber.

[0035] It should be appreciated that the specific steps illustrated in FIG. 2 provide a particular method of growing graphene according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 2 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0036] Utilizing embodiments of the present invention as discussed in relation to FIG. 2, graphene growth on copper foils has been performed at growth temperatures ranging from about 800 °C to about 1,000 °C. Accordingly, growth at temperatures lower than conventional grapheme growth temperatures are provided by some embodiments of the present invention. FIG. 3 shows data (i.e., spectral data collected using Raman spectroscopy) for a graphene film grown using conventional techniques (plot A) and for a graphene film grown using the method discussed in relation to FIG. 2 (plot B). As illustrated in FIG. 3, the graphene grown on single crystal copper at 1,000 °C (plot A) and the graphene grown on copper foil using a low temperature plasma clean process followed by 800 °C growth (plot B) are characterized by the two sharp features of the Raman spectra at ~ 1580 and 2700 cm^{-1} and the absence of a pronounced defect peak at ~1350 cm^{-1}, indicating that embodiments of the present invention produce a high quality graphene film utilizing the plasma assist conditions described herein.

[0037] In some embodiments utilizing a two-step clean/growth process, the substrate is maintained in an inert environment during the time between the plasma treatment used to clean the surface and the exposure to the carbon source during growth. The ability to keep the substrate in this inert environment (e.g., maintain the process under vacuum) enables the

treated surface to remain in the treated state since copper quickly forms an oxide when exposed to oxygen.

[0038] Utilizing the system illustrated in FIG. 1, graphene was formed as follows. An RF plasma was formed in the processing chamber in the vicinity of the substrate (a copper foil) using an Evenson cavity with an input power of 40 W for a period of 15 minutes with a flow rate of hydrogen of 2 sccm. During the application of the RF plasma, a significant amount of copper was observed in the vicinity of the microwave cavity, indicating that the RF plasma was etching or otherwise removing copper from the substrate. The RF plasma was extinguished and the substrate was heated under a flow of 2 sccm of hydrogen at 42 mTorr to 800 °C.

[0039] Subsequently, a flow of CH_4 was added at a flow rate of 35 sccm and the total pressure in the processing chamber was increased to 500 mTorr. After 15 minutes of these conditions, the substrate was cooled under the same flow and pressure. Upon cooling, the substrate was removed and Raman spectroscopy was performed (plot A in FIG. 5), demonstrating that graphene had been formed on the backside of the substrate adjacent the susceptor, which can also be referred to as a sample holder. This procedure was repeated at growth temperatures of 700 °C and 600 °C with similar results. In addition to single layers of graphene, embodiments of the present invention are useful for forming other isomorphs of carbon, including multi-layer grapheme, carbon nanotubes (e.g., using a VLS process), diamond like carbon, graphite, amorphous carbon, Bucky Balls, and the like. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0040] FIG. 4 is a simplified flowchart illustrating a method of growing graphene according to another embodiment of the present invention. The method shares some similar processes with the graphene growth process associated with the Raman spectra in plot A of FIG. 5 and the description related to this high temperature (e.g., 800 °C) growth process is applicable to the growth process illustrated in FIG. 4 as appropriate.

[0041] The method includes providing a substrate in a processing chamber at a reduced pressure environment (410). In an embodiment, the substrate can be a copper foil or other suitable substrate and the reduced pressure environment can be a vacuum environment in the processing chamber 110 illustrated in FIG. 1, for example, pressures ranging from about 1 to about 500 mTorr. The pressure can be less than 500 mTorr in some implementations. In some embodiments, the method also includes introducing a flow of hydrogen gas into the processing chamber (412), for example, at a flow rate of 2 sccm. Other gases can also be

[0046] As illustrated in FIG. 4, after the substrate is placed in a reduced pressure environment, an optional flow of hydrogen gas (412) can be used in generating an RF hydrogen plasma in the processing chamber (414).

[0047] It should be appreciated that the specific steps illustrated in FIG. 4 provide a particular method of growing graphene according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 4 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0048] FIG. 5 shows data for a graphene film grown using conventional techniques and for a graphene film grown using another embodiment of the present invention. As illustrated in FIG. 5, the Raman spectra for graphene grown using conventional techniques (i.e., single crystal copper substrate with growth performed at 1,000 °C is plotted as plot A. Plot B illustrates the Raman spectra for graphene formed on a copper foil after plasma cleaning followed by growth at 800 °C. Plot C illustrates the Raman spectra for graphene formed on copper foil using the method illustrated in FIG. 4, i.e., an RF plasma clean process followed by room temperature deposition of the graphene. The graphene films used for the data collection in FIG. 5 were all grown using 35 sccm of CH_4 and 2 sccm of H_2, with a growth time of 15 minutes under 500 mTorr total pressure. As illustrated in FIG. 5, the graphene grown at room temperature (i.e., 24 °C and 8000 °C have similar Raman spectra to graphene grown by thermal CVD at 1,000 C. The two sharp features of the Raman spectra at ~ 1580 and 2700 cm^{-1} and the absence of a pronounced defect peak at ~1350 cm^{-1} indicate that both films are of good quality.

[0049] Some embodiments of the present invention utilize one of several methods to treat the substrate surface prior to growth. As an example, a copper foil substrate can be cleaned using low temperature processes, producing a build-up of copper on the inside of the quartz processing tube, which is evidence of copper removal from the foil during the cleaning process and preparation of the growth surface for graphene production. In some embodiments, metrology can be performed to measure the level of copper deposition on the inside of the processing chamber, for example, near the substrate, and thereby determine the status of the substrate and/or as a result of the Evenson cavity plasma treatment. One

WHAT IS CLAIMED IS:

1. A method of forming a film of graphene, the method comprising:
placing a substrate in a processing chamber at a reduced pressure;
performing a surface treatment process on at least a portion of the substrate;
providing a carbon containing material in the processing chamber;
exposing the substrate to the carbon containing material; and
converting a portion of the carbon containing material to a film of graphene on the substrate.

2. The method of claim 1 further comprising providing a gas and exposing the substrate to the gas prior to performing the surface treatment process.

3. The method of claim 2 wherein the gas is hydrogen.

4. The method of claim 3 wherein the surface treatment process comprises an RF hydrogen plasma.

5. The method of claim 1 wherein the surface treatment process comprises an RF plasma cleaning process.

6. The method of claim 1 where the substrate comprises a copper foil.

7. The method of claim 1 wherein the reduced pressure is less than 500 mTorr.

8. The method of claim 1 wherein the carbon containing material comprises at least one of methane, ethane, propane, or butane.

9. A method for forming graphene, the method comprising:
providing a substrate;
subjecting the substrate to a reduced pressure environment;
providing a carrier gas;
providing a carbon source;
exposing at least a portion of the substrate to the carrier gas and the carbon source;
performing a surface treatment process on the at least a portion of the substrate; and

converting a portion of the carbon source to graphene disposed on the at least a portion of the substrate.

10. The method of claim 9 wherein the substrate comprises a copper foil.

11. The method of claim 9 wherein the surface treatment process comprises an RF plasma cleaning process.

12. The method of claim 9 wherein the carrier gas comprises hydrogen and the surface treatment process comprises an RF hydrogen plasma process.

13. The method of claim 9 wherein the carbon source comprises methane.

14. The method of claim 9 wherein providing the carrier gas and providing the carbon source are performed concurrently.

15. The method of claim 14 wherein the carbon source comprises less than 0.1% of a combined carrier gas and carbon source flow.

16. The method of claim 9 wherein the surface treatment process is performed at a pressure less than or equal to500 mTorr.

17. A system for graphene production, the system comprising:

a plurality of gas sources;

a plurality of mass flow controllers, each of the plurality of mass flow controllers coupled to one of the plurality of gas sources;

a processing chamber in fluid communication with the plurality of mass flow controllers;

a plasma source operable to form a plasma in the processing chamber;

a vacuum pump in fluid communication with the processing chamber;

a processor; and

a non-transitory computer-readable storage medium comprising a plurality of computer-readable instructions tangibly embodied on the computer-readable storage medium, which, when executed by a data processor, provide for graphene production, the plurality of instructions comprising:

instructions that cause the data processor to subject a substrate to a reduced pressure environment;

instructions that cause the data processor to provide a carrier gas and a carbon source;

instructions that cause the data processor to expose at least a portion of the substrate to the carrier gas and the carbon source;

instructions that cause the data processor to perform a surface treatment process on the at least a portion of the substrate; and

instructions that cause the data processor to convert a portion of the carbon source to graphene disposed on the at least a portion of the substrate.

18. The method of claim 17 wherein the substrate comprises a copper foil.

19. The method of claim 17 wherein the carrier gas comprises hydrogen and the surface treatment process comprises an RF hydrogen plasma cleaning process.

20. The method of claim 17 wherein the carbon source comprises methane.

21. The method of claim 17 wherein providing the carrier gas and providing the carbon source are performed concurrently.

gases present in the processing chamber can be provided as will be evident to one familiar with CVD systems.

[0034] The method further includes subjecting the substrate to a flow of a carbon precursor for a predetermined period of time (218). As an example, the carbon precursor can be one of several gaseous species, including methane, acetylene, cyclohexane, toluene, PMMA, polystyrene, benzene, a combination thereof, or the like. After growth, the substrate is cooled and removed from the growth chamber.

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[0037] In some embodiments utilizing a two-step clean/growth process, the substrate is maintained in an inert environment during the time between the plasma treatment used to clean the surface and the exposure to the carbon source during growth. The ability to keep the substrate in this inert environment (e.g., maintain the process under vacuum) enables the

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[0038] Utilizing the system illustrated in FIG. 1, graphene was formed as follows. An RF plasma was formed in the processing chamber in the vicinity of the substrate (a copper foil) using an Evenson cavity with an input power of 40 W for a period of 15 minutes with a flow rate of hydrogen of 2 sccm. During the application of the RF plasma, a significant amount of copper was observed in the vicinity of the microwave cavity, indicating that the RF plasma was etching or otherwise removing copper from the substrate. The RF plasma was extinguished and the substrate was heated under a flow of 2 sccm of hydrogen at 42 mTorr to 800 °C.

[0039] Subsequently, a flow of CH_4 was added at a flow rate of 35 sccm and the total pressure in the processing chamber was increased to 500 mTorr. After 15 minutes of these conditions, the substrate was cooled under the same flow and pressure. Upon cooling, the substrate was removed and Raman spectroscopy was performed (plot A in FIG. 5), demonstrating that graphene had been formed on the backside of the substrate adjacent the susceptor, which can also be referred to as a sample holder. This procedure was repeated at growth temperatures of 700 °C and 600 °C with similar results. In addition to single layers of graphene, embodiments of the present invention are useful for forming other isomorphs of carbon, including multi-layer graphene, carbon nanotubes (e.g., using a VLS process), diamond like carbon, graphite, amorphous carbon, Bucky Balls, and the like. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

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[0041] The method includes providing a substrate in a processing chamber at a reduced pressure environment (410). In an embodiment, the substrate can be a copper foil or other suitable substrate and the reduced pressure environment can be a vacuum environment in the processing chamber 110 illustrated in FIG. 1, for example, pressures ranging from about 1 to about 500 mTorr. The pressure can be less than 500 mTorr in some implementations. In some embodiments, the method also includes introducing a flow of hydrogen gas into the processing chamber (412), for example, at a flow rate of 2 sccm. Other gases can also be

[0046] As illustrated in FIG. 4, after the substrate is placed in a reduced pressure environment, an optional flow of hydrogen gas (412) can be used in generating an RF hydrogen plasma in the processing chamber (414).

[0047] It should be appreciated that the specific steps illustrated in FIG. 4 provide a particular method of growing graphene according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 4 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

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[0049] Some embodiments of the present invention utilize one of several methods to treat the substrate surface prior to growth. As an example, a copper foil substrate can be cleaned using low temperature processes, producing a build-up of copper on the inside of the quartz processing tube, which is evidence of copper removal from the foil during the cleaning process and preparation of the growth surface for graphene production. In some embodiments, metrology can be performed to measure the level of copper deposition on the inside of the processing chamber, for example, near the substrate, and thereby determine the status of the substrate and/or as a result of the Evenson cavity plasma treatment. One

WHAT IS CLAIMED IS:

1. A method of forming a film of graphene, the method comprising:
placing a substrate in a processing chamber at a reduced pressure;
performing a room temperature surface treatment process on at least a portion of the substrate;
providing a carbon containing material in the processing chamber;
exposing the substrate to the carbon containing material; and
converting, at room temperature, a portion of the carbon containing material to a film of graphene on the substrate.

2. The method of claim 1 further comprising providing a gas and exposing the substrate to the gas prior to performing the surface treatment process.

3. The method of claim 2 wherein the gas is hydrogen.

4. The method of claim 3 wherein the surface treatment process comprises an RF hydrogen plasma.

5. The method of claim 1 wherein the surface treatment process comprises an RF plasma cleaning process.

6. The method of claim 1 where the substrate comprises a copper foil.

7. The method of claim 1 wherein the reduced pressure is less than 500 mTorr.

8. The method of claim 1 wherein the carbon containing material comprises at least one of methane, ethane, propane, or butane.

9. A method for forming graphene, the method comprising:
providing a substrate;
subjecting the substrate to a reduced pressure environment;
providing a carrier gas;
providing a carbon source;
exposing at least a portion of the substrate to the carrier gas and the carbon source;

performing a room temperature surface treatment process on the at least a portion of the substrate; and

converting, at room temperature, a portion of the carbon source to graphene disposed on the at least a portion of the substrate.

10. The method of claim 9 wherein the substrate comprises a copper foil.

11. The method of claim 9 wherein the room temperature surface treatment process comprises an RF plasma cleaning process.

12. The method of claim 9 wherein the carrier gas comprises hydrogen and the surface treatment process comprises an RF hydrogen plasma process.

13. The method of claim 9 wherein the carbon source comprises methane.

14. The method of claim 9 wherein providing the carrier gas and providing the carbon source are performed concurrently.

15. The method of claim 14 wherein the carbon source comprises less than 0.6% of a combined carrier gas and carbon source flow.

16. The method of claim 9 wherein the surface treatment process is performed at a pressure less than or equal to 500 mTorr.

17. The method of claim 1 further comprising providing an atmospheric gas in the processing chamber.

18. The method of claim 17, wherein the atmospheric gas comprises nitrogen gas.

19. The method of claim 17, wherein performing the room temperature surface treatment comprises etching the substrate.

20. The method of claim 9 wherein the carrier gas includes an atmospheric gas.

21. The method of claim 20 wherein the atmospheric gas comprises nitrogen gas.

22. The method of claim 9 wherein performing the room temperature surface treatment comprises etching the substrate.

23. A system for graphene production, the system comprising:

a plurality of gas sources;

a plurality of mass flow controllers, each of the plurality of mass flow controllers coupled to one of the plurality of gas sources;

a processing chamber in fluid communication with the plurality of mass flow controllers;

a plasma source operable to form a plasma in the processing chamber;

a vacuum pump in fluid communication with the processing chamber;

a processor; and

a non-transitory computer-readable storage medium comprising a plurality of computer-readable instructions tangibly embodied on the computer-readable storage medium, which, when executed by a data processor, provide for graphene production, the plurality of instructions comprising:

instructions that cause the data processor to subject a substrate to a reduced pressure environment;

instructions that cause the data processor to provide a carrier gas and a carbon source;

instructions that cause the data processor to expose at least a portion of the substrate to the carrier gas and the carbon source;

instructions that cause the data processor to perform a surface treatment process on the at least a portion of the substrate; and

instructions that cause the data processor to convert a portion of the carbon source to graphene disposed on the at least a portion of the substrate.

24 The system of claim 23 wherein the substrate comprises a copper foil.

25. The system of claim 23 wherein the carrier gas comprises hydrogen and the surface treatment process comprises an RF hydrogen plasma cleaning process.

26. The system of claim 23 wherein the carbon source comprises methane.

27. The system of claim 23 wherein providing the carrier gas and providing the carbon source are performed concurrently.