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(54) **MOLECULAR ION GENERATION**

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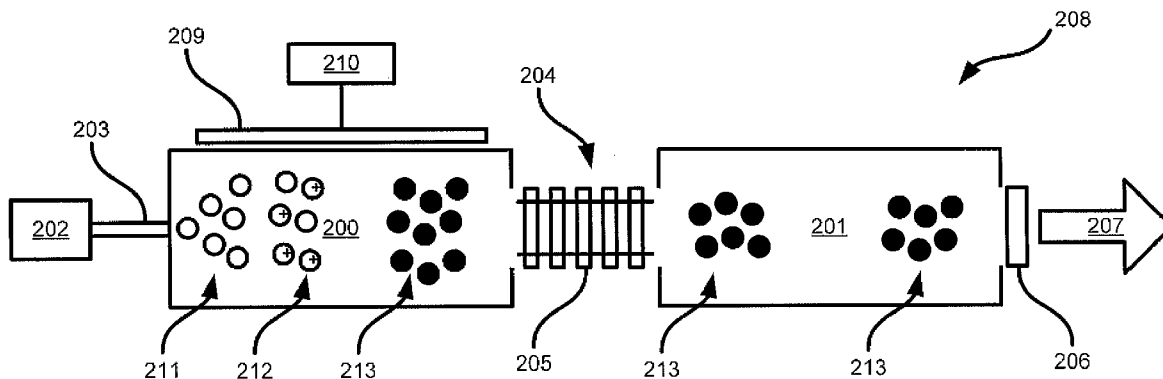
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(57) **ABSTRACT**

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An apparatus that generates molecular ions and methods to generate molecular ions are disclosed. At least a first species is ionized in an ion source. The first species ions and/or first species combine to form molecular ions. These molecular ions may be transported to a second chamber, which may be an arc chamber or diffusion chamber, and are extracted. The molecular ions may have a larger atomic mass than the first species or first species ions. A second species also may be ionized with the first species to form molecular ions. In one instance, the first and second species are both molecules.

(22) Filed: **Apr. 20, 2010**



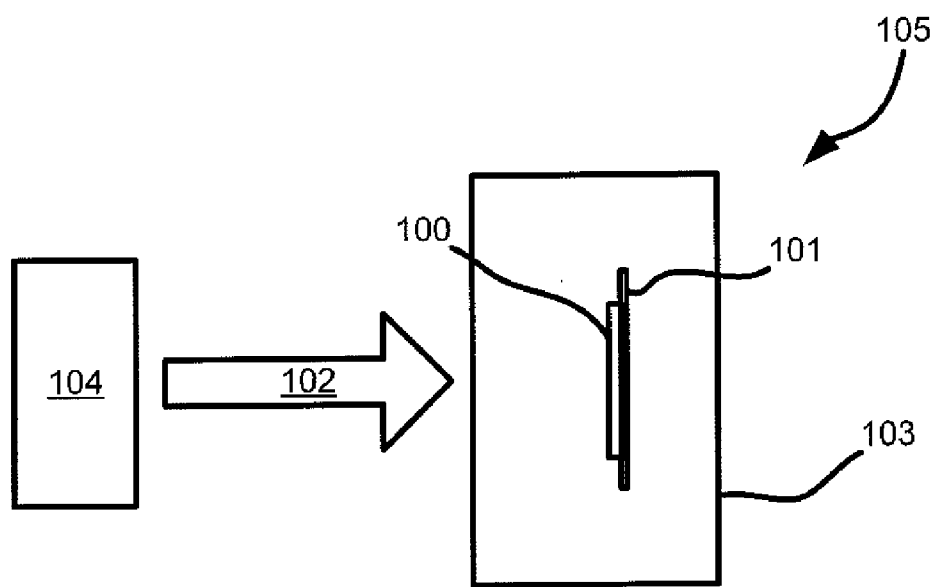


FIG. 1  
(Prior Art)

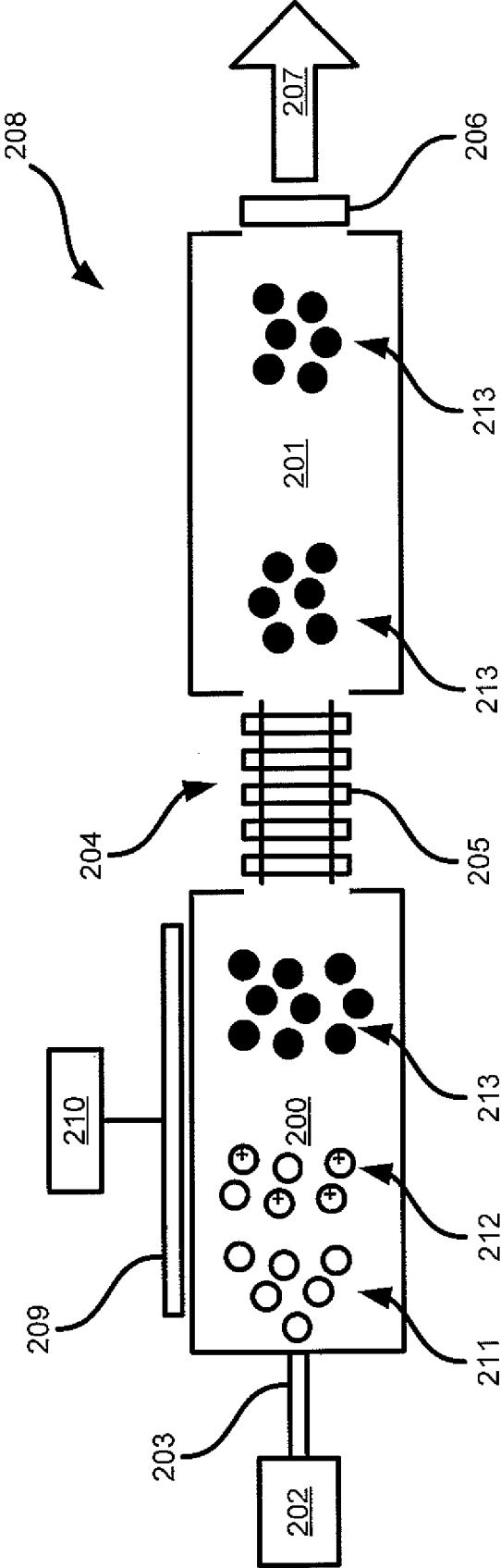


FIG. 2

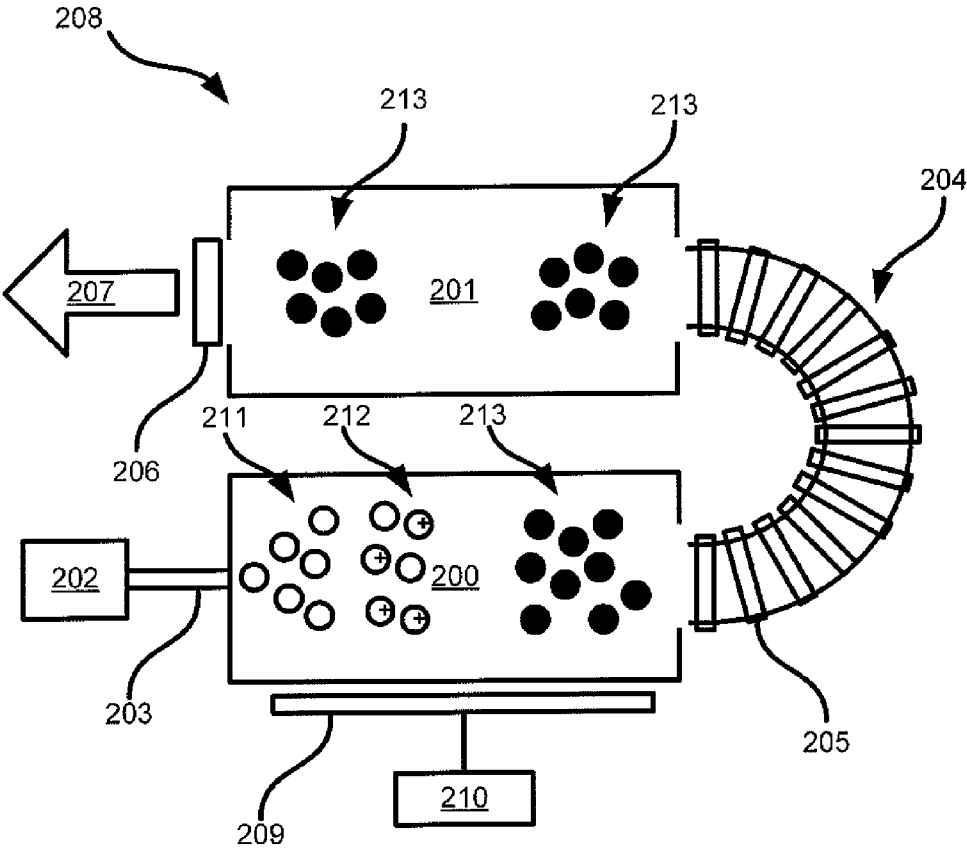


FIG. 3

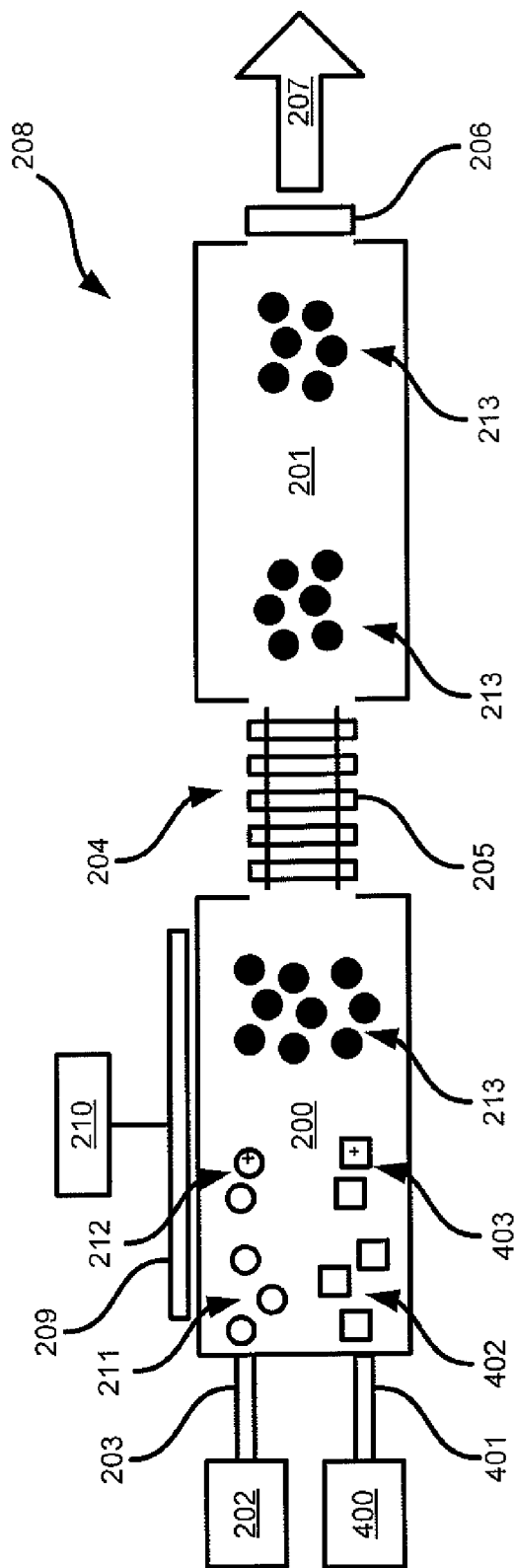


FIG. 4

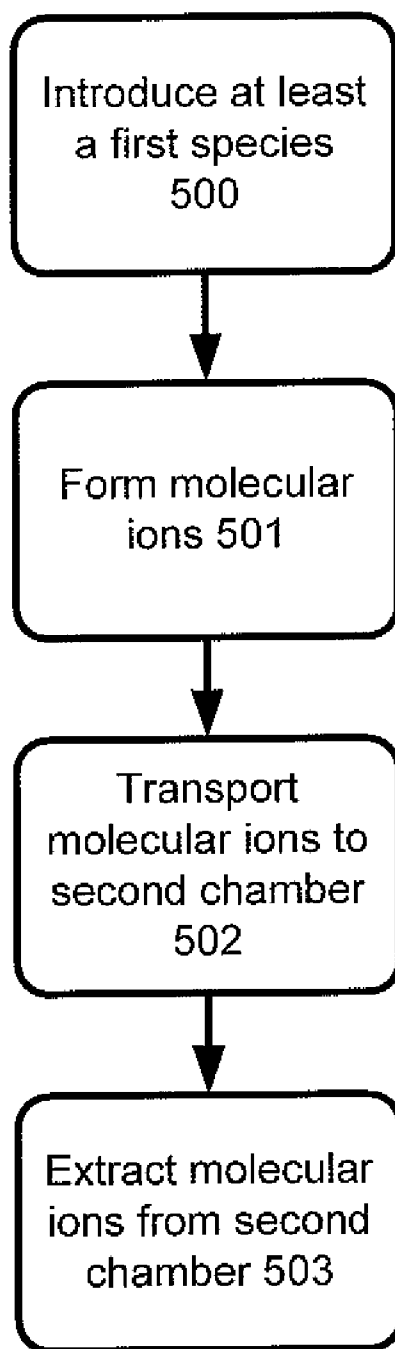


FIG. 5

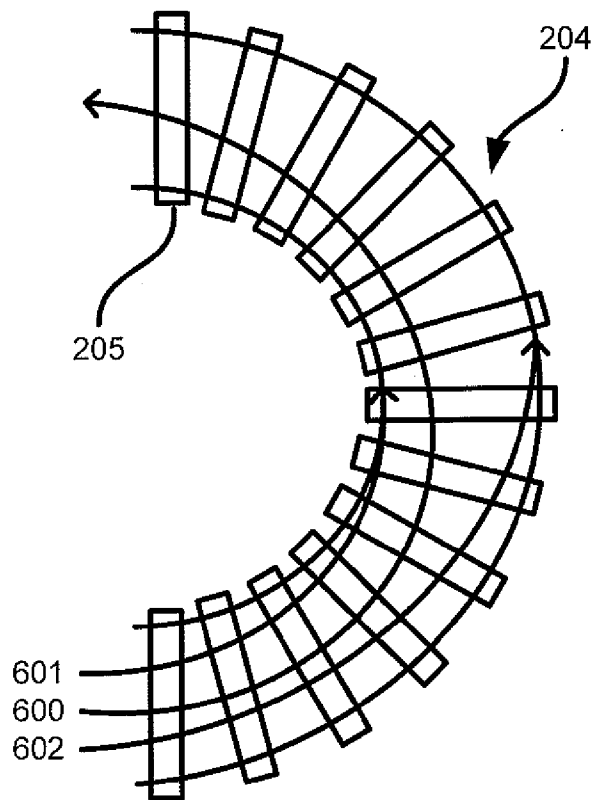


FIG. 6

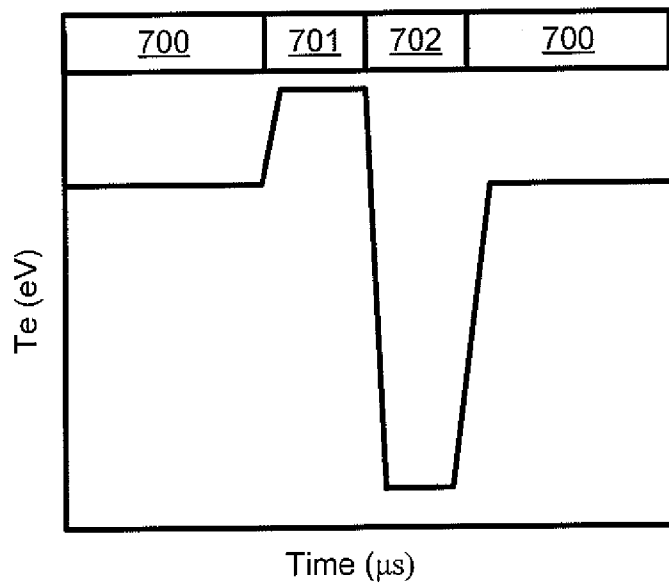


FIG. 7

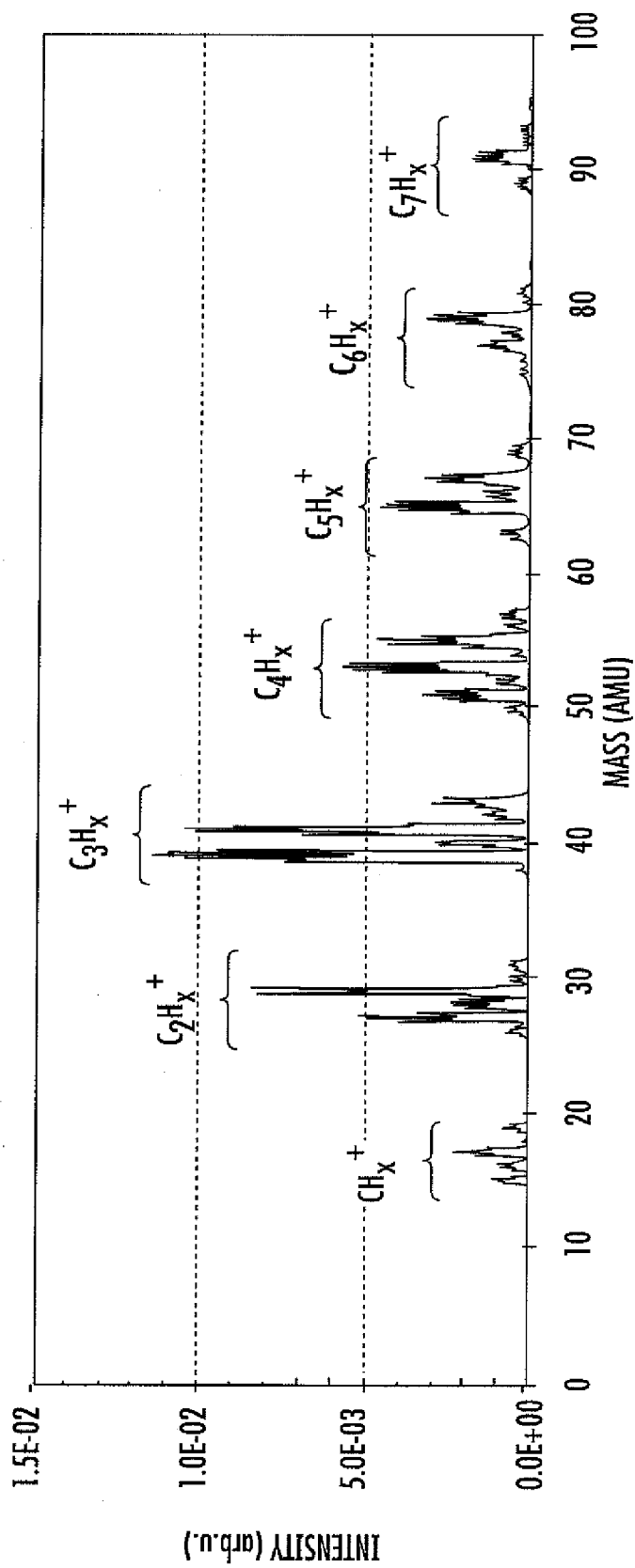


FIG. 8



## MOLECULAR ION GENERATION

### FIELD

**[0001]** This invention relates to the formation of ions and, more particularly, to the formation of molecular ions.

### BACKGROUND

**[0002]** Ion implantation is a standard technique for introducing conductivity-altering impurities into a workpiece. A desired impurity material is ionized in an ion source, the ions are accelerated to form an ion beam of prescribed energy, and the ion beam is directed at the surface of the workpiece. The energetic ions in the beam penetrate into the bulk of the workpiece material and are embedded into the crystalline lattice of the workpiece material to form a region of desired conductivity.

**[0003]** Molecular ion beams may be more easily transported at a higher energy and lower beam current than atomic ion beams. The atoms (including dopant species) in a molecular ion share an overall kinetic energy of the molecular ion according to their respective atomic masses. Furthermore, by having fewer ions implanted to obtain the same dose, any space charge effect in the ion beam and, consequently, beam “blow up” may be minimized.

**[0004]** Molecular ions, however, may be difficult to form and maintain during the ionization or implantation process. Use of an ion source, such as an indirectly heated cathode (IHC) or Bernas source, tends to break up molecules into atomic ions. For example, dopant molecules like  $\text{BF}_3$ ,  $\text{PH}_3$ ,  $\text{PF}_5$ ,  $\text{AsH}_3$ ,  $\text{B}_2\text{H}_4$ , or  $\text{GeF}_5$  tend to dissociate easily in the thermal plasmas formed using an IHC or Bernas source. Thus, atomic ions may be formed instead of molecular ions. A plasma doping system that generates a plasma of ions and neutrals and biases a workpiece for implantation may not adequately control electron temperature or other plasma conditions such as pressure, power, frequency, or gas flow to form molecular ions. Thus, molecular ions may dissociate within a high voltage sheath of such a plasma doping system. This may be due to the pressure inside the high voltage sheath. So, for example,  $\text{BF}_3$  may only survive as  $\text{B}^+$  ions after crossing the high voltage sheath and implanting a workpiece. Additionally, as the molecular ions increase in molecular weight, it may become more difficult to not dissociate these molecular ions into atomic ions or smaller molecular ions in a conventional ion source. Other ion source systems may have lifetime issues due to depositions on components of the ion source caused by molecular ion formation. Use of certain dopants may cause deposits of, for example, B, C, As, or P to build up on surfaces within the ion source.

**[0005]** Accordingly, there is a need in the art for an improved method of forming molecular ions.

### SUMMARY

**[0006]** According to a first aspect of the invention, a method to generate molecular ions is provided. The method comprises introducing a first species into an ion source. First species ions are formed from the first species. Molecular ions are formed using the first species ions. The molecular ions have a larger atomic mass than an atomic mass of the first species ions. The molecular ions are transported from the ion source to a second chamber and are extracted from the second chamber.

**[0007]** According to a second aspect of the invention, a method to generate molecular ions is provided. The method comprises introducing a first gas and a second gas into an ion source. The first gas and the second gas are ionized to form first gas ions and second gas ions. The first gas ions and the second gas ions are combined to form molecular ions. The molecular ions are transported from the ion source to a second chamber and are extracted from the second chamber.

**[0008]** According to a third aspect of the invention, a method to generate molecular ions is provided. The method comprises ionizing an alkane species having a formula  $\text{C}_a\text{H}_b$  in an RF ion source. Molecular ions of the formula  $\text{C}_x\text{H}_y$ , wherein  $x > a$ , are generated in the RF ion source from the alkane species. The molecular ions are extracted from the RF ion source and are implanted into a workpiece.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0009]** For a better understanding of the present disclosure, reference is made to the accompanying drawings, which are incorporated herein by reference and in which:

**[0010]** FIG. 1 is a block diagram of a beamline ion implanter;

**[0011]** FIG. 2 is a block diagram of a first embodiment of an ion source;

**[0012]** FIG. 3 is a block diagram of a second embodiment of an ion source;

**[0013]** FIG. 4 is a block diagram of a third embodiment of an ion source;

**[0014]** FIG. 5 is a flowchart of a method of molecular ion generation;

**[0015]** FIG. 6 is a cross-sectional view of an embodiment of an ion filter;

**[0016]** FIG. 7 is an example of electron temperature modulation using pulsing; and

**[0017]** FIG. 8 is molecular ion formation from  $\text{CH}_4$  using an embodiment disclosed herein.

### DETAILED DESCRIPTION

**[0018]** These embodiments are described herein in connection with an ion implanter. However, the various embodiments can be used with other systems and processes involved in semiconductor manufacturing or other systems that use ions. Thus, the invention is not limited to the specific embodiments described below.

**[0019]** FIG. 1 is a block diagram of a beamline ion implanter. Those skilled in the art will recognize that the beamline ion implanter 105 is only one of many examples of beamline ion implanters that can provide ions. In general, the beamline ion implanter 105 includes an ion source 104 to generate ions that are extracted to form an ion beam 102, which may be, for example, a ribbon beam or a spot beam. The ion beam 102 may be mass analyzed and converted from a diverging ion beam to a ribbon ion beam with substantially parallel ion trajectories in one instance. In another embodiment, the ion beam 102 is not mass analyzed. The beamline ion implanter 105 may further include an acceleration or deceleration unit in some embodiments.

**[0020]** An end station 103 supports one or more workpieces, such as workpiece 100, in the path of the ion beam 102 such that ions of the desired species are implanted into workpiece 100. The workpiece 100 may be, for example, a semiconductor wafer, a solar cell, a flat panel, a light-emitting diode (LED), or some other workpiece known to those skilled

in the art. The end station **103** may include a platen **101** to support the workpiece **100**. The end station **103** also may include in one embodiment a scanner for moving the workpiece **100** perpendicular to the long dimension of the ion beam **102** cross-section, thereby distributing ions over the entire surface of workpiece **100**. The ion implanter **105** may include additional components known to those skilled in the art such as automated workpiece handling equipment, Faraday sensors, or an electron flood gun. It will be understood to those skilled in the art that the entire path traversed by the ion beam **102** is evacuated during ion implantation. The beamline ion implanter **105** may incorporate hot or cold implantation of ions in some embodiments.

**[0021]** While the beamline ion implanter **105** is specifically illustrated, the embodiments described herein may be applied to other ion implanters or plasma processing systems. For example, a plasma doping tool (such as one that biases the workpiece to implant), plasma immersion tool, flood implanter, focused ion beam tool, or plasma-enhanced chemical vapor deposition (PECVD) system may benefit from the embodiments disclosed herein.

**[0022]** FIG. 2 is a block diagram of a first embodiment of an ion source. The ion source **208**, which may correspond to the ion source **104** of FIG. 1, in one instance may have multiple modes of operation and includes a first ion source **200**. This first ion source **200** has a gas source **202** connected by a gas feed **203**. The gas source **202** may be, for example, a gas bottle or vaporizer.

**[0023]** The gas source **202** may supply a first species **211** such as  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , another alkane,  $\text{B}_2\text{H}_6$ ,  $\text{CO}_2$ ,  $\text{C}_2\text{F}_4$ ,  $\text{BF}_3$ ,  $\text{AsH}_3$ ,  $\text{PH}_3$ ,  $\text{GeH}_4$ ,  $\text{GeF}_4$ ,  $\text{PI}_3$ ,  $\text{AsI}_3$ ,  $\text{N}_2$ ,  $\text{NH}_3$ , or other species known to those skilled in the art. This first species **211** is a molecule in one particular embodiment. In an alternate embodiment, an alkane of the formula  $\text{C}_a\text{H}_b$  is supplied. The first species **211** also may have the formula  $\text{P}_x\text{H}_y$ ,  $\text{C}_x\text{F}_y$ ,  $\text{Al}_x\text{Cl}_y$ ,  $\text{Ge}_x\text{H}_y$ , or  $\text{Ge}_x\text{F}_y$ , wherein  $x$  and  $y$  are greater than zero. Other organometallic molecules known to those skilled in the art also may be used as a first species **211**.

**[0024]** The first ion source **200** may be, for example, an RF or DC pulsed ion source. An antenna **209** resonates RF or DC currents from the power source **210**. In one instance, the antenna **209** is attached to an RF matching network.

**[0025]** The power supply **210** may be either an RF or DC power supply. This produces an oscillating magnetic field that induces RF or DC currents within the first ion source **200**. The RF or DC currents in the first ion source **200** excite and ionize a fraction of the first species **211** to form first species ions **212** (illustrated by the positive sign in FIG. 2). The first ion source **200** may be floating or biased. The first ion source **200** in an alternate embodiment may have an immersed RF antenna or may be an electron cyclotron resonance (ECR) or microwave ion source.

**[0026]** In one particular embodiment, the first ion source **200** is a multi-set point RF ion source. A multi-set point RF ion source enables RF power to be modulated as a function of time. Such an RF source may be coupled to a power supply that can pulse. RF frequency, power, or duty cycle may be modified using such an ion source. This may be used to balance any reactions within the first ion source **200**. For example, by using a short and high RF power, higher density plasma may be formed within the first ion source **200** and more electrons are available to remove any charge accumu-

lation. In yet another example, reducing the duty cycle may reduce any deposition or etching within the first ion source **200**.

**[0027]** A bipolar bias supply may be used to extract electrons or positive ions at certain energies during different periods of the RF pulsing in one embodiment. A positive bias will attract negative ions while a negative bias will attract positive ions.

**[0028]** The ion source **200** will ionize a portion of the first species **211** to form first species ions **212**. The first species ions **212** may be charged either positively or negatively. Molecular ions **213** (darkened in FIG. 2) are formed from the first species ions **212** and/or first species **211**. For example, a first species **211** and a first species ion **212** may combine to form a molecular ion **213**. Two first species ions **212** also may combine to form a molecular ion **213**. A certain plasma energy may be required to cause this reaction. The collisions that form the molecular ions **213** occur in the gas phase. An associative ionization collision between two first species **211** molecules or a first species **211** molecule and a first species ion **212** may be one mechanism that causes the formation of the molecular ions **213**, but other mechanisms are possible. In another instance, molecular ions **213** may be created from two body or three body recombination when, for example, a first species **211** molecule or some atom formed during ionization reacts with a first species ion **212**. These mechanisms may occur in the plasma or on a surface of the first ion source **200**.

**[0029]** The molecular ions **213** may be, for example,  $\text{C}_x\text{H}_y$ ,  $\text{B}_x\text{H}_y$ ,  $\text{B}_x\text{F}_y$ , or  $\text{C}_x\text{F}_y$ ,  $\text{Al}_x\text{Cl}_y$ ,  $\text{Ge}_x\text{H}_y$ , or  $\text{Ge}_x\text{F}_y$ , wherein  $x$  and  $y$  are greater than zero. These molecular ions **213** have a larger atomic mass than the first species **211** or first species ions **212**. In one particular embodiment, the first species **211** is an alkane with the formula  $\text{C}_a\text{H}_b$ . The molecular ions **213** are an alkane with the formula  $\text{C}_x\text{H}_y$ . In this instance  $x > a$ . Thus, a larger alkane molecular ion may be generated from smaller alkane molecular ions. In another particular embodiment,  $\text{BF}_3$  is the first species **211** and the molecular ions **213** formed may be  $\text{B}_2\text{F}_3^+$ ,  $\text{B}_2\text{F}_4^+$ , or  $\text{B}_2\text{F}_5^+$ . Modulating plasma parameters such as power, frequency, duty cycle, pressure, or gas flow can increase generation or retention of molecular ions **213** and, consequently, may increase formation of the molecular ions **213**.

**[0030]** The first ion source **200** may operate in a pulse mode to enhance the fraction of molecular ions **213** formed. For example, pulsing the first ion source **200** may enhance the recombination of the first species ions **212** and/or first species **211** by controlling the average electron temperature. This is the temperature of a group of electrons that have velocities following the Maxwell-Boltzmann distribution or a percentage of an average energy of such a group of electrons. Pulsing the first ion source **200** allows parameters of the plasma or ions, such as ion and electron density, electron temperature, or plasma potential, to be changed. Such changes will affect whether certain reactions occur and form molecular ions **213**. Changing electron temperature may enable reactions that form the molecular ions **213** or a desired molecular ion **213**. For example, a lower electron temperature can increase attachment and recombination that form the molecular ions **213**. In another example, lower electron temperature may enable recombination of particular molecular ions **213** with a neutral molecule, such as a background gas or first species **211**, to enlarge the molecular ion **213**. Pulsing the first ion source **200** also can modify the first species ion **212** formed.

For example, with  $\text{BF}_3$  as a first species **211**, a higher energy is required to form  $\text{B}^+$  ions as a first species ion **212** than  $\text{BF}_2^+$ . In one instance, 30 eV is required to form  $\text{B}^+$  while 16 eV is required to form  $\text{BF}_2^+$ .

[0031] The duty cycle of the pulse also may be optimized for the first species **211**. Each particular molecule used as a first species **211** has a particular optimal duty cycle to increase generation of the molecular ions **213**. By changing the duty cycle, the occurrence of particular reactions that form a molecular ion **213** is modified. Each reaction requires a different energy or amount of time to occur. For example, a heavier molecular ion **213** may be created during an afterglow period but may be destroyed when the first species **211** is being ionized. Therefore, the duty cycle may be adjusted such that the formation rate of the molecular ion **213** is higher than the dissociation rate.

[0032] The molecular ions **213** formed in the first ion source **200** are transported to a second chamber **201** using a plasma pipe **204**. The plasma pipe **204** has a plurality of ring magnets **205**. The ring magnets **205** may form a multi-cusp arrangement to provide optimal plasma or ion confinement. These ring magnets **205** may be aluminum-coated to prevent contamination. In an alternate embodiment, the plasma pipe **204** uses solenoids. The solenoids provide plasma confinement and, in one particular embodiment, may provide variable confinement because the driving current to the solenoid may be adjusted. Extraction optics may be located between the first ion source **200** and the plasma pipe **204** or between the plasma pipe **204** and the second chamber **201** to extract the molecular ions **213**. An Einzel lens may be used in one embodiment.

[0033] The second chamber **201** may be a diffusion chamber or an arc chamber. This arc chamber may be part of an existing ion implanter and may contain, for example, an IHC or Bemis ion source. This arc chamber may or may not be operating while the molecular ions **213** are transported to the second chamber **201**. In one embodiment, surfaces within the second chamber **201** may be coated with a catalyst that prevents dissociation of the molecular ions **213** on these surfaces.

[0034] In one embodiment, the second chamber **201** is an arc chamber and has a separate gas feed. Thus, the ion source **208** can operate in both a "hot" and "cold" mode of operation and can provide a wide range of atomic and molecular ions. For example,  $\text{BF}_3$  may be supplied to the arc chamber to generate  $\text{B}^+$  ions in "hot" mode while the first ion source **200** provides molecular ions **213** in "cold" mode. Thus, portions of the ion source **208** may be retrofitted onto an existing ion source.

[0035] The molecular ions **213** are then extracted from the second chamber **201** as the molecular ions **207**. The molecular ions **207** may be an ion beam, such as the ion beam **102** seen in FIG. 1. The molecular ions **207** may be extracted at a low pressure to minimize dissociation into atomic ions. This extraction may use extraction optics **206**, which in one particular embodiment is an Einzel lens. The molecular ions **207** may or may not be subsequently mass analyzed. Thus, the ion source **208** may be used in plasma doping, plasma immersion, flood implant, or sheath modulation tools.

[0036] The pressure in the second chamber **201** may be lower than the pressure in the first ion source **200**. A gradient of pressure may occur in the plasma pipe **204** going from the higher pressure in the first ion source **200** to the lower pressure in the second chamber **201**. The pressure in, for example,

a beamline ion implanter **105** illustrated in FIG. 1 or elsewhere that the molecular ions **207** are extracted may be lower than the pressure in the second chamber **201**. Valves between the first ion source **200**, second chamber **201**, and plasma pipe **204** may enable pressure control. A lower pressure within a region of the ion source **208** will reduce collisions between, for example, the molecular ions **213**. A lower collision probability will reduce dissociation of the molecular ions **213**.

[0037] The temperature of the first ion source **200**, second chamber **201**, and plasma pipe **204** may be controlled to reduce or control deposition on the surfaces of the ion source **208**. For example, reducing the temperature may reduce deposition of B from  $\text{B}_2\text{H}_4$  ions. However, increasing the temperature may reduce deposits of  $\text{BF}_x$  from  $\text{BF}_3$  ions or  $\text{CF}_x$  from  $\text{C}_2\text{F}_4$  ions. Heaters and cooling pipes or cooling jackets may be used in one instance.

[0038] Control of the temperature also may enhance formation and retention of the molecular ions **213**. High temperatures may cause the molecular ions **213** to dissociate. The temperature of the first ion source **200**, second chamber **201**, and plasma pipe **204** may be controlled in some embodiments using active cooling, such as water or fluid pipes within the walls of these systems.

[0039] The second chamber **201** may have a second gas feed. A gas may be supplied to the second chamber **201** to control pressure or clean the surfaces of the second chamber **201**. For example,  $\text{NF}_3$ , Ar,  $\text{NH}_3$ , or a combination thereof may be used to clean the surfaces of the second chamber **201**. These cleaning species may be ionized in a remote plasma source in one particular embodiment. Controlling the pressure with the second gas feed may enhance formation or retention of the molecular ions **213** in the second chamber **201**. In one instance, this is at least partly because the pressure in the second chamber **201** is lower than in the first ion source **200**. Use of a background gas such as He or Ar also may reduce any losses of the molecular ions **213** on the surfaces of the second chamber **201**.

[0040] FIG. 3 is a block diagram of a second embodiment of an ion source. In this particular embodiment, the plasma pipe **204** is curved. The curvature of the plasma pipe **204** may enable the molecular ions **213** to be filtered within the plasma pipe **204**. Transport of the molecular ions **213** or plasma may be enhanced due to magnetic confinement in the plasma pipe **204**. FIG. 6 is a cross-sectional view of an embodiment of an ion filter. The ring magnets **205** may be configured so that only the desired molecular ions **213** pass to the second chamber **201** as illustrated by the path **600**. Undesired molecular ions **213**, first species ions **212**, first species **211**, or other atomic or molecular species or ions may impact the walls of the plasma pipe **204** due to the magnetic fields of the ring magnets **205** as illustrated by the paths **601**, **602**. Thus, ionic species, neutral particles, and undesired molecular ions may be filtered by the plasma pipe **204**.

[0041] FIG. 4 is a block diagram of a third embodiment of an ion source. In this particular embodiment, a second gas source **400** is connected by a second gas feed **401** to the first ion source **200**. The second gas source **400** supplies a second species **402** (illustrated as squares in FIG. 4). The second species **402** is ionized to form second species ions **403** (illustrated by the positive sign in FIG. 4), which may be positive or negative. The first species **211**, first species ions **212**, second species **402**, and/or second species ions **403** combine to form the molecular ions **213**. Both the first species **211** and second species **402** are gases and may be, for example,  $\text{B}_2\text{H}_6$ ,  $\text{CO}_2$ ,

$C_2F_4$ ,  $BF_3$ ,  $AsH_3$ ,  $PH_3$ ,  $GeH_4$ ,  $GeF_4$ ,  $PI_3$ ,  $AsI_3$ ,  $N_2$ , and  $NH_3$ , other alkanes, or other species known to those skilled in the art. The first species **211** and second species **402** also may have the formula  $P_xH_y$ ,  $C_xF_y$ ,  $Al_xCl_y$ ,  $Ge_xH_y$ , or  $Ge_xF_y$ . Other organometallic molecules known to those skilled in the art also may be used as a first species **211** or second species **402**. The molecular ions **213** generated may be, for example,  $P_xC_yH_z$ ,  $P_xC_yF_z$ ,  $P_xC_yN_z$ ,  $B_xC_yN_z$ ,  $B_xC_yF_z$ ,  $B_xC_yN_z$ ,  $As_xC_yH_z$ ,  $As_xC_yF_z$ ,  $As_xC_yN_z$ ,  $Ge_xC_yH_z$ ,  $Ge_xC_yF_z$ ,  $Ge_xC_yN_z$ ,  $Al_xC_yF_z$ ,  $Al_xC_yCl_z$ ,  $Al_xP_yH_z$ , or other molecular ions known to those skilled in the art wherein x, y, and z are greater than zero. Other molecular ions **213** also may be formed combining a metal with carbon, boron, or phosphorus. These listed formulas for the molecular ions **213** may vary as known to those skilled in the art, wherein, for example, the listed  $B_xC_yH_z$  includes  $C_xB_yH_z$ . Of course, more than two species may be provided to form the molecular ions **213**, such as an embodiment with a mixture of three or more species. In one specific embodiment,  $CH_4$  and  $PH_3$  are the first species **211** and second species **402**. These form molecular ions **213** of  $C_2H_x^+$  or  $CP_2H_x^+$  ions using an embodiment disclosed herein.

**[0042]** In an alternate embodiment, a first species **211** is mixed with a second species **402** in the first ion source **200** to form molecular ions **213**. The second species **402** in this instance is an inert. An inert metastable atom, such as He or Ar, may help control electron temperature and may enhance formation of the molecular ions **213**. In yet another embodiment, the plasma pipe **204** may be curved as illustrated in FIG. 3 to filter the molecular ions **213**.

**[0043]** FIG. 5 is a flowchart of a method of molecular ion generation. At least a first species is introduced **500**. This first species is ionized and combines to form molecular ions **501**. The molecular ions are transported to a second chamber **502** and extracted from the second chamber **503**. Of course, other gases may be introduced or a first species and second species may be combined to form molecular ions. In another embodiment, more than two species are introduced to form molecular ions. Of course, it is possible that molecular ions **213** may be generated and extracted without passing through the second chamber.

**[0044]** FIG. 7 is an example of electron temperature modulation using pulsing. Pulsing affects electron temperature and, consequently, will modify the reaction rates in the plasma that forms the molecular ions **213**. Electron temperature ( $T_e$ ) may be modulated less than approximately 20 eV in one particular embodiment. As seen in FIG. 7, three time periods are illustrated during the pulsing. These include low power period **700**, high power period **701**, and off period **702**. The low power period **700** may operate at approximately 750W in one instance. The electron temperature varies as the pulsing operates in the low power period **700**, high power period **701**, and off period **702**. Varying the pulse periods or bias during the pulse may result in different electron temperatures, which may enable different reactions that form the molecular ions **213** to occur. In one embodiment, 25% RF on at 155 Hz frequency may be used with between 1% and 95% duty cycle.

**[0045]** FIG. 8 is molecular ion formation from  $CH_4$  using an embodiment disclosed herein. The result in FIG. 8 may use the embodiments seen in FIGS. 2-3.  $C_2H_x^+$ ,  $C_3H_x^+$ , and  $C_4H_x^+$  may be formed from the  $CH_4$  as seen in FIG. 8. Furthermore, even larger molecules like  $C_5H_x^+$ ,  $C_6H_x^+$ , or  $C_7H_x^+$  may be formed. Using the embodiments disclosed herein the dominant ion formed from  $CH_4$  may be  $C_3H_x^+$ . This may be

because the electron energy is higher and the formation rate of  $C_3H_x^+$  is lower compared to other reactions that may occur in the plasma or compared to the formation of  $CH_x^+$  using electron impact ionization. Thus, using the embodiments disclosed herein may increase the atomic mass of the molecular ions **213** that are formed. The molecular ions **213** may be subsequently mass analyzed to select a particular ion or the parameters may be configured to form the desired ion.

**[0046]** The molecular ions **213** may be used for multiple applications. These include doping of a workpiece, strain modification of a workpiece, or other material modification of the workpiece. This material modification may include, for example, amorphization or damage engineering of a workpiece. Molecular ions **207** also may be used for ultra-shallow junctions (USJ), to manufacture low k dielectrics, to fabricate optical coatings, or for implanting workpieces with three-dimensional surface structures.

**[0047]** Embodiments of the ion source disclosed herein have multiple benefits. First, it may enable molecular ion production with fewer atomic ions generated or with less dissociation of the molecular ions into atomic ions. Second, deposits from ionization may be reduced. This will increase uptime and lower the frequency of preventative maintenance. Third, cheaper, more common species may be used to form more expensive, uncommon molecular ions. This may reduce material costs.

**[0048]** The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments of and modifications to the present disclosure, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Furthermore, although the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose, those of ordinary skill in the art will recognize that its usefulness is not limited thereto and that the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full breadth and spirit of the present disclosure as described herein.

What is claimed is:

1. A method to generate molecular ions comprising:
  - introducing a first species into an ion source;
  - forming first species ions from said first species;
  - forming molecular ions using said first species ions, said molecular ions having a larger atomic mass than an atomic mass of said first species ions;
  - transporting said molecular ions from said ion source to a second chamber; and
  - extracting said molecular ions from said second chamber.
2. The method of claim 1, wherein said forming said molecular ions comprises combining said first species ions with said first species.
3. The method of claim 1, wherein said first species is an alkane having a formula  $C_aH_b$  and said molecular ions have a formula  $C_xH_y$ , wherein  $x>a$ .
4. The method of claim 1, wherein said first species is selected from the group consisting of an alkane,  $B_2H_6$ ,  $CO_2$ ,  $C_2F_4$ ,  $BF_3$ ,  $AsH_3$ ,  $PH_3$ ,  $GeH_4$ ,  $GeF_4$ ,  $PI_3$ ,  $AsI_3$ ,  $N_2$ ,  $NH_3$ ,  $P_xH_y$ ,  $C_xF_y$ ,  $Al_xCl_y$ ,  $Ge_xH_y$ , and  $Ge_xF_y$ .

5. The method of claim 1, wherein said molecular ions are selected from the group consisting of  $C_xH_y$ ,  $B_xH_y$ ,  $B_xF_y$ , or  $As_xH_y$ ,  $P_xH_y$ ,  $C_xF_y$ ,  $Al_xCl_y$ ,  $Ge_xH_y$ , and  $Ge_xF_y$ .

6. The method of claim 1, wherein said first species and said first species ions comprise molecules.

7. The method of claim 1, further comprising filtering said molecular ions during said transporting.

8. The method of claim 1, wherein said forming said molecular ions occurs at a higher pressure than said extracting said molecular ions.

9. The method of claim 1, further comprising introducing a second species into said ion source.

10. The method of claim 1, wherein said forming said first species ions comprises applying an RF pulse or a DC pulse.

11. The method of claim 10, wherein said forming said first species ions comprises applying said RF pulse and further comprising modulating an RF parameter selected from the group consisting of frequency, power, and duty cycle to modify an electron temperature during said RF pulse.

12. The method of claim 1, further comprising modifying a temperature of a surface of said second chamber to reduce deposition within said second chamber.

13. The method of claim 1, further comprising implanting said molecular ions into a workpiece.

14. A method to generate molecular ions comprising:

introducing a first gas and a second gas into an ion source; ionizing said first gas and said second gas to form first gas ions and second gas ions;

combining said first gas ions and said second gas ions to form molecular ions;

transporting said molecular ions from said ion source to a second chamber; and

extracting said molecular ions from said second chamber.

15. The method of claim 14, wherein said first gas and said second gas are selected from the group consisting of an alkane,  $B_2H_6$ ,  $CO_2$ ,  $C_2F_4$ ,  $BF_3$ ,  $AsH_3$ ,  $PH_3$ ,  $GeH_4$ ,  $GeF_4$ ,  $PI_3$ ,  $AsI_3$ ,  $N_2$ ,  $NH_3$ ,  $P_xH_y$ ,  $C_xF_y$ ,  $Al_xCl_y$ ,  $Ge_xH_y$ , and  $Ge_xF_y$ .

16. The method of claim 14, wherein said molecular ions are selected from the group consisting of  $P_xC_yH_z$ ,  $P_xC_yF_z$ ,  $P_xC_yN_z$ ,  $B_xC_yH_z$ ,  $B_xC_yF_z$ ,  $B_xC_yN_z$ ,  $As_xC_yH_z$ ,  $As_xC_yF_z$ ,  $As_xC_yN_z$ ,  $Ge_xC_yH_z$ ,  $Ge_xC_yF_z$ ,  $Ge_xC_yN_z$ ,  $Al_xC_yH_z$ ,  $Al_xC_yF_z$ ,  $Al_xC_yCl_z$ , and  $Al_xP_yH_z$ .

17. The method of claim 14, wherein said first gas, said second gas, said first gas ions, and said second gas ions comprise molecules.

18. The method of claim 14, further comprising filtering said molecular ions during said transporting.

19. The method of claim 14, wherein said ionizing said first gas and said second gas comprises applying an RF pulse or a DC pulse.

20. The method of claim 19, wherein said ionizing said first gas and said second gas comprises applying said RF pulse and further comprising modulating an RF parameter selected from the group consisting of frequency, power, and duty cycle to modify an electron temperature during said RF pulse.

21. The method of claim 14, further comprising modifying a temperature of a surface of said second chamber to reduce deposition within said second chamber.

22. The method of claim 14, further comprising implanting said molecular ions into a workpiece.

23. A method to generate molecular ions comprising:

ionizing an alkane species having a formula  $C_aH_b$  in an RF ion source;

generating a molecular ions having a formula  $C_xH_y$  in said RF ion source from said alkane species, wherein  $x>a$ ;

extracting said molecular ions from said RF ion source; and implanting said molecular ions into a workpiece.

24. The method of claim 23, further comprising transporting said molecular ions from said RF ion source to a second chamber and extracting said molecular ions from said second chamber.

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