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(54) MULTIBEAM SYSTEM

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(57) **ABSTRACT**

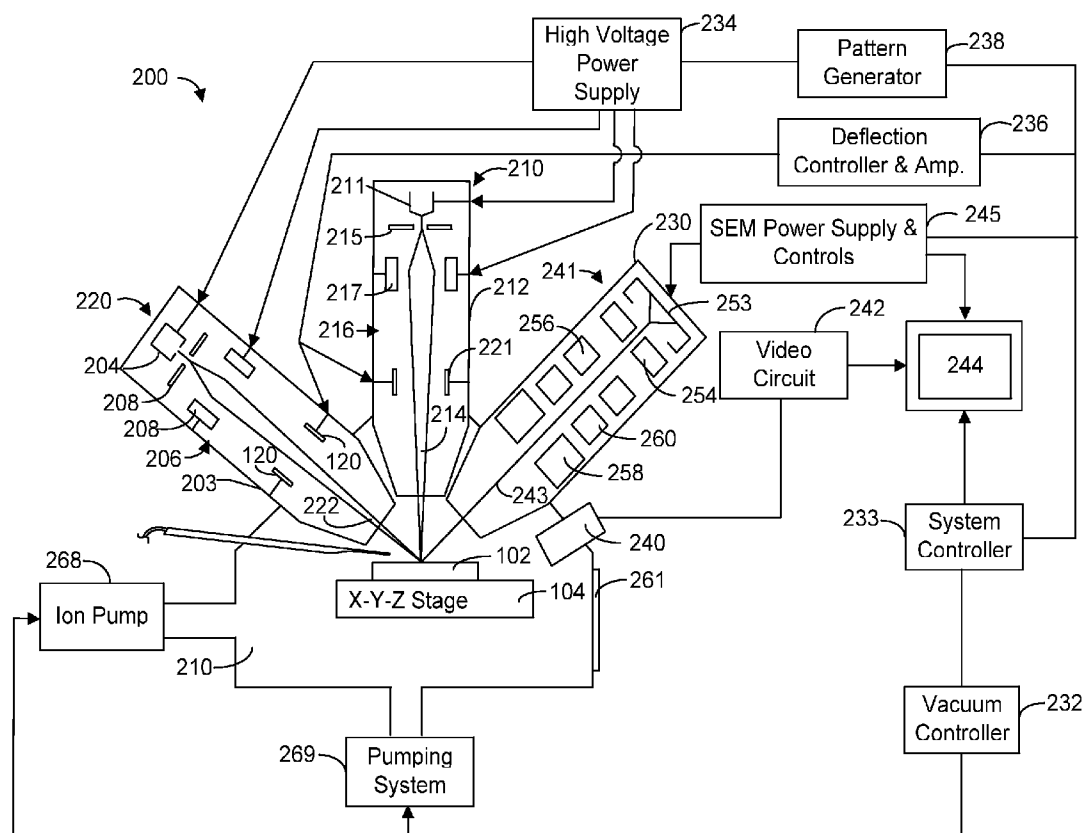
A multibeam system in which a charged particle beam and one or more additional beams can be directed to the target within a single vacuum chamber. A first beam column preferably produces a beam for rapid processing, and a second beam column produces a beam for more precise processing. A third beam column can be used to produce a beam useful for forming an image of the sample while producing little or no change in the sample.

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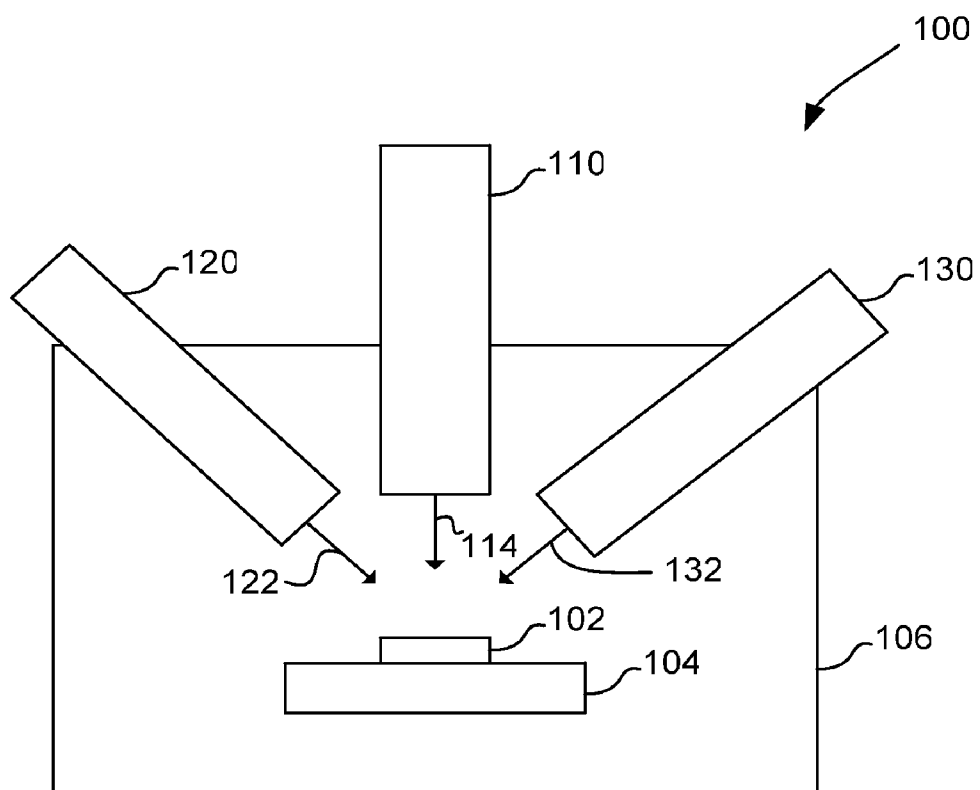


FIG. 1

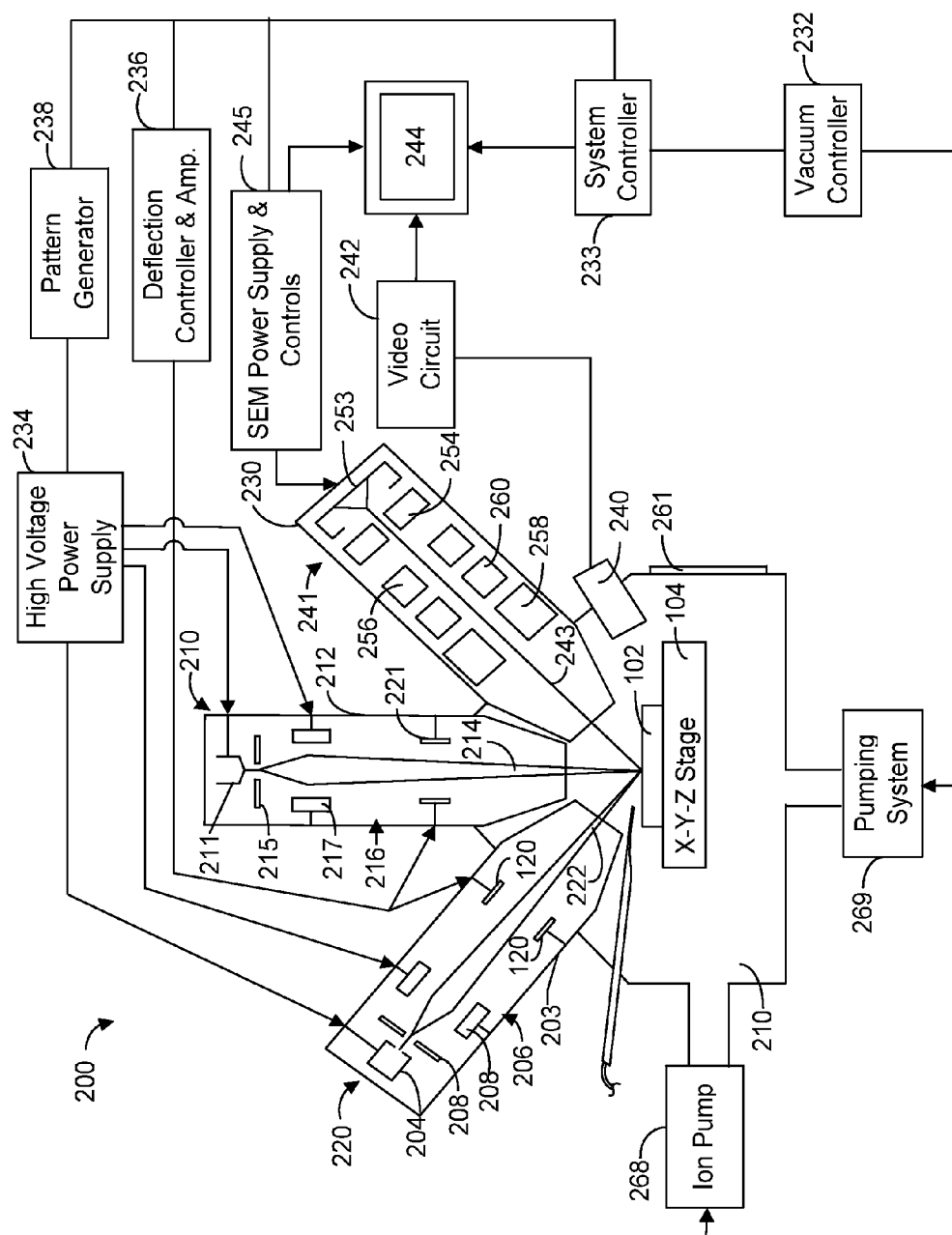


FIG. 2

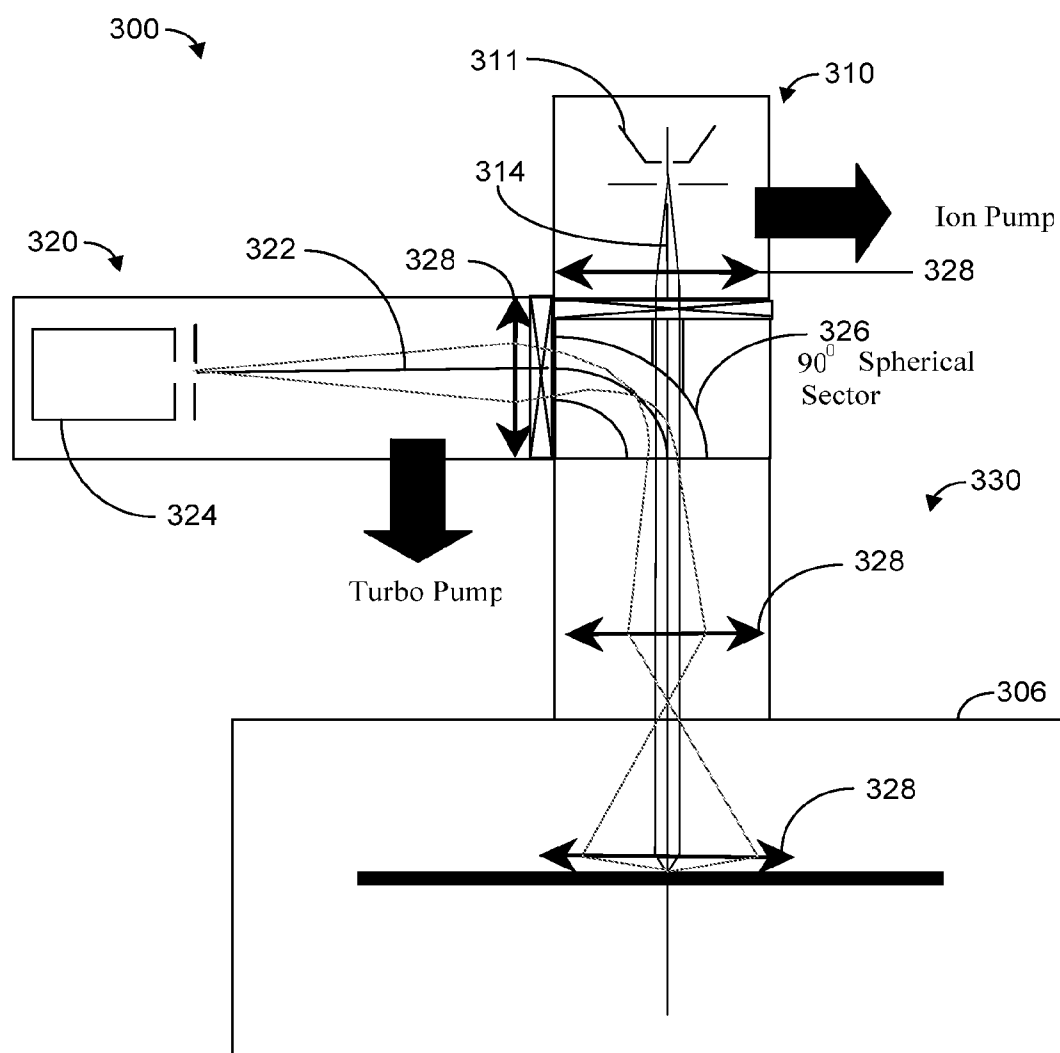


FIG. 3

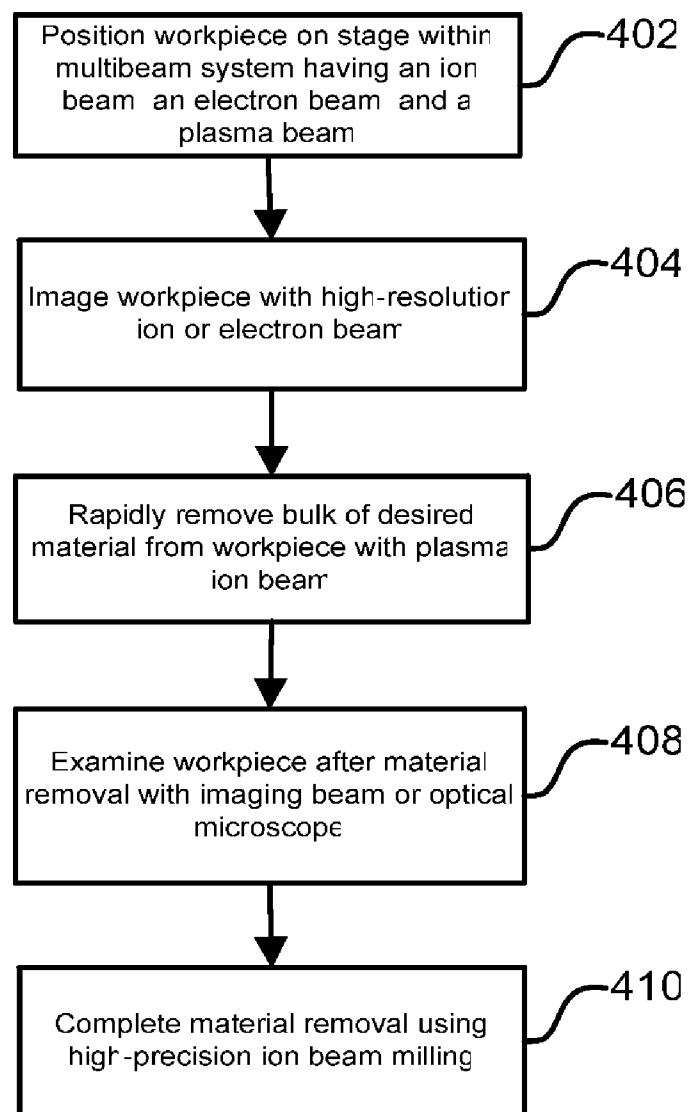


FIG. 4

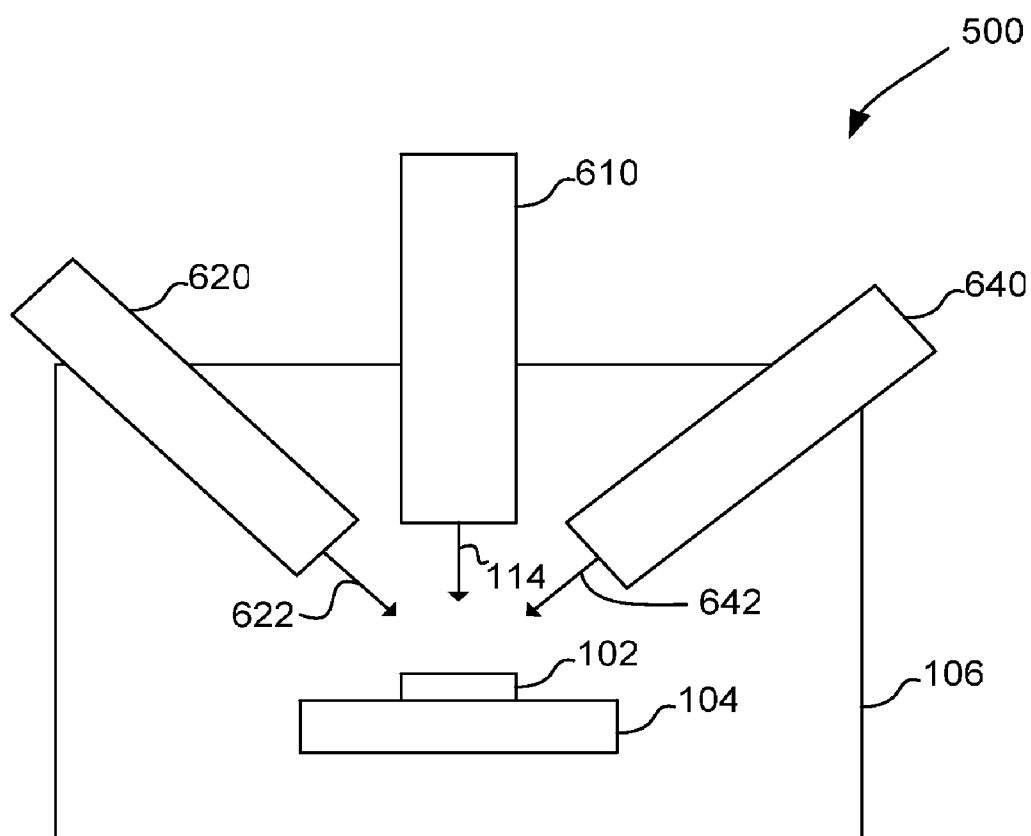


FIG. 5

MULTIBEAM SYSTEM

TECHNICAL FIELD OF THE INVENTION

[0001] The present invention relates to charged-particle beam multibeam systems.

BACKGROUND AND SUMMARY OF THE INVENTION

[0002] Charged particle beam systems are used in a variety of applications, including the manufacturing, repair, and inspection of miniature devices, such as integrated circuits, magnetic recording heads, and photolithography masks. Dual beam systems often include a scanning electron microscope (SEM) that can provide a high-resolution image with minimal damage to the target, and an ion beam system, such as a focused or shaped beam system, that can be used to alter workpieces and to form images. Ion beam systems using gallium liquid metal ion sources (LMIS) are widely used in manufacturing operations because of their ability to image, mill, deposit and analyze with great precision. Ion columns in FIB systems using gallium liquid metal ion sources (LMIS), for example, can provide five to seven nanometers of lateral resolution.

[0003] Dual beam systems including a liquid metal focused ion beam and an electron beam are well known. Systems, such as the Expida™ 1255 DualBeam™ System, available from FEI Company of Hillsboro, Oreg., the assignee of the present invention. The ion beam can be used, for example, to cut a trench in an integrated circuit, and then the electron beam can be used to form an image of the exposed trench wall.

[0004] Unfortunately, high-precision milling or sample removal often requires some tradeoffs. The processing rate of the liquid metal ion source is limited by the current in the beam. As the current is increased, it is harder to focus the beam into a small spot. Lower beam currents allow higher resolution, but result in lower erosion rates and hence longer processing times in production applications and in laboratories. As the processing rate is increased by increasing the beam current, the processing precision is decreased.

[0005] In contrast to FIB systems, plasma etch systems used in semiconductor manufacturing, unlike beams of gallium atoms, typically use ions in a plasma to chemically react with the workpiece. Such systems, however, typically provide a reactive plasma over the entire surface of a wafer and are not used to locally etch or deposit fine features.

[0006] U.S. Pat. App. Pub. No. 2005/0183667 for a "Magnetically enhanced, inductively coupled plasma source for a focused ion beam system" describes an ion source that can be used to produce a finely focused beam with a relatively large beam current, thereby overcoming many of the problems of a gallium LMIS system. However, it may be desirable to include both a LMIS and a plasma source in the same system.

[0007] Other techniques, such as milling with a femtosecond laser can also be used for faster material removal but the resolution of these techniques is much lower than a typical LMIS FIB system.

[0008] U.S. Pat. Pub. No. 2007/0045560 by Takahashi et al. describes a system that combines a liquid metal ion beam column, a gas ion beam column, and an electron beam column. The liquid metal ion column is used to extract a sample from workpiece, and then the gas ion beam, is used to produce a finished surface on the sample. The gas ion beam described

in Takahashi is used to produce a finished surface on the sample, but has insufficient resolution to extract a sample or to mill/deposit fine features.

[0009] Dual source FIB columns have been also been made with two plasma sources, or more typically with a surface ionization source (Cesium) and a plasma source (oxygen or inert), to allow quick switching (i.e., a few tens of seconds) between different ion species, and to limit the number of objective lenses competing for space around the sample.

[0010] What is needed is system that allows rapid removal technique such as plasma or laser to be used with a high precision LMIS ion beam.

SUMMARY OF THE INVENTION

[0011] An object of the invention is to provide a system that has the versatility to rapidly fabricate nanoscale structures for a variety of application. In a preferred embodiment, this invention provides a multiple beam system in which a charged particle beam and two additional beams can be directed to the target within a single vacuum chamber. A first beam column produces a beam for rapid processing, a second beam column for producing a beam for more precise processing, and a third beam column for producing a beam useful for forming an image of the sample while producing little or no change in the sample.

[0012] The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] For a more thorough understanding of the present invention, and advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0014] FIG. 1 shows a preferred embodiment of a multi-beam system of the present invention in which a charged particle beam and two additional beams can be directed at a target within a single vacuum chamber.

[0015] FIG. 2 shows a preferred embodiment of the multi-beam system as shown in FIG. 1, combining a focused ion beam column with a LMI source, a plasma ion column, and an electron beam column, all positioned within the same vacuum chamber.

[0016] FIG. 3 shows a schematic representation of a multi-beam system with two ion beams having a common lower optics column, which allows multiple beams each having the same short working distance, and a single lower column set of power supplies.

[0017] FIG. 4 is a flowchart showing the steps in a process of material removal using the multibeam system of FIG. 2.

[0018] FIG. 5 shows a preferred embodiment of the present invention in which a charged particle beam column for pre-

cise high-resolution material processing is combined with a laser that produces a pulsed laser beam capable of rapid material removal.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0019] Preferred embodiments of the present invention combine a high resolution LMIS FIB with an additional beam for rapid material removal or processing, for example a plasma beam or a femtosecond laser, in order to provide an extended range of milling applications within the same system. In some embodiments, one or more additional beams can be used, including for example an electron beam for nondestructive imaging of the sample.

[0020] FIG. 1 shows a preferred embodiment of a multi-beam system 100 of the invention in which a charged particle beam and two additional beams can be directed at a target within a single vacuum chamber. A first beam column produces a beam for rapid processing, a second beam column for producing a beam for more precise processing, and a third beam column for producing a beam useful for forming an image of the sample while producing little or no changes in the sample.

[0021] Multibeam system 100 includes a charged particle beam column 110 capable of generating a sub-one tenth micron beam 114 for performing precise processing of a workpiece 102 positioned on a movable stage 104 in a vacuum chamber 106. The material removal rate of the beam 114 generated is relatively low. Skilled persons will understand that the removal rate and the beam spot size vary with the beam current. The removal rate also varies with the material being removed and the species of etch-enhancing gas, if any, that is used with the beam.

[0022] A second beam generating column 120 produces a beam 122 suitable for rapid sample processing. Beam 122 preferably has a higher beam current and is capable of a higher material removal rate than beam 104. Beam 122 also preferably has a larger spot size than beam 104. Beam 122 is capable of producing relatively precise structures, but not as fine as the structures produced by beam 114.

[0023] Multibeam system 100 also includes a third beam generating column 130 used. Beam column 130 produces a beam 132 having a spot size that is preferably smaller than that of beam 114 and beam 122. Also, Beam 132 preferably produces less surface damage than beam 114 and beam 122 and is, therefore, particularly useful for imaging the workpiece 102. Beam 132 can also be used to process certain workpieces, assisted sometimes by a precursor gas.

[0024] FIG. 2 shows a preferred embodiment of the multi-beam system 200 as shown in FIG. 1, combining a focused ion beam column with a LMI source, a plasma ion column, and an electron beam column, all positioned within the same vacuum chamber. The embodiment shown in FIG. 2 includes a LMIS ion column 210 as the first beam generating column. LMIS ion column 210 is preferably capable of generating a sub-one tenth micron beam 214 for performing precise processing of a workpiece 102 positioned on a movable stage 104 in a vacuum chamber 210. The material removal rate of the beam 214 generated is relatively low. Skilled persons will understand that the removal rate varies with the beam current, the material being removed, and the species of etch-enhancing gas, if any, that is used with the beam.

[0025] Multibeam system 200 also includes a second ion beam producing column, such a plasma column 220. This

second column produces a larger beam 222 than beam 214 produced by the first column. Beam 222 is capable of a higher material removal rate than beam 214. Beam 222 is capable of producing relatively precise structures, but not as fine as the structures produced by beam 214. Although plasma sources have been combined with conventional FIBs before, those plasma sources have not been capable of forming a beam having a diameter sufficiently small for many application. The utility of such a combination is to be able to performing milling at very high speed using the large probe "beam," while using the fine probe "beam" to produce well-defined structures, to clean, or to image the structures being worked on.

[0026] First beam generating column 210 preferably comprises a LMIS column with an evacuated chamber having an upper neck portion 212 within which are located an ion source 211 and an ion focusing column 216 including extractor electrodes and an electrostatic optical system. The ion focusing column 216 includes an ion source 211, such as a GA LMIS, an extraction electrode 215, a focusing element 217, deflection elements 221, and a focused ion beam 214. Ion beam 214 passes from ion source 211 through column 216 and between electrostatic deflection means schematically indicated at 221 toward workpiece 102, which comprises, for example, a semiconductor device positioned on movable X-Y stage 104 within lower vacuum chamber 210.

[0027] A turbo-molecular pump (not shown) is employed for evacuating the source and maintaining high vacuum in the upper column optics region. The vacuum chamber 210 is evacuated with ion pump 268 and mechanical pumping system 269 under the control of vacuum controller 232. The vacuum system provides within vacuum chamber 210 a vacuum of typically between approximately 1×10^{-7} Torr and 5×10^{-4} Torr. The LMIS source region and the plasma source region (discussed below) can be isolated via gun isolation valves (also serving as differential pumping apertures).

[0028] High voltage power supply 234 is connected to liquid metal ion source 211 as well as to appropriate electrodes in ion beam focusing column 216 for forming an approximately 1 keV to 60 keV ion beam 214 and directing the same toward a sample. High voltage power supply 234 also provides an appropriate acceleration voltage to electrodes in ion beam focusing column focusing 216 for energizing and focusing ion beam 214. High voltage power 234 also connected to the plasma source and column as described below.

[0029] Deflection controller and amplifier 236, operated in accordance with a prescribed pattern provided by pattern generator 238, is coupled to deflection plates 221 whereby ion beam 214 may be controlled manually or automatically to trace out a corresponding pattern on the upper surface of workpiece 102. In some systems the deflection plates are placed before the final lens, as is well known in the art. An operator viewing the image may adjust the voltages applied to various optical elements in column 216 to focus the beam and adjust the beam for various aberrations. Beam blanking electrodes (not shown) within ion beam focusing column 216 cause ion beam 214 to impact onto blanking aperture (not shown) instead of workpiece 102 when a blanking controller (not shown) applies a blanking voltage to the blanking electrode.

[0030] The liquid metal ion source 211 typically provides a metal ion beam of gallium. The source typically is capable of being focused into a sub one-tenth micrometer wide beam at workpiece 102 for either modifying the workpiece 102 by ion

milling, enhanced etch, material deposition, or for the purpose of imaging the workpiece 102. When it strikes workpiece 102, material is sputtered, that is physically ejected, from the sample. Alternatively, ion beam 214 can decompose a precursor gas to deposit a material.

[0031] Plasma column 220 comprises an evacuated envelope 203 upon which is located a plasma source 204 with an RF antenna (not shown) to provide a dense plasma for plasma focusing column 206. Plasma ion beam 222 passes from source 204 through column optics 208 and between electrostatic deflection mechanism 120 toward workpiece 102. A turbo-molecular pump (not shown) is employed for evacuating the source and maintaining high vacuum in the upper column optics region. The vacuum system provides a vacuum of nominally 10 mTorr in the plasma source and $<1 \times 10^{-6}$ Torr in the column optics chamber.

[0032] High voltage power 234 is connected to ion source 204 as well as to appropriate electrodes 208 in plasma focusing column 206 for forming an approximately 0.1 keV to 50 keV ion plasma ion beam 222 and directing the same downward. Deflection controller and amplifier 236, operated in accordance with a prescribed pattern provided by pattern generator 238, is coupled to deflection plates 120 whereby beam 222 may be controlled to trace out a corresponding pattern on the upper surface of workpiece 102. In some systems, the deflection plates are placed before the final lens, as is well known in the art.

[0033] As discussed above, signals applied to deflection controller and amplifier 236 can also cause the focused plasma ion beam 222 to move within a target area to be imaged or milled according to a pattern controlled by pattern generator 238. Emissions from each sample point are collected by charged particle multiplier 240 to create an image that is displayed on video monitor 244 by way of video circuit 242.

[0034] Focusing optics in plasma focusing column 206 may comprise mechanisms known in the art for focusing or methods to be developed in the future. For example, two cylindrically symmetric electrostatic lenses can be implemented to produce a demagnified image of the round virtual source. Because of the low axial energy spread in the extracted beam, chromatic blur is minimal and efficient focusing of the beam can be achieved even at low acceleration voltages (i.e., low beam energies). These properties in conjunction with appropriate focusing optics can be used to generate nanometer, to micrometer scale spot sizes with a range of kinetic energies (0.1 keV-50 keV) and beam currents from a few pico-amperes to several micro-amperes.

[0035] Ion beams produced by both sources can preferably be brought to a coincident focus at workpiece 102 for either modifying the workpiece 102 by ion milling, material deposition, or for the purpose of imaging the workpiece 102. A charged particle detector 240, such as an Everhart Thornley or multi-channel plate, used for detecting secondary ion or electron emission is connected to a video circuit 242 that supplies drive signals to video monitor 244 and receives deflection signals from system controller 233. The location of charged particle detector 240 within lower vacuum chamber 210 can vary in different embodiments.

[0036] A scanning electron microscope 241, along with power supply and control unit 245, is provided with multi-beam system 200. An electron beam 243 is emitted from a cathode 253 by applying voltage between cathode 253 and an anode 254. Electron beam 243 is focused to a fine spot by

means of a condensing lens 256 and an objective lens 258. Electron beam 243 is scanned two-dimensionally on the specimen by means of a deflection coil 260. Operation of condensing lens 256, objective lens 258, and deflection coil 260 is controlled by power supply and control unit 245.

[0037] Electron beam 243 can also be focused onto workpiece 102, which is on movable X-Y stage 225 within lower vacuum chamber 210. When the electrons in the electron beam strike workpiece 102, secondary electrons are emitted. These secondary electrons are detected by secondary electron detector 240 as discussed above. Scanning electron microscope 241 is thus suitable for producing a beam that can be used to form an image of a sample while producing little or no change in the sample.

[0038] A system controller 233 controls the operations of the various parts of multi-beam system 200. Through system controller 233, a user can cause ion beam 214, plasma ion beam 222, or electron beam 243 to be scanned in a desired manner through commands entered into a conventional user interface (not shown). Alternatively, system controller 233 may control multi-beam system 200 in accordance with programmed instructions.

[0039] In a preferred embodiment, plasma column 220 is a noble gas column, which produces an ion beam consisting of non-reactive, high energy ions such as argon, krypton or xenon. This type of column allows a usable ion beam at a much higher beam current than a typical Gallium LMIS ion column. A Gallium LMIS ion column normally allows a maximum beam current of around 20 nanoamps (although higher beam currents can be used, the resulting ion beam will be of very poor quality). In contrast, a noble gas column can produce usable beam quality and current density at beam currents greater than 100 nanoamps. The use of a noble gas column also avoids real or perceived problems of metal contamination that may occur with a traditional Gallium ion beam.

[0040] A suitable plasma source is described in U.S. Pat. No. 7,241,361 to Keller et al. for "Magnetically enhanced, inductively coupled plasma source for a focused ion beam system," which is assigned to FEI Company, the assignee of the present invention, and which is incorporated by reference. Other types of plasma sources could also be used to practice the invention, including Electron Cyclotron Resonance (ECR) sources in which the plasma is generated by resonantly coupling microwave energy into the ion source; Penning type sources in which the plasma is generated by striking a direct current discharge between a suitably shaped anode and cathode; direct current (DC) driven volume sources in which an electric arc is struck between heated filaments and an anode; and radio frequency (RF) driven volume sources in which radio frequency energy is coupled to the gas in the ion source by a suitably configured antenna.

[0041] The beam current used for the plasma column would preferably be from 300 to 20,000 nanoamps, most preferably from 1500 to 5,000 nanoamps. As is well known, a higher current ion beam results in an increased sputter rate. The higher beam current of a noble gas column makes it possible to achieve a much higher rate of material removal than a typical LMIS column. One disadvantage of a higher beam current is, of course, a larger beam diameter. Using an advanced argon column with a beam current of 5,000 nanoamps, the beam diameter will be around 50 μm . In contrast, the LMIS provides an ion beam that is capable of being focused into a beam with a diameter of <10 nm.

[0042] The plasma beam could also be operated in either source imaging or Kohler illumination modes to facilitate high through-put milling, in conjunction with the use of the LMIS beam for imaging and navigation.

[0043] FIG. 3 shows a schematic representation of a multi-beam system 300 with two ion beams (314 and 322) having a common lower optics column 330, which allows multiple beams each having the same short working distance, and a single lower column set of power supplies. The ability to operate both beams at a reduced working distance will result in improved optical performance. Common lower column optics and power supplies will result in lower overall system cost, when compared to a typical dual beam system with two separate ion columns. Further, in preferred embodiments of the present invention, the rapid milling beam and the high resolution beams are coincident (directed at the same area of the sample without requiring stage moves) and have the same angle of incidence on the sample.

[0044] Preferred embodiments of the present invention provide a high performance FIB system suitable for the conventional low-current, high-resolution Ga-LMIS applications, as well as high current and non-Gallium beam applications. Embodiments of the invention also simplify beam coincidence issues and the usual problems of one beam having a sub-optimum (i.e., long) working distance.

[0045] In the multi-beam system of FIG. 3, FIB column 310 with a LMI source 311 is vertically mounted, while plasma ion column 320 with a plasma source 322 is located off-axis at an angle of approximately 90 degrees from the vertical. A stigmatic imaging, 90 degree electrostatic spherical sector 326 is used to deflect the plasma beam 322 on to the optical axis of the lower optics column 330. Here the column bend would also serve as a "neutral dump" to absorb non-interacting neutral particles. As a result, the plasma beam 322 and the LMIS ion beam 314 will be coincident on the sample.

[0046] This sector field could also be a stigmatically imaging magnetic mass-filter if mass selection is required when careful control of implanted ion species is critical. However, it is anticipated that, for an ion beam only system, all gas isotopes and molecular fragments would be focused into the final probe for maximum current density and milling rate. It may be beneficial to use a 90 degree sector field with a small radius or a simple <90 degree cylindrical condenser field to reduce the deflection angle and transverse dispersion in the beam due to the energy spread in the beam (lateral beam dispersion is proportional to sector radius for 90 degree spherical sector). Alternatively, if the virtual object of the plasma source is imaged onto the center of the sector field so that the image coincides with the virtual center of dispersion, the location of this virtual image is energy independent and there is no/minimal transverse broadening of the source image due to the beam deflection.

[0047] The common section of the optics column 330 preferably has two common lenses 328 suitable for achieving the higher optical demagnification (i.e., 500x to 1000x demagnification) required for a plasma source. Both the FIB column section and the plasma ion column sections may have additional lenses 328 upstream from the spherical sector 326 and the common lower optics column 330.

[0048] A third column could also be added to the multi-beam system shown in FIG. 3, with the third column comprising, for example, an electron beam column. This electron beam column could also make use of the common lower optics. In this embodiment, the final lens will preferably be a

mixed magnetic/electrostatic lens. One advantage of this configuration would be that it would mitigate problems switching between a FIB beam and the SEM since all beams would co-axial to the magnetic objective lens. As a result, there would be little or no ion beam shift as the magnetic lens field strength slowly decays after the magnetic lens is switched off. This configuration would also serve to facilitate beam coincidence for all beams without stage moves and would allow one short working distance for all columns.

[0049] FIG. 4 describes a process using multibeam system 200. This process could also be employed using the multi-beam system shown in FIG. 3 with an electron beam column. In step 402, a workpiece is positioned on a stage in a sample chamber that has been or will be evacuated to a sufficiently low pressure for operation of focused ion beam column 210, plasma column 220, and electron column 230. In step 404, features of the workpiece, such as registration marks, are observed using the imaging function of the focused ion beam or the electron beam. In step 406, a beam of inert plasma ions is directed toward the workpiece to rapidly remove material. The material can be removed to nearly expose a buried feature, such as a portion of a semiconductor circuit, or to form the basic shape of a structure. The plasma ion beam can be repeatedly scanned over the desired portion of the workpiece to remove material or form a feature. In step 408, the electron beam is directed toward the workpiece to form an image of the results of step 406. Alternatively, the results of step 406 can be examined using an optional optical microscope in system 200. In step 410, a beam of liquid metal ions is directed toward the surface by ion column 210 to complete material removal or produce a desired fine structure at a higher resolution than is possible using the plasma beam.

[0050] The process described above can also make use of gas-assisted ion beam etching to selectively etch materials, depending on the materials to be etched and the surrounding materials. In one specific example, a multibeam system can be used to rapidly modify a semiconductor structure by cutting a buried metallic conductor. First, the plasma ion beam can be used to form a trench, rapidly removing a large amount of silicon material covering the buried conductor. Milling should be continued until the trench approaches the conductor, but should be stopped before the conductor is exposed. The ion beam is then used with an iodine etch precursor to etch away the remaining silicon and expose the buried conductor. The conductor can then be severed using the ion beam, assisted by an appropriate etch precursor gas that selectively etches the metal, leaving the insulator layer below the metal. The results can be viewed and monitored at various stages to monitor the process.

[0051] FIG. 5 shows another multibeam system 500 according to a preferred embodiment of the present invention in which a charged particle beam column 610 for precise high-resolution material processing is combined with a laser 640 that produces a pulsed laser beam 642 capable of rapid material removal. Laser 640 is preferably an ultra-fast pulsed laser such as a femtosecond laser described in U.S. Pat. No. 5,656,186 to Mourou et al. Such lasers can remove material much more quickly from a workpiece than can a typical ion beam produced by a liquid metal ion source, although the laser is not as precisely as the liquid metal focused ion beam. Multibeam system 600 also includes an electron beam column 620 producing electron beam 622, as described above.

[0052] In another preferred embodiment of the present invention, the high-resolution column could comprise an ion

column to be used primarily for imaging, such as an ALIS helium ion microscope available from Carl Zeiss SMT AG of Oberkochen, Germany. The column used for material removal could comprise a conventional Ga-FIB column.

[0053] In another preferred embodiment of the present invention, the multibeam system could comprise a FIB column combined with two different SEM columns in a three beam configuration. An advantage of this configuration is that the two SEMs could be optimized for different purposes. For example, one SEM could be optimized for electron beam-assisted etching and deposition, which is slower than ion beam processing but does not result in ion implantation or as much damage to the sample surface. The other SEM could be optimized for sample imaging and/or metrology. In another possible configuration, one SEM could be oriented at an angle with respect to the sample stage and the other SEM oriented at normal incidence to avoid the need for a tilting sample (or tilting SEM) capability while still maintaining dual SEM viewpoints.

[0054] A preferred method or apparatus of the present invention has many novel aspects, and because the invention can be embodied in different methods or apparatuses for different purposes, not every aspect need be present in every embodiment. Moreover, many of the aspects of the described embodiments may be separately patentable.

[0055] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made to the embodiments described herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

We claim as follows:

1. A charged-particle beam system, comprising:

a vacuum chamber;

a workpiece support for supporting a workpiece within the vacuum chamber;

an ion beam system including an ion source for generating ions and a focusing column for forming the ions into a beam having a sub-micron diameter at the workpiece;

an electron beam system including a source for generating electrons and a focusing column for forming the electrons into a beam having a sub-micron diameter at the workpiece; and

a third beam system including a source of focused beam capable of rapid material removal, the third beam system having a resolution significantly less than that of the ion beam system and a removal rate significantly greater than that of the ion beam system;

wherein the third beam system is suitable for rapid removal of material, the ion beam system is suitable for producing a feature at a higher resolution than the third beam

system, and the electron beam is suitable for forming a high resolution image of the workpiece.

2. The charged particle beam system of claim **1** in which the third beam comprises a laser.

3. The charged particle beam system of claim **2** in which the laser comprises a femtosecond laser.

4. The charged particle beam system of claim **1** in which the third beam comprises a plasma ion beam system.

5. The charged particle beam system of claim **4** in which the plasma ion beam system comprises an inductively coupled, magnetically enhanced plasma ion beam system.

6. The charged particle beam system of claim **4** in which the plasma ion beam system includes:

an antenna in proximity to the vessel, the antenna excited by an RF electrical source to induce ionization of the plasma;

circuitry that couples the antenna to the electrical source to substantially reduce oscillations in the ionized plasma; and

an extraction mechanism to extract the ionized plasma into a beam.

7. The charged particle beam system of claim **1** in which: the ion beam system comprises a liquid metal ion beam system;

the electron beam system includes a secondary electron detector for imaging the workpiece; and the third beam system comprises a laser.

8. The charged particle beam system of claim **1** in which: the ion beam system comprises a liquid metal ion beam system;

the electron beam system includes a secondary electron detector for imaging the workpiece; and the third beam system comprises a plasma ion beam system.

9. A charged-particle beam system, comprising:

a vacuum chamber;

a workpiece support for supporting a workpiece within the vacuum chamber;

a liquid metal ion beam system including a source for generating metal ions; and a focusing column for forming the metal ions into a beam having a sub-micron diameter at the workpiece;

an electron beam system including a source for generating electrons and a focusing column for forming the electrons into a beam having a sub-micron diameter at the workpiece; and

a plasma ion system including a plasma source of ions, and a focusing column for forming the ions from the plasma ion source into a beam and directing the beam to the workpiece.

10. A charged-particle beam system, comprising:

a vacuum chamber;

a workpiece support for supporting a workpiece within the vacuum chamber;

a liquid metal ion beam system including a source for generating metal ions; and a focusing column for forming the metal ions into a beam having a sub-micron diameter at the workpiece;

a plasma ion system including a plasma source of ions, and a focusing column for forming the ions from the plasma ion source into a beam and directing the beam to the workpiece;

the ion focusing column and the plasma focusing column sharing a common optical column comprising one or

more lenses for focusing either the metal ions or the plasma ions onto the workpiece.

11. The charged-particle beam system of claim **10** in which:

- the metal ion beam source is located on the same axis as the common optical column;
- the plasma ion beam source is located off the axis of the common optical column; and
- an electrostatic spherical sector is used to deflect the plasma beam onto the axis of the common optical column so that the metal ion beam and the plasma ion beam will be coincident on a sample.

12. The charged-particle beam system of claim **11** in which the electrostatic spherical sector is a stigmatic imaging, 90 degree electrostatic spherical sector.

13. The charged-particle beam system of claim **11** in which the electrostatic spherical sector is a stigmatic imaging magnetic mass filter.

14. The charged-particle beam system of claim **10** in which the common optical column has two common lenses suitable for achieving optical demagnification from 500× to 1000× for a plasma source.

15. The charged-particle beam system of claim **10** further comprising an electron beam column.

16. The charged-particle beam system of claim **15** in which the electron column also shares the common optical column and in which the common optical column includes a mixed magnetic/electrostatic lens.

17. A method of processing a sample using a multibeam system, the system having a first ion column, a second ion

column, and an electron beam column, with the first ion column producing an ion beam that has a greater beam current and a larger beam diameter than the ion beam produced by the second ion column, the method comprising:

- imaging the sample using the second ion beam column or the electron beam column;
- directing a beam of ions using the first ion column toward the sample to rapidly remove material from the sample;
- re-imaging the sample using the second ion beam column or the electron beam column after the material has been removed by the ion beam from the first ion column; and
- directing a beam of ions toward the sample using the second ion column to complete the desired material removal.

18. The method of claim **17** in which the first ion column is a plasma ion column and the second ion column is a liquid metal ion column.

19. The system of claim **4** in which the plasma ion beam has a beam current greater than 100 nanoamps.

20. The system of claim **4** in which the plasma ion beam has a beam diameter of 10 nm to 50 μm.

21. The system of claim **4** in which the plasma ion beam has a beam current of 300 to 20,000 nanoamps.

22. The system of claim **4** in which the plasma ion beam has a beam current of 1500 to 5000 nanoamps.

23. The system of claim **4** in which the ion beam has a beam current less than 20 nanoamps.

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