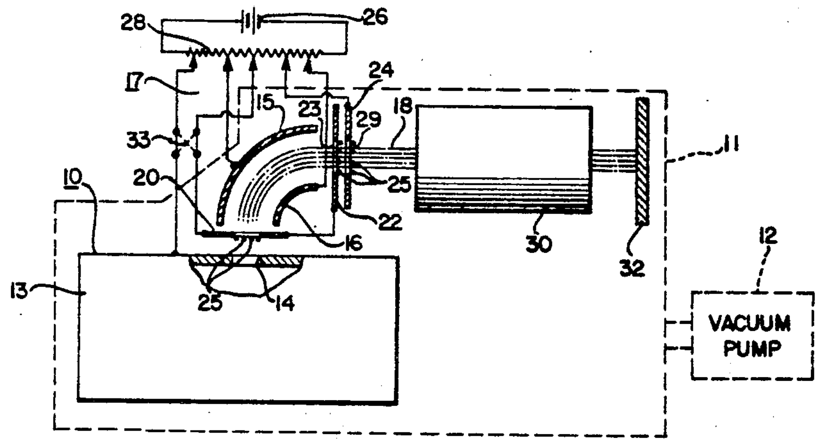
Jan. 7, 1964 G. A. BRONSON ETAL 3,117,022

DEPOSITION ARRANGEMENT

Filed Sept. 6, 1960

FIG. 1.



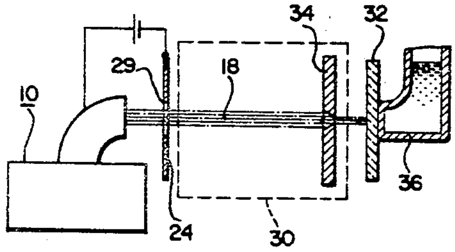


FIG. 2.

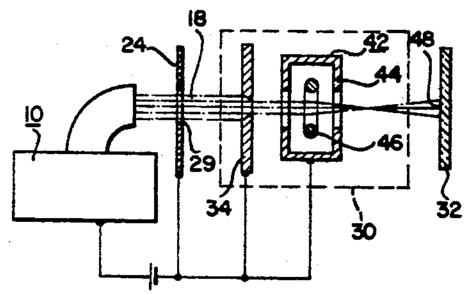


FIG. 3.

FIG. 4.

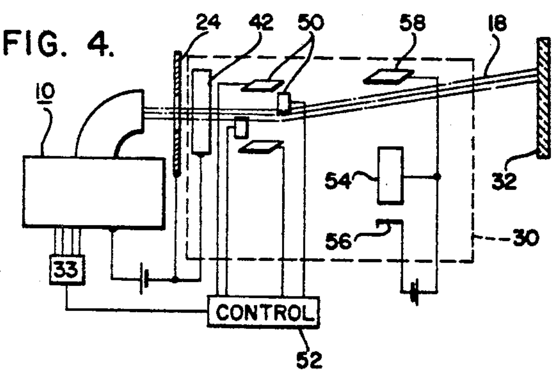
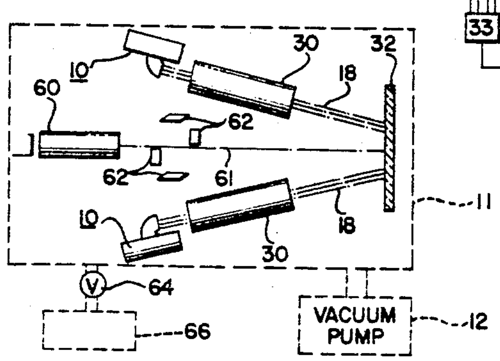


FIG. 5.



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United States Patent Office 3,117,022
Patented Jan. 7, 1964

3,117,022

DEPOSITION ARRANGEMENT

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Filed Sept. 6, 1960, Ser. No. 54,042
12 Claims. (Cl. 117—212)

The present invention relates to a deposition arrangement and more particularly to an arrangement for depositing ions on a substrate to obtain preselected metal deposition configurations.

It is recognized that the laying down of a thin metal film in intricate patterns, particularly miniaturized circuit patterns requisite for microminiaturized cryogenic computer elements, requires techniques which provide extremely precise control of deposition. Prior art techniques utilizing evaporation for applying a metal through a mask are subject to various problems such as the re-evaporation of atoms having excessive kinetic energies and the difficulty of constructing masks of the required accuracy. Minute dust particles or burrs on the mask cause undesired alteration of the deposition pattern, and the finite size of the source often results in lack of sharpness of the edges of the deposited film. Not only must the mask be extremely accurate and clean, but the various portions of it must be supported in a way which will not cause unwanted shadows in the deposited film. In addition, the evaporated particles always have a wide range of velocities whereby fast molecules overtake and collide with slow molecules and cause scattering and deposition of metal on portions of the substrate which are intended to be shielded from the source of metal.

If metal ions rather than neutral atoms are utilized in making the deposits, the velocity and trajectories of the ions may be controlled.

Therefore, an object of the present invention is to provide an arrangement accurately controlling ionized metal atoms whereby they may be systematically applied to a substrate.

Although metal ions have a mass several orders of magnitude greater than that of an electron, they can be deflected in much the same way by electric and magnetic fields, can be accelerated and decelerated, and can be focused by an ion lens. Because of the larger mass of the metal ions, the theoretical limit of resolution is far better than for electrons, such as in an electron microscope. In practice, the resolution is not limited by diffraction at all, but by the aberrations in the ion lens.

Therefore, a further object is to provide an arrangement for developing a focused ion beam which may be directed to a substrate.

Another object is to provide an arrangement for deflecting a focused ion beam to impinge on selected portions of a substrate.

In accordance with one embodiment of the present invention, ionized atoms are discharged toward a substrate. The ions are accelerated and sorted according to charge to mass ratio and are sorted according to velocity, whereby they emerge as a homogeneous ion beam. This homogeneous ion beam is substantially collimated and is of a known predetermined velocity. The velocity, and therefore the kinetic energy of the ions, is regulated for minimum re-evaporation. Since all of the ions have substantially the same velocity, there is also a minimal scattering within the beam because of collisions between the particles. When such a beam traverses a mask which is close to the substrate, the resulting deposition has sharply defined edges.

In accordance with another embodiment of the present invention, the collimated beam passes through a mask and is then focused on the substrate. In this arrangement, the mask may be substantially removed from the substrate and the image created on the substrate by the ion lens may be much smaller than the aperture of the mask. Consequently, any re-evaporation or scattering of metal atoms from the edges of the mask are widely dispersed and do not impair the pattern of deposition. In addition, since the mask may be much larger than the deposited pattern, the problems connected with construction of the mask are vastly alleviated and minute burrs and dust particles cannot seriously impair the definition of the image. Since the image on the substrate is actually a focused image of the mask, there is no lack of sharpness due to the size of the source.

In accordance with another embodiment of the invention, the collimated beam is focused to a minute spot or fine line and is electrostatically or magnetically deflected across the substrate to develop a deposition of predetermined configuration.

The subject matter which is regarded as this invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, as to its organization and operation, together with further objects and advantages thereof, will best be understood by reference to the following description taken in connection with the accompanying drawing in which:

FIG. 1 is a schematic plan view of an arrangement illustrating the present invention;

FIG. 2 is a schematic diagram illustrating one arrangement of the invention illustrated in FIG. 1;

FIG. 3 is a schematic diagram of another arrangement of the invention illustrated in FIG. 1;

FIG. 4 is a schematic diagram of still another arrangement of the invention illustrated in FIG. 1; and

FIG. 5 is a block diagram illustrating an arrangement of the present invention for depositing a complex circuit on a substrate.

Referring now to the drawing, wherein like numbers indicate similar parts, there is shown in FIG. 1 an ion gun **10** within an evacuated container **11** defined by dashed lines. During operation of the ion gun **10**, the pressure within the evacuated container is maintained at about 10^{-8} mm. of mercury by a vacuum pump **13**. In practicing the present invention there are several types of ion sources suitable for developing ion beams. The particular details of the ion sources are not a portion of the present invention. However, several ion sources are described in some detail in "High Efficiency Ion Source," by A. T. Finkelstein, in "Reviews of Scientific Instruments," volume 11, 1940; "A Mass Spectrometer for Isotope and Gas Analysis," by A. O. Nier, in "Reviews of Scientific Instruments," volume 18, page 398, 1947; "Sources and Collectors for Use in Calutrons," by Wakerling and Guthrie, published in 1949 by the Office of Technical Services, Department of Commerce, Washington 25, D.C.; and "Problems of Physics in the Ion Source," by Barnes, MacNeille, and Starr, published in 1951 by the Office of Technical Services, Department of Commerce, Washington 25, D.C. Each of the sources accomplishes a vapor of particles, some of which are ionized. Ion guns adapted for use in the present invention selectively provide one of many types of metal ions such as copper, tin, lead, indium, etc., and several guns may be used together to deposit alloys.

Another ion gun arrangement, as illustrated in FIG. 1, utilizes an ion source **13**, producing positive metallic ions. A portion of the positively charged ions will pass through an aperture **14** and enter a velocity discriminating arrangement **17**, including a pair of arcuate deflection electrodes **15** and **16** energized to potentials such that the deflection electrode **16** attracts the ions and the deflection electrode **15** repels the ions, whereby they will follow circular paths of radii dependent upon their charges and velocities. One arrangement for establishing an average velocity of the ions emitted from the aperture **14** suitable for providing a collimated ion beam **18** utilizes an accelerating electrode **20** adjacent the aperture **14**. Another electrode **22** is provided having a central aperture **23** defining the size of the ion beam **18**. The electrodes **20** and **22** are coupled together to have the same potential. The final velocity of the ions is established by a velocity selecting electrode **24**. It is preferred that each of the electrodes **20**, **22**, and **24** be provided with grids **25** covering their respective apertures to develop a linear field therebetween. As a result, there will not be developed any ion focusing fields therebetween and a variation of the potential of the electrodes will change only the velocity of the collimated ion beam **18**.

The voltages applied to the deflection electrodes **15** and **16**, the electrodes **20** and **22**, and the velocity selecting electrode **24** relative to the ion source **13** are established by a unidirectional voltage source **26** which develops a voltage across a voltage divider arrangement **28** having a plurality of taps thereon whereby the electrode **16** is negative with respect to the ion source **13** and the deflection electrode **15** is positive with respect to the deflection electrode **16**. Electrodes **20** and **22** are at a potential intermediate to the deflection electrodes **15** and **16** and the electrode **24** is at a potential, dependent upon the desired velocity of the ion beam **18**. The voltage differential across the entire voltage divider arrangement **28** is maintained at a relatively low magnitude to establish a relatively low velocity ion beam which will not cause the energy of ions to be great enough to erode the substrate upon which they are to be deposited. The ions flowing from the ion gun **10**, which escape through a small central screened aperture **29** of the velocity selecting electrode **24**, define the uniform velocity collimated ion beam **18**. Any ions of a velocity slightly different from that of the ion beam **18** will impinge upon the electrode **22**, and any ions of a velocity substantially different or of a different charge to mass ratio will impinge upon one of the deflection electrodes **15** or **16**. The collimated beam **18** passes into an ion deposition arrangement **30** to a substrate **32**, both of which are also within the evacuated container **11**. When it is necessary to terminate abruptly the flow of the ion beam **18**, a reversing switch **33** is energized to reverse the potential between this ion source **13** and the electrode **20**. This switch **33** could, of course, be an electronic switch.

Referring now to FIG. 2 there is shown one arrangement for obtaining an improved metallic deposition on the substrate **32**. The collimated ion beam **18** is presented to the ion deposition arrangement **30** through the small aperture **29** of the velocity selecting electrode **24** with the result that the ions flow at a uniform velocity and in substantially parallel paths within the narrow collimated ion beam **18**. The ion gun **10** generates an ion beam producing a more defined deposition as a function of the aperture arrangement of a mask **34** than is experienced in hot vapor deposition. The uniform velocity of the ion beam **18** eliminates scattering due to ion collisions. Moreover, the collimated ion flow eliminates any penumbra effect, resulting from a large vapor source.

Often it is desired to maintain the substrate **32** at relatively low temperature to prevent re-evaporation and excessive migration of the ions on the surface. One means of removing any excess heat presented thereto by the ion beam **18** is by the placing of a heat absorbing arrangement, such as a liquid air container **36**, adjacent to the substrate **32**.

Referring now to FIG. 3 there is shown another ion deposition arrangement **30** wherein the collimated ion beam **18** traverses a focusing arrangement so that the ions may be deposited on the substrate to provide a film which is a miniature size image **48** of the apertures in the mask **34**. As shown, the mask **34** is located along

the axis of the ion beam **18** where the beam is of a relatively large radius. The particular ion focusing arrangement **42** illustrated herein is known in the electron optical art as an Einzel lens, wherein an annular shell **44** shields a toroidal member **46** with the toroidal member **46** being maintained at a potential different from that of the shell **44**.

This voltage relationship develops electrostatic fields which effectively turns the ions and bring them to a focus as an image **48** at the surface of the substrate **32**. The electrostatic fields established within the lens **42** are curved so that the ions near the periphery of the collimated ion beam **18** are accelerated toward the center thereof while the ions at the center are substantially unaffected. It is preferred that the annular shell **44** of the lens **42** be at potential equal to the potential which establishes the velocity of the beam. Therefore, the shell **44** is coupled both to the velocity selecting electrode **24** and to the mask **34**. This potential will be on the order of a few volts relative to the ion source **13** to provide a relatively low velocity ion beam.

Referring now to FIG. 4, an arrangement is illustrated wherein no mask is utilized. However, the electrode **24** establishes the outer periphery of the collimated ion beam **18** which is then focused during its passage through the ion lens **42**. The desired selective deposition on the substrate **32** is accomplished by deflecting the ion beam **18**. Although electromagnetic deflection is useful in the present invention, FIG. 4 illustrates electrostatic deflection by means of both horizontal and vertical deflection plates **50** which are energized in accordance with signal information supplied thereto from a control **52** operated from magnetic tape or other information storage means. Usually the control **52** will also operate the switch means **33** to terminate the electron beam.

It is recognized that space charge effects in an ion beam are more serious than in an electron beam of the same current density operating with the same accelerating voltage. Although the ion beam particles are much heavier than electrons, their velocity is lower so that for equal current the number of particles must be larger per unit length of the beam. Thus the space charge forces are greater and act for a longer period of time, giving rise to more beam dispersion than would be experienced by an electron beam.

It is also preferred that the ions impinging upon the substrate **32** do not develop thereon a positive space charge which will repel the positive ion beam. This space charge is particularly troublesome when the substrate surface upon which the ion beam is directed is an insulator such as plastic, quartz, etc., or an insulation coating such as may be placed on a previous metal coating. One arrangement for eliminating the positive charge of the ion beam is to place electrons in the beam. Although some electrons are developed by the collisions between metal ions and residual gas ions within the evacuated container **11**, these may not be of sufficient numbers to completely balance the charges of the ion beam.

Therefore, as shown in FIG. 4, electrons may be placed in the ion beam by a low velocity electron gun **54** having a cathode **56** of a potential only slightly negative relative to a collector electrode **58**. The electrons which drift into the ion beam **18** will be attracted as long as the beam has an average positive charge and will pass through to be collected by the electrode **58** when the ion beam is exactly neutralized. Moreover, because there is no longitudinal field in the region of insertion of the electrons, they will not be swept out of the ion beam but will tend to stay with the ion beam and neutralize any tendency to positively charge the substrate **32**. In arrangements where magnetic deflection is used, the electrons may be inserted prior to the deflection of the beam. Such a space charge neutralizing arrangement may also be used in the arrangements illustrated in FIGS. 1, 2, and 3.

It should be kept in mind that the arrangement of the of radii dependent upon their charges and velocities. One arrangement for establishing an average velocity of the ions emitted from the aperture **14** suitable for providing a collimated ion beam **18** utilizes an accelerating electrode **20** adjacent the aperture **14**. Another electrode **22** is provided having a central aperture **23** defining the size of the ion beam **18**. The electrodes **20** and **22** are coupled together to have the same potential. The final velocity of the ions is established by a velocity selecting electrode **24**. It is preferred that each of the electrodes **20**, **22**, and **24** be provided with grids **25** covering their respective apertures to develop a linear field therebetween. As a result, there will not be developed any ion focusing fields therebetween and a variation of the potential of the electrodes will change only the velocity of the collimated ion beam **18**.

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This voltage relationship develops electrostatic fields which effectively turns the ions and bring them to a focus as an image **48** at the surface of the substrate **32**. The electrostatic fields established within the lens **42** are curved so that the ions near the periphery of the collimated ion beam **18** are accelerated toward the center thereof while the ions at the center are substantially unaffected. It is preferred that the annular shell **44** of the lens **42** be at potential equal to the potential which establishes the velocity of the beam. Therefore, the shell **44** is coupled both to the velocity selecting electrode **24** and to the mask **34**. This potential will be on the order of a few volts relative to the ion source **13** to provide a relatively low velocity ion beam.

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It is recognized that space charge effects in an ion beam are more serious than in an electron beam of the same current density operating with the same accelerating voltage. Although the ion beam particles are much heavier than electrons, their velocity is lower so that for equal current the number of particles must be larger per unit length of the beam. Thus the space charge forces are greater and act for a longer period of time, giving rise to more beam dispersion than would be experienced by an electron beam.

It is also preferred that the ions impinging upon the substrate **32** do not develop thereon a positive space charge which will repel the positive ion beam. This space charge is particularly troublesome when the substrate surface upon which the ion beam is directed is an insulator such as plastic, quartz, etc., or an insulation coating such as may be placed on a previous metal coating. One arrangement for eliminating the positive charge of the ion beam is to place electrons in the beam. Although some electrons are developed by the collisions between metal ions and residual gas ions within the evacuated container **11**, these may not be of sufficient numbers to completely balance the charges of the ion beam.

Therefore, as shown in FIG. 4, electrons may be placed in the ion beam by a low velocity electron gun **54** having a cathode **56** of a potential only slightly negative relative to a collector electrode **58**. The electrons which drift into the ion beam **18** will be attracted as long as the beam has an average positive charge and will pass through to be collected by the electrode **58** when the ion beam is exactly neutralized. Moreover, because there is no longitudinal field in the region of insertion of the electrons, they will not be swept out of the ion beam but will tend to stay with the ion beam and neutralize any tendency to positively charge the substrate **32**. In arrangements where magnetic deflection is used, the electrons may be inserted prior to the deflection of the beam. Such a space charge neutralizing arrangement may also be used in the arrangements illustrated in FIGS. 1, 2, and 3.

It should be kept in mind that the arrangement of the present invention is suitable for developing relatively complex combinations of depositions on the substrate 32. Referring now to FIG. 5, there is shown a plurality of ion guns 10 and a plurality of deposition arrangements 30 of the type described above. The resulting ion beams may be made to overlap selectively various portions of the substrate 32 by slanting the ion deposition arrangements 30 as shown in FIGS. 2 and 3 or by use of the ion deposition arrangement shown in FIG. 4. When an alloy deposition is required, ion beams of the different metal ions may be simultaneously directed to the same region of the substrate 32 and, by careful regulation of the ion currents alloy solution, deposition of precise percentages of the different metals are obtained.

Often it is necessary to deposit two or more layers of conductive metals having a layer of insulation therebetween. The arrangement of FIG. 5 will accomplish such a process by selective operation of one of the ion guns 10 to place a single type of metal on the substrate 32 or by selective operation of both of the ion guns to place two different types of metal at different locations on the substrate 32 and then de-energizing the ion guns by operation of a switch means 33 to temporarily terminate metal deposition. Next, a layer of insulation is accomplished over selected portions of the conductive metal depositions by admitting to the evacuated container 11 an insulation forming material such as certain of the silicone monomers which may be polymerized on the surface of the substrate 32 by the application of an electron beam 61 from a gun 60 with the points of location of the polymerization being controlled by the energization of electron beam deflection plates 62. The insulation material is normally prevented from entering the evacuated container 11 during the deposition of metal by a control valve 64 connected between the container 11 and an insulation reservoir 66. During application of the insulation, the characteristics of the vacuum pump 12 are modified so that the vapor pressure within the container may be substantially above 10^{-8} mm. of mercury. After a desired configuration of insulation has been polymerized over such portions of the substrate 32, the valve 64 is closed and the container 11 is re-evacuated whereby other layers of metal may be selectively applied to the substrate 32 and to the layer of insulation.

Thus the arrangement of FIG. 5 illustrates a method for developing a complete sub-circuit assembly having overlapping portions of different conductive materials with the overlapping portions being selectively insulated from one another. As a result of such a method of operation the substrate 32 may have developed thereon a complete cryogenic sub-circuit component including connection leads and necessary insulation. When placing cryogenic sub-circuits and elements, the metal coatings will have dimensions as small as one micron or less in width and a few Angstrom units in thickness. When it is desired to operate the deposition arrangement of the present invention for long periods with a minimum of maintenance, it is preferred that all portions of the ion gun 10 be maintained at a temperature slightly above the melting temperature of the metal flowing therethrough so that any particles which strike a surface of the gun will flow downward to a region which will not greatly influence the character of the collimated ion beam 18.

What is claimed is:

1. A deposition arrangement including an ion gun comprising: an ion source for generating positive metal ions; velocity control means associated with said ion source for developing a flow of ions of a predetermined average velocity; velocity sorting means associated with said ion source for preventing flow of ions excepting those of a preselected velocity whereby the ions released from the ion source flow as a collimated ion beam with each ion being substantially of said preselected velocity; and means maintained at a potential substantially equal to that of said velocity sorting means for directing the ion beam to a substrate to obtain metal deposition thereon of a predetermined configuration.

2. A deposition arrangement for selectively coating a substrate, comprising: an ion gun for generating positive metal ions directed toward the substrate; velocity control means associated with said ion gun for developing a flow of ions of a predetermined average velocity; velocity sorting means associated with said ion gun for deflecting ions as a function of their velocity and charge to mass ratio to pass through a central aperture only ions of a preselected velocity whereby the ions released from said ion gun flow as a collimated ion beam with each ion being substantially of said preselected velocity; and means maintained at a potential substantially equal to that of said velocity sorting means for maintaining a constant velocity of the ion beam between said ion gun and the substrate, said constant velocity being low enough to obtain metal deposition of a predetermined configuration on the substrate without eroding the substrate surface.

3. A deposition arrangement for developing metal coatings on selected portions of a substrate, comprising: a first ion gun producing a first collimated beam of metal ions all having substantially the same low velocity; an ion lens positioned in the path of the first collimated beam; electrostatic deflection means arranged to program the impingement of the first collimated ion beam on the substrate; means neutralizing the average charge of the first collimated ion beam to prevent developing a space charge on the substrate; a second ion gun producing a second collimated beam of metal ions having a uniform velocity, said second collimated beam being constituted of ions of a metal different from the first collimated ion beam; and means for controlling exposure of the substrate to ions of the second collimated ion beam to develop selected coated regions of the different metal.

4. A deposition arrangement for developing a complex deposition coating on a substrate, comprising: a first ion gun for generating a collimated beam of metal ions; a second ion gun for generating a collimated beam of different metal ions; means for energizing each of said ion guns to deposit coatings of interleaved metal configurations; valve means operable during a time duration between operation of said ion guns for releasing an insulation producing vapor adjacent to the coated surface; means for selectively causing said vapor to adhere to the substrate as an insulation film covering portions of said configurations; and means for removing said vapor to allow additional metal coatings on the substrate and on the insulation film.

5. A method of selectively coating a substrate in vacuum, comprising:
- developing a vapor of metal ions;
- accelerating the metal ions to a low velocity;
- sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a uniform velocity ion beam;
- and focusing the ion beam to cause it to impinge on selected regions only of said substrate.

6. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; accelerating the metal ions to a low velocity; sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a constant velocity ion beam; and causing the ion beam to impinge on only selected portions of the substrate.

7. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; accelerating the metal ions to a low velocity; sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a constant velocity ion beam; passing the ion beam through a mask; and focusing the ion beam to develop an image of the mask on the substrate.

8. A process for selectively coating a substrate in vac-

uum, comprising the steps of: developing a vapor of metal ions; accelerating the metal ions to a low velocity; sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a constant velocity ion beam; and passing the ion beam through a mask to impinge on only selected portions of the substrate.

9. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; accelerating the metal ions to a low velocity; sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a constant velocity ion beam; focusing the constant velocity ion beam; and deflecting the focused ion beam to impinge on selected portions of the substrate.

10. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; accelerating the metal ions to a low velocity; sorting the accelerated ions to trap any but those of a preselected charge and a preselected low velocity to thereby develop a constant velocity ion beam; neutralizing the space charge of the constant velocity beam, and causing the ion beam to impinge on only selected portions of the substrate.

11. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; intermittently accelerating the metal ions to form an intermittent low velocity ion flow; sorting the accelerated ions to trap any but those of a preselected

charge and a preselected low velocity to thereby develop a constant velocity ion beam during periods of ion flow; focusing the constant velocity ion beam, and deflecting the ion beam during periods of ion flow and changing the deflection arrangement during periods between ion flows to develop depositions on the substrate with space therebetween.

12. A process for selectively coating a substrate in vacuum, comprising the steps of: developing a vapor of metal ions; intermittently accelerating the metal ions to form an intermittent low velocity ion flow; sorting the accelerated ions to trap any but those of a preselected charge and a preselceted low velocity to thereby develop a constant velocity ion beam during periods of ion flow; focusing the constant velocity ion beam, deflecting the ion beam during periods between ion flows to develop depositions on the substrate with space therebetween; and neutralizing the space charge of the deflected ion beam, to prevent developing of a charge on the surface of the substrate.

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