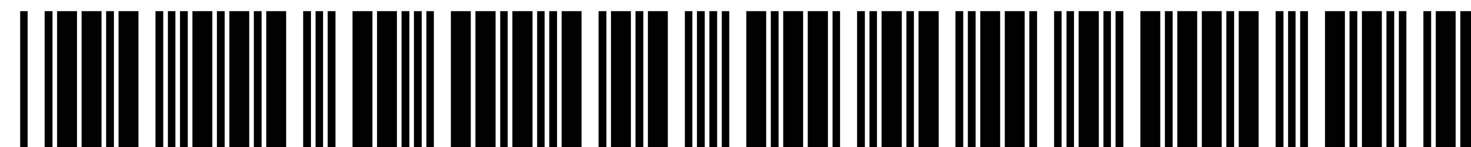

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(54) **BI MODE ION IMPLANTATION WITH NON-PARALLEL ION BEAMS**

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(58) **Field of Classification Search** 250/492.21, 250/442.11

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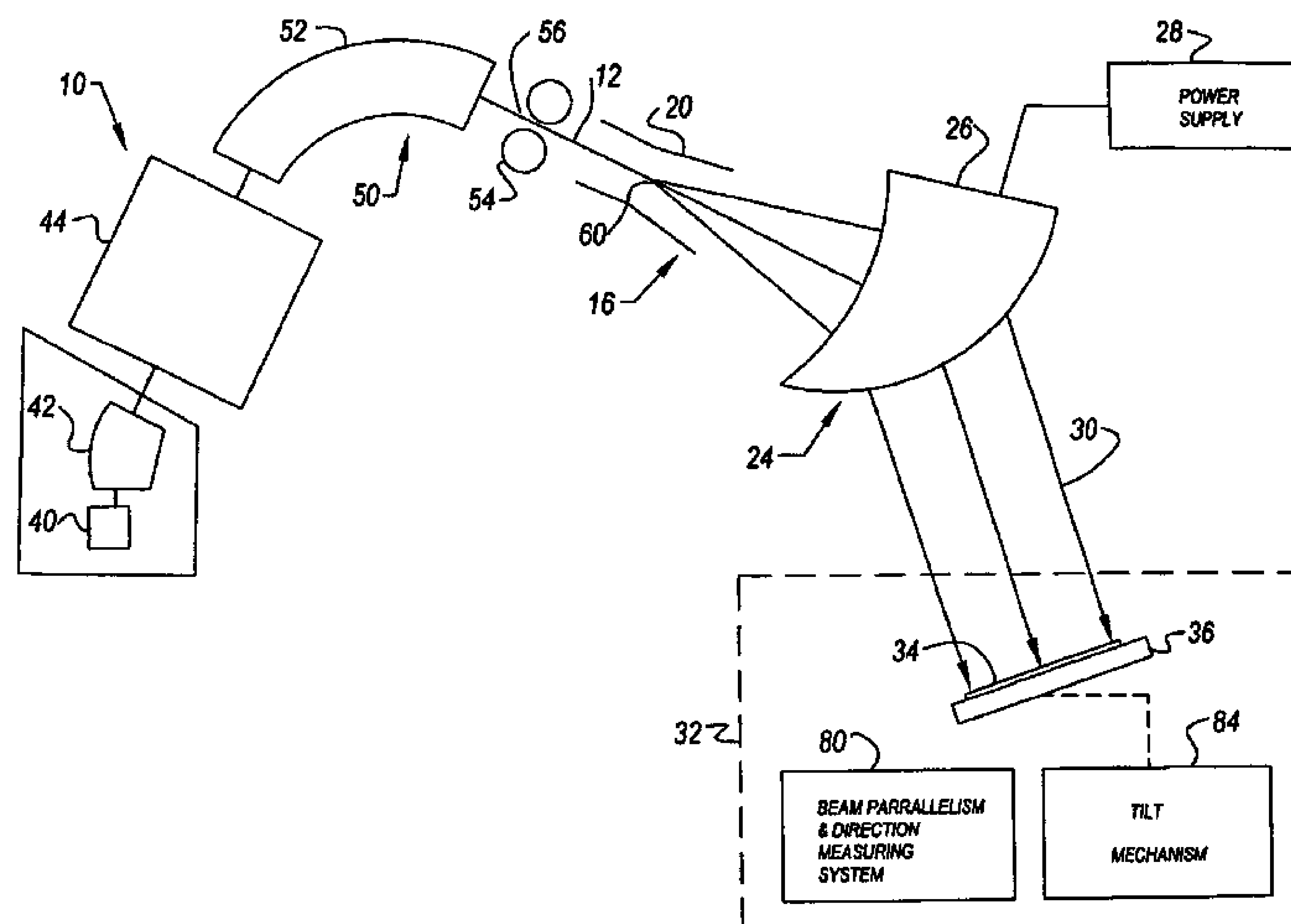
(57) **ABSTRACT**

A method for implanting ions into a workpiece, such as a semiconductor wafer, includes the steps of generating an ion beam, measuring an angle of non-parallelism of the ion beam, tilting the wafer at a first angle, performing a first implant at the first angle, tilting the wafer at a second angle, and performing a second implant at the second angle. The first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism. Preferably, the first and second implants are controlled to provide substantially equal ion doses in the workpiece.

49 Claims, 7 Drawing Sheets



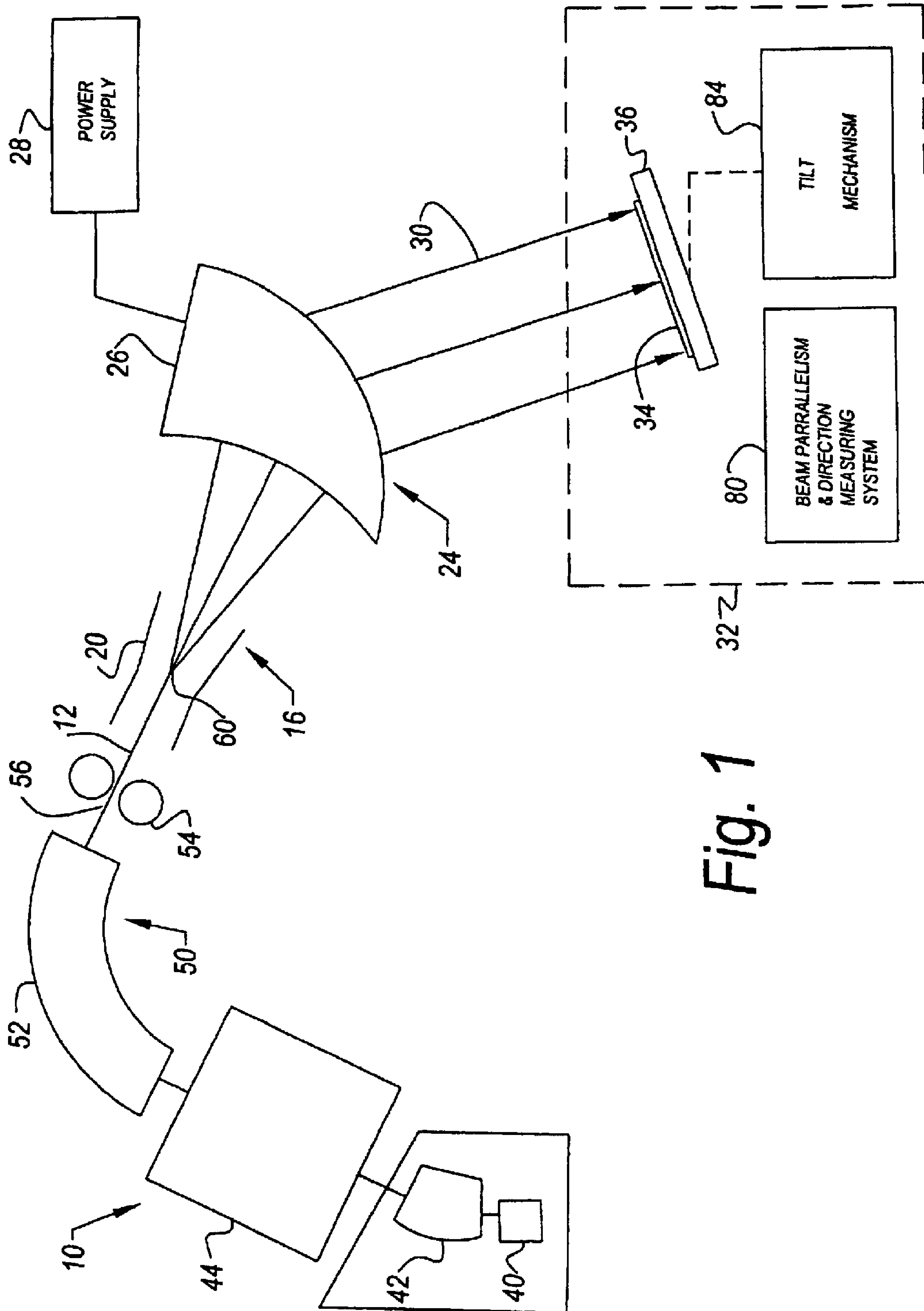


Fig. 1

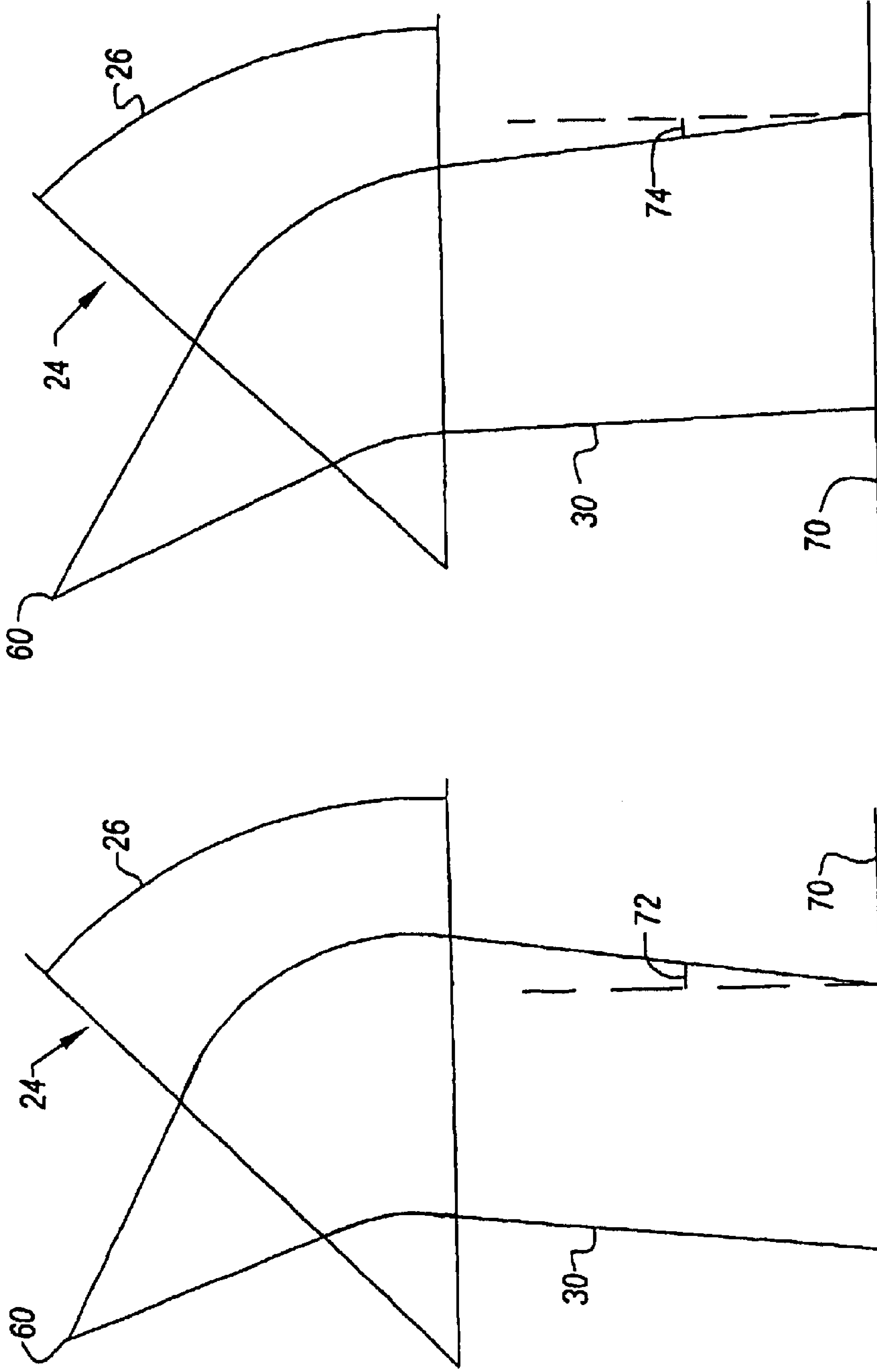


Fig. 3

Fig. 2

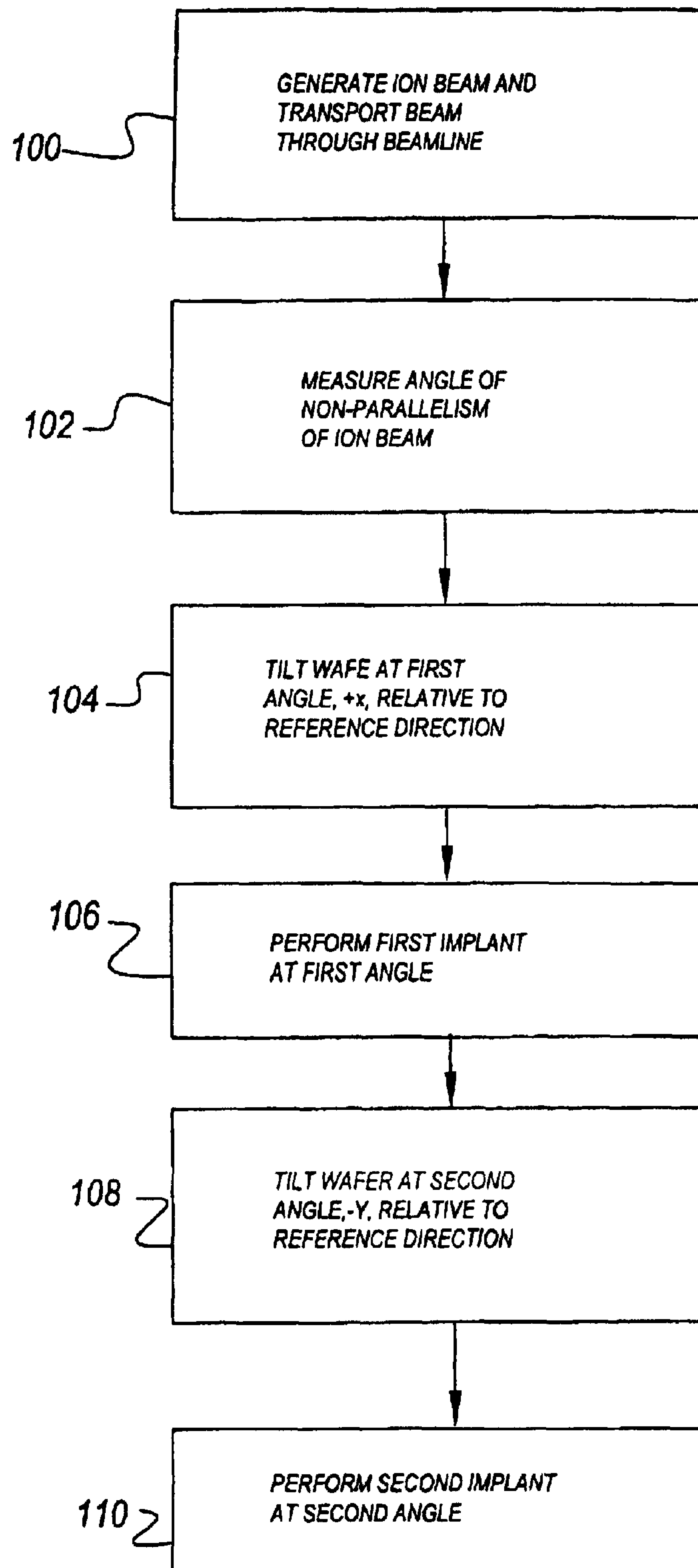


Fig. 4

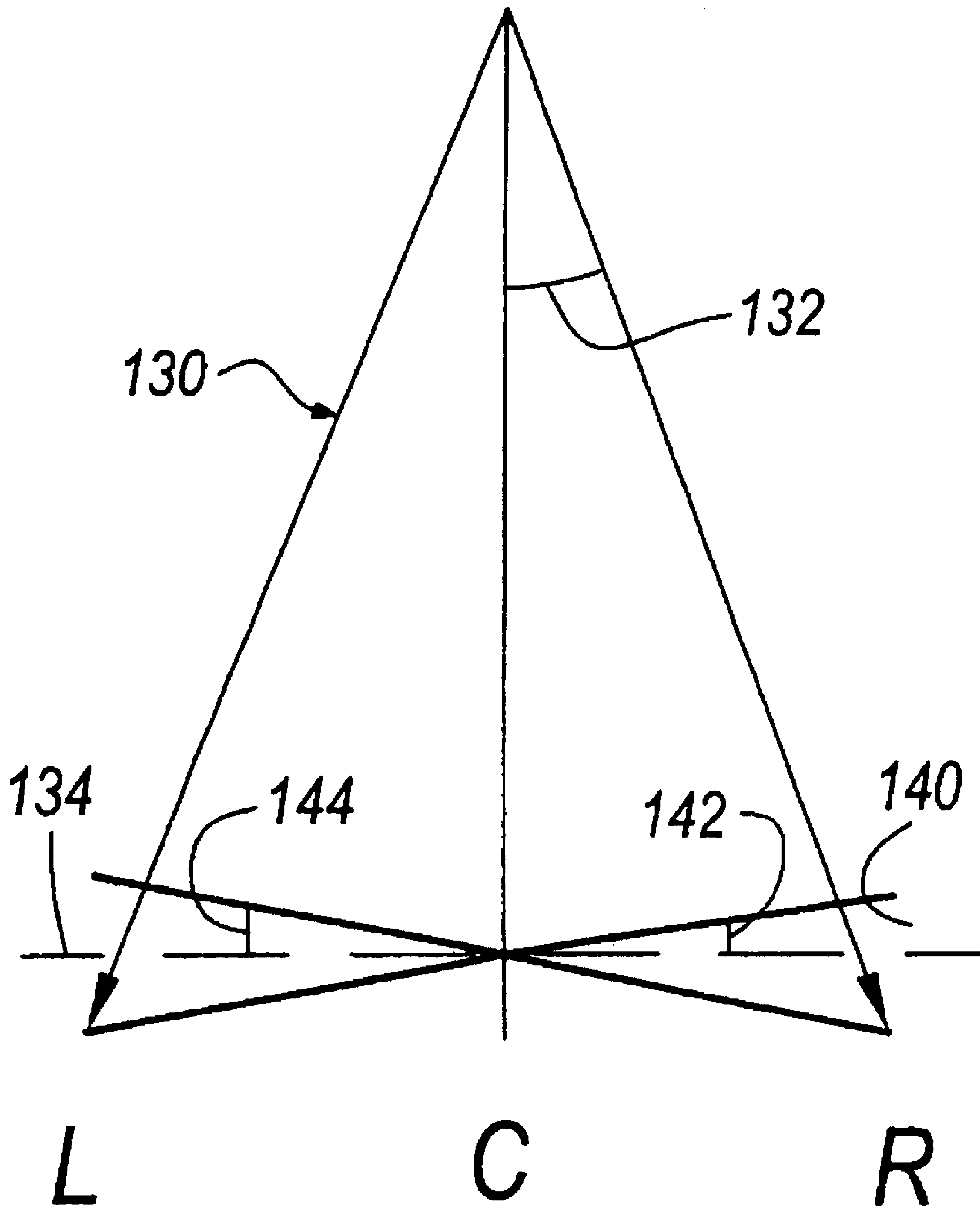


Fig. 5

	L	C	R
FIRST BI MODE IMPLANT	2	1	0
SECOND BI MODE IMPLANT	0	-1	-2
BI MODE AVERAGE	1	1	1

Fig. 6

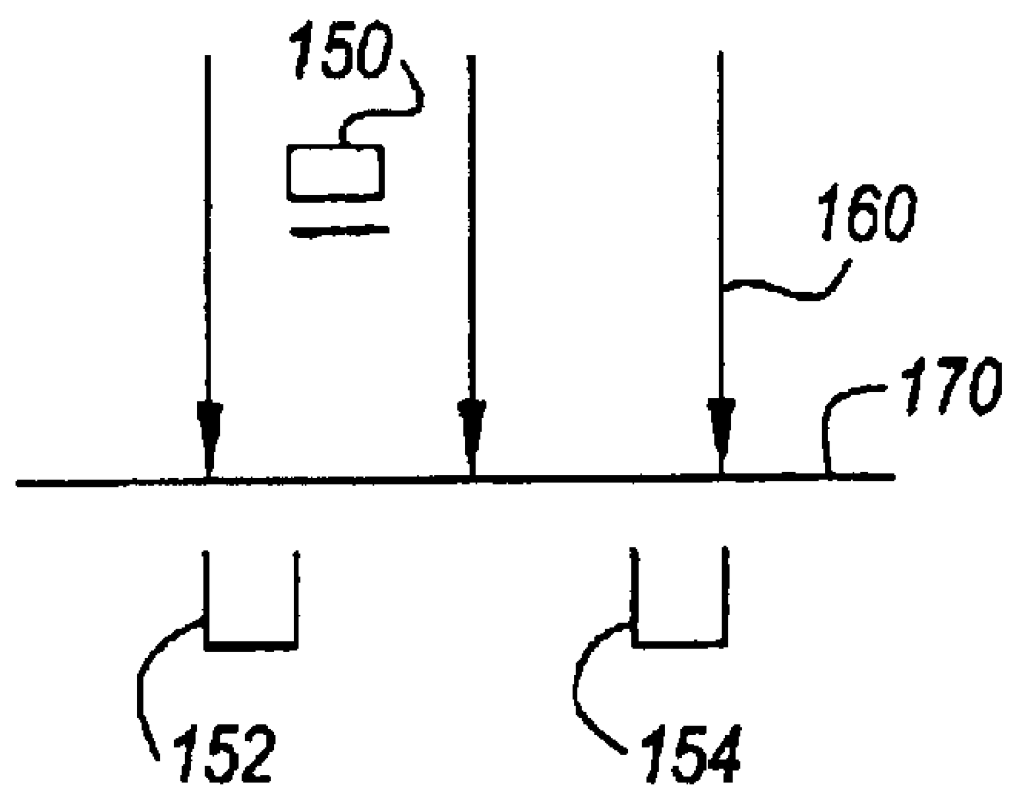


Fig. 7A

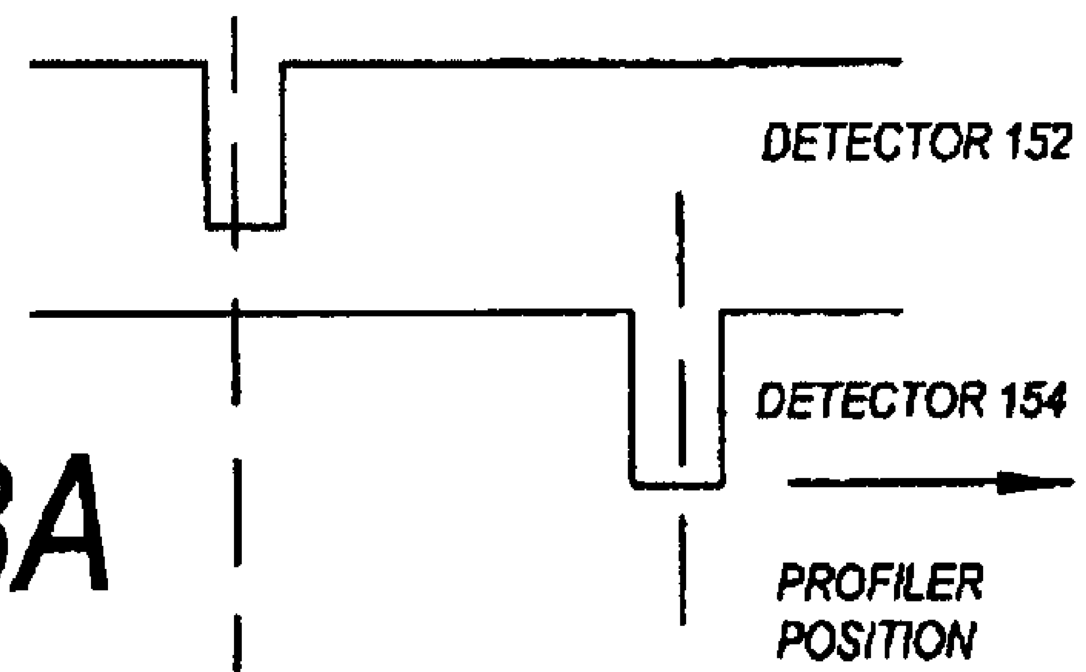


Fig. 8A

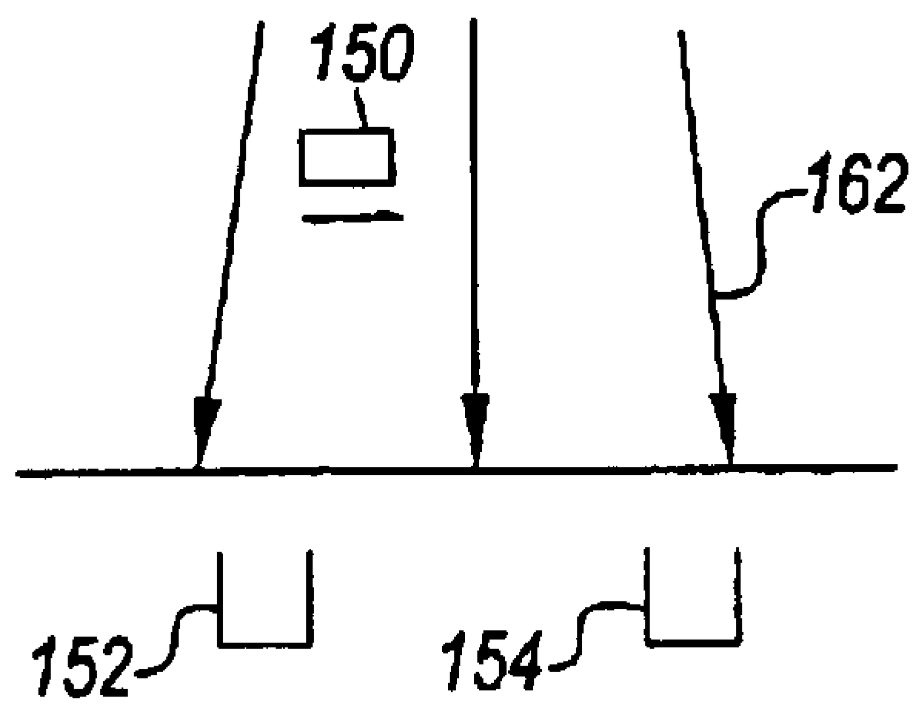


Fig. 7B

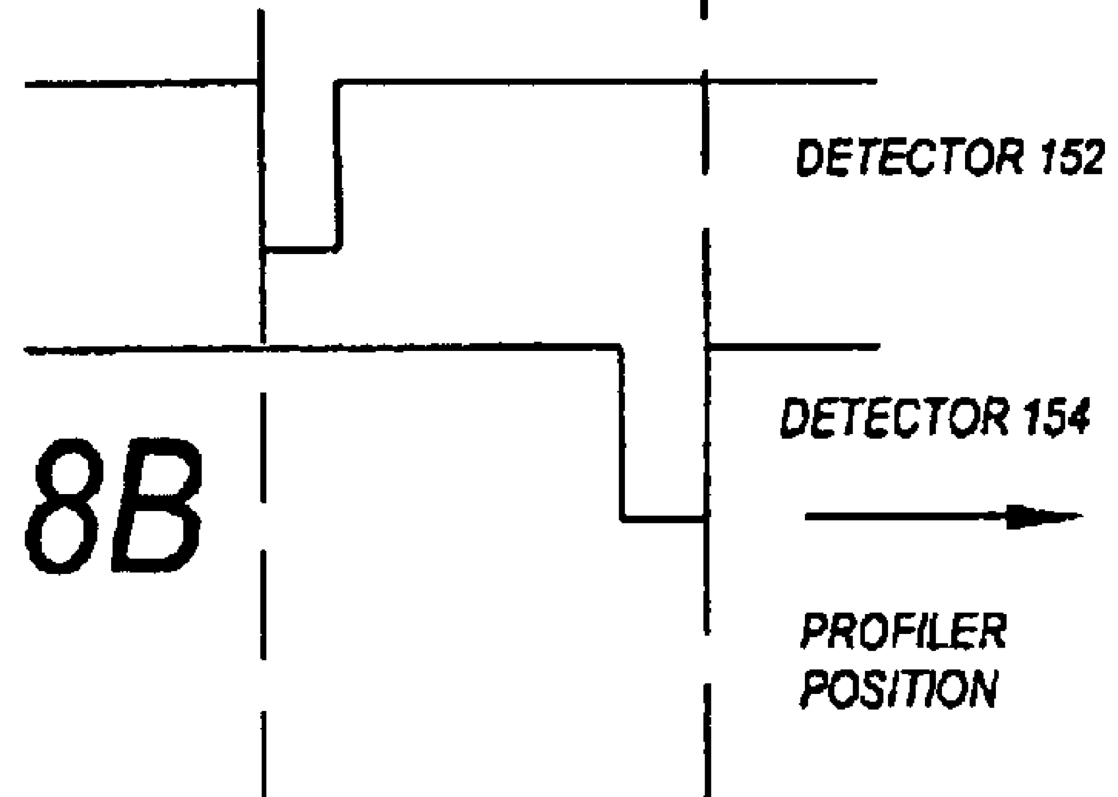


Fig. 8B

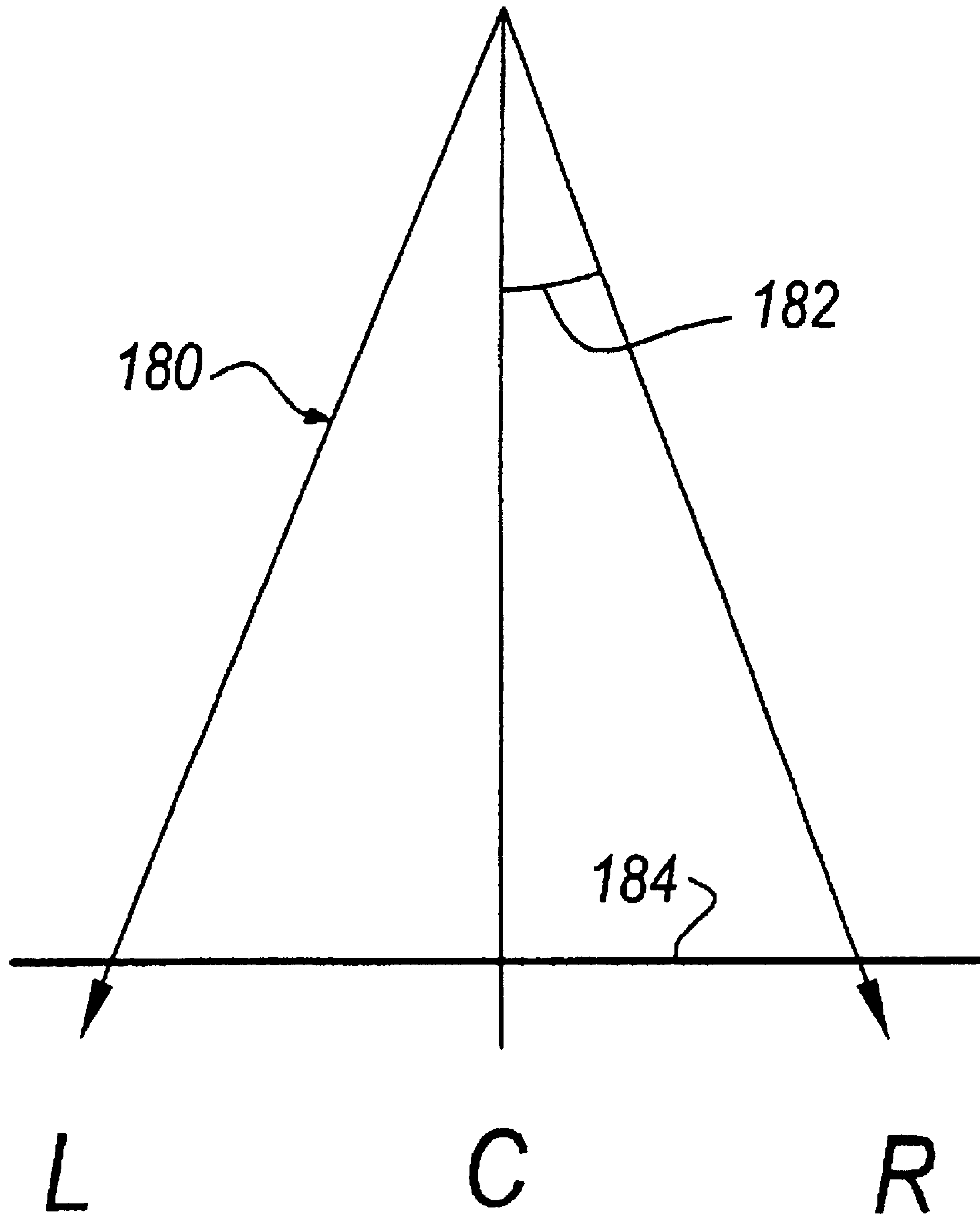


Fig. 9

PRIOR ART

BI MODE ION IMPLANTATION WITH NON-PARALLEL ION BEAMS

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

FIELD OF THE INVENTION

This invention relates to systems and methods for ion implantation of semiconductor wafers or other workpieces and, more particularly, to methods and apparatus for achieving uniform ion implantation over the surface of a semiconductor wafer with non-parallel ion beams.

BACKGROUND OF THE INVENTION

Ion implantation is a standard technique for introducing conductivity-altering impurities into semiconductor wafers. 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 wafer. The energetic ions in the beam penetrate into the bulk of the semiconductor material and are embedded into the crystalline lattice of the semiconductor material to form a region of desired conductivity.

Ion implantation systems usually include an ion source for converting a gas or a solid material into a well-defined ion beam. The ion beam is mass analyzed to eliminate undesired ion species, is accelerated to a desired energy and is directed onto a target plane. The beam is distributed over the target area by beam scanning, by target movement or by a combination of beam scanning and target movement. An ion implanter which utilizes a combination of beam scanning and target movement is disclosed in U.S. Pat. No. 4,922,106 issued May 1, 1990 to Berrian et al.

The delivery of a parallel ion beam to the semiconductor wafer is an important requirement in many applications. A parallel ion beam is one which has parallel ion trajectories over the surface of the semiconductor wafer. In cases where the ion beam is scanned, the scanned beam is required to maintain parallelism over the wafer surface. The parallel ion beam prevents channeling of incident ions in the crystal structure of the semiconductor wafer or permits uniform channeling in cases where channeling is desired. Typically, a serial ion implanter is utilized when a high degree of beam parallelism is required.

In one approach, the beam is scanned in one dimension so that it appears to diverge from a point, referred to as the scan origin. The scanned beam is then passed through an ion optical element which performs focusing. The ion optical element converts the diverging ion trajectories to parallel ion trajectories for delivery to the semiconductor wafer. Focusing can be performed with an angle corrector magnet or with an electrostatic lens. The angle correction magnet produces both bending and focusing of the scanned ion beam. Parallelism may be achieved with an electrostatic lens, but energy contamination can be a drawback.

The output ion beam from the angle corrector magnet or other focusing element may be parallel or may be converging or diverging, depending on the parameters of the ion beam and the parameters of the focusing element. When an angle corrector magnet is utilized, parallelism can be adjusted by varying the magnetic field of the angle corrector magnet. The angle corrector magnet typically has a single magnetic field adjustment which varies both parallelism and bend angle, or beam direction. It will be understood that the

ion implanter is often required to run a variety of different ion species and ion energies. When the beam parameters are changed, readjustment of the angle corrector magnet is required to restore beam parallelism.

The requirement for readjustment of beam parallelism adds complexity and delay to ion implanter operation. Furthermore, the angle corrector magnet or other ion optical element used to produce a parallel ion beam adds to the cost of the ion implanter and increases the length of the ion implanter beamline.

Accordingly, there is a need for ion implantation methods and apparatus in which the requirement for beam parallelism is relaxed, without degrading ion implantation uniformity over the surface of the semiconductor wafer.

SUMMARY OF THE INVENTION

According to a first aspect of the invention, a method is provided for implanting ions into a workpiece. The method comprises the steps of generating an ion beam, measuring an angle of non-parallelism of the ion beam, performing a first implant with the workpiece oriented at a first angle, and performing a second implant with the workpiece oriented at a second angle. The first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

In one embodiment, the reference direction comprises the direction of the ion beam at the workpiece. In another embodiment, the reference direction comprises a selected implant angle relative to the direction of the ion beam at the workpiece.

Preferably, the first and second implants are controlled to provide substantially equal ion doses in the workpiece. The workpiece may comprise a semiconductor wafer. In one preferred embodiment, the first and second angles are equal in magnitude to the measured angle of non-parallelism.

In a first embodiment, the ion beam is generated utilizing a parallelizing device. In a second embodiment, the ion beam is generated without utilizing a parallelizing device.

According to another aspect of the invention, a method is provided for implanting ions into a semiconductor wafer. The method comprises the steps of generating an ion beam, measuring an angle of non-parallelism of the ion beam, tilting the wafer at a first angle, performing a first implant at the first angle, tilting the wafer at a second angle, and performing a second implant at the second angle. The first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

According to a further aspect of the invention, apparatus is provided for implanting ions into a semiconductor wafer. The apparatus comprises means for generating an ion beam, means for measuring an angle of non-parallelism of the ion beam, means for tilting the wafer at a first angle, means for performing a first implant at the first angle, means for tilting the wafer at a second angle, and means for performing a second implant at the second angle. The first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, reference is made to the accompanying drawings, which are incorporated herein by reference and in which:

FIG. **1** is a schematic diagram of an ion implanter suitable for implementing the present invention;

FIG. **2** is a schematic diagram that illustrates the operation of an angle corrector magnet for the case of a relatively large bend angle and converging ion trajectories;

FIG. **3** is a schematic diagram that illustrates the operation of an angle corrector magnet for the case of a relatively small bend angle and diverging ion trajectories;

FIG. **4** is a flow chart of an ion implantation process in accordance with an embodiment of the invention;

FIG. **5** is a schematic diagram that illustrates bi-mode ion implantation in accordance with an embodiment of the invention;

FIG. **6** is a table that illustrates an example of the uniformity of implant angle obtained with bi-mode ion implantation;

FIGS. **7**A and **7**B are schematic diagrams that illustrate operation of an example of a device for measuring beam parallelism;

FIGS. **8**A and **8**B are graphs of beam detector output as a function of beam profile position for the beam conditions illustrated in FIGS. **[6]** 7A and **[6]** 7B, respectively; and

FIG. **9** is a schematic diagram that illustrates prior art ion implantation with a non-parallel ion beam.

DETAILED DESCRIPTION

A simplified block diagram of an example of an ion implanter suitable for incorporating the present invention is shown in FIG. **1**. An ion beam generator **10** generates an ion beam of a desired species, accelerates ions in the ion beam to desired energies, performs mass/energy analysis of the ion beam to remove energy and mass contaminants and supplies an energetic ion beam **12** having low level of energy and mass contaminants. A scanning system **16**, which includes a scanner **20** and an angle corrector **24**, deflects the ion beam **12** to produce a scanned ion beam **30** having parallel or nearly parallel ion trajectories. An end station **32** includes a platen **36** that supports a semiconductor wafer **34** or other workpiece in the path of scanned ion beam **30** such that ions of the desired species are implanted into the semiconductor wafer **34**. The ion implanter may include additional components well known to those skilled in the art. For example, the end station **32** typically includes automated wafer handling equipment for introducing wafers into the ion implanter and for removing wafers after implantation, a dose measuring system, an electron flood gun, etc. It will be understood that the entire path traversed by the ion beam is evacuated during ion implantation.

The principal components of the ion beam generator **10** include an ion beam source **40**, a source filter **42**, an acceleration/deceleration column **44** and a mass analyzer **50**. The source filter **42** is preferably positioned in close proximity to ion beam source **40**. The acceleration/deceleration column **44** is positioned between source filter **42** and mass analyzer **50**. The mass analyzer **50** includes a dipole analyzing magnet **52** and a mask **54** having a resolving aperture **56**.

The scanner **20**, which may be an electrostatic scanner, deflects ion beam **12** to produce a scanned ion beam having ion trajectories which diverge from a scan origin **60**. The scanner **20** may comprise spaced-apart scan plates connected to a scan generator. The scan generator applies a scan voltage waveform, such as a sawtooth waveform, for scanning the ion beam in accordance with the electric field between the scan plates.

Angle corrector **24** is designed to deflect ions in the scanned ion beam to produce scanned ion beam **30** having parallel ion trajectories. In particular, angle corrector **24** may comprise magnetic pole pieces **26** which are spaced apart to define a gap and a magnet coil (not shown) which is coupled to a power supply **28**. The scanned ion beam passes through the gap between the pole pieces **26** and is deflected in accordance with the magnetic field in the gap. The magnetic field may be adjusted by varying the current through the magnet coil. Beam scanning and beam focusing are performed in a selected plane, such as a horizontal plane.

In the embodiment of FIG. **1**, end station **32** includes a beam parallelism and direction measuring system **80**. System **80** measures beam parallelism and direction as described below. In addition, end station **32** includes a tilt mechanism **84** for tilting wafer support platen **36** with respect to the scanned ion beam **30**. In one embodiment, tilt mechanism **84** may tilt wafer support platen **36** with respect to two orthogonal axes.

Examples of operation of angle corrector **24** are shown in FIGS. **2** and **3**. As shown, the pole pieces **26** of angle corrector **24** may be wedged shaped or similarly shaped so that different ion trajectories have different path lengths through the gap between the pole pieces. In FIG. **2**, a relatively high intensity magnetic field is applied. The ion trajectories have a relatively large bend angle and may be converging as they exit from angle corrector **24**. In the example of FIG. **3**, a relatively low intensity magnetic field is applied. The ion trajectories have a relatively small bend angle and may be diverging as they exit from angle corrector **24**. Thus, scanned ion beam **30** is incident on a wafer plane **70** at a positive angle **72** with respect to a normal to wafer plane **70** in the example of FIG. **2** and is incident on wafer plane **70** at a negative angle **74** with respect to a normal to wafer plane **70** in the example of FIG. **3**. It will be understood that parallel or nearly parallel ion trajectories can be produced by appropriate adjustment of the magnetic field in angle corrector **24**. However in general, the magnetic field that provides the best parallelism does not necessarily result in normal incidence of scanned ion beam **30** on wafer plane **70**.

A flow chart of a process for implanting ions into a workpiece in accordance with an embodiment of the invention is shown in FIG. **4**. In step **100**, an ion beam is generated and is transported through the beamline of an ion implanter. As shown in FIG. **1**, ion beam **12** is generated by ion beam generator **12** and is transported through scanner and angle corrector **24** to end station **32**.

In step **102**, the parallelism of the ion beam is measured at or near the plane where the ion beam is incident on the semiconductor wafer or other workpiece. The parallelism measurement provides an angle of non-parallelism of the ion beam and, in particular, typically provides a half angle of convergence or divergence of the ion beam. The measured angle of non-parallelism represents the maximum excursion of the ion beam trajectories from the center ray of the ion beam. An example of a technique for measuring ion beam parallelism is described below in connection with FIGS. **7**A, **7**B, **8**A and **8**B. A non-parallel ion beam **130** having a half angle **132** of divergence is shown in FIG. **5**. The amount of divergence of ion beam **130** is exaggerated in FIG. **5** for purposes of illustration. Beam parallelism is measured in the plane of scanning and focusing of the ion beam.

Referring again to FIG. **4**, the wafer is tilted at a first bi-mode angle, +x, relative to a reference direction in step **104**. As shown in FIG. **1**, tilt mechanism **84** is used to tilt wafer support platen **36** relative to scanned ion beam **30**. The first bi-mode angle is defined below. In step **106**, a first implant is performed with the water **140** tilted at the first

bi-mode angle. In step **108**, the wafer is tilted at a second bi-mode angle, −y, relative to the reference direction, as defined below. In step **110**, a second implant is performed **110** with the wafer tilted at the second bi-mode angle. Preferably, the first implant of step **106** and the second implant of step **110** have equal energies and doses to ensure implant uniformity over the surface of the semiconductor wafer.

The first bi-mode angle +x and the second bi-mode angle −y are opposite in sign relative to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism. In describing the reference direction, it is useful to consider the so-called “implant angle”, which is the angle between the incident ion beam and a normal to the wafer surface. The implant angle, which is typically in a range of 0° to 7°, is used to control channeling of the energetic ions in the crystalline lattice of the semiconductor wafer.

In the simple case where the implant angle is 0°, the reference direction for the first and second bi-mode angles is the direction of the ion beam. In this case, the wafer is tilted by bi-mode angles of opposite sign relative to the incident ion beam, as shown in FIG. **5**. Wafer **140** is tilted by a first bi-mode angle **142** relative to wafer plane **134** for the first implant and is tilted by a second bi-mode angle **144** relative to wafer plane **134** for the second implant. Angles **142** and **144** are opposite in sign relative to wafer plane **134** and in magnitude are equal to or greater than the measured angle **132** of non-parallelism of ion beam **130**. Preferably, angles **142** and **144** are as close in magnitude as is practical to the measured angle of non-parallelism. In a preferred embodiment, angles **142** and **144** are equal in magnitude to the measured angle of non-parallelism. In general however, angles **142** and **144** are not required to have equal magnitudes.

A non-zero implant angle may be set by tilting the wafer in a direction parallel to the plane of scanning and focusing, i.e., the plane of FIG. **5**, or may be set by tilting the wafer in a direction orthogonal to the plane of scanning and focusing. Where the non-zero implant angle is set by tilting the wafer in a direction orthogonal to the plane of scanning and focusing, the reference direction for the first and second angles is the direction of the ion beam, as illustrated in FIG. **5** and described above. Where the non-zero implant angle is set by tilting the wafer in a direction parallel to the plane of scanning and focusing, the reference direction is normal to a wafer tilted at the selected implant angle. In this case, the first implant is performed at the first bi-mode angle relative to the second implant angle and the second implant is performed at the second bi-mode angle relative to the selected implant angle. In the case where the first and second bi-mode angles are equal in magnitude to the measured angle of non-parallelism, the first implant is performed at the selected implant angle plus the measured angle of non-parallelism, and the second implant is performed at the selected implant angle minus the measured angle of non-parallelism. For example, assume a selected implant angle of 7° and a measured angle of non-parallelism of 1°. In this example, the first bi-mode implant (step **106**) is performed at a tilt angle of 7°+1°=8°, and the second bi-mode implant (step **110**) is performed at a tilt angle of 7°−1°=6°. It will be understood that this approach can be utilized with any selected implant angle and bi-mode angles. Furthermore, the order of the first and second implants can be reversed.

The averaging effect of a bi-mode implant in accordance with the present invention is described with reference to FIG. **6**. In the example of FIG. **6**, the desired implant angle is zero degrees, and the non-parallel ion beam is assumed to have a measured angle of non-parallelism of 1°. In a first bi-mode implant, wafer **140** in FIG. **5** is tilted by first bi-mode angle **142** of 1° with respect to wafer plane **134**. With this tilt angle, the left side of wafer **140** is implanted at an angle of 2°, the center of wafer **140** is implanted at an angle of 1° and the right side of wafer **140** is implanted at an angle of 0°, as summarized in FIG. **6**. In a second bi-mode implant, wafer **140** is tilted by second bi-mode angle **144** of −1° with respect to wafer plane **134**. With this tilt angle, the left side of wafer **140** is implanted at an angle of 0°, the center of wafer **140** is implanted at an angle of −1° and the right side of wafer **140** is implanted at an angle of −2°, as summarized in FIG. **6**. As further illustrated in FIG. **6**, the average of the two implants is a uniform angle of 1° across the wafer surface. The determination of the average of the first and second bi-mode implants is based on the assumption that implants at positive and negative angles of equal magnitude are equivalent.

A prior art single mode implant using a non-parallel ion beam is illustrated schematically in FIG. **9**. A non-parallel ion beam **180** having an angle of non-parallelism **182** is used to implant a wafer **184** with normal incidence. The prior art implant technique shown in FIG. **9** results in a variation in incident angle of the ion beam over the wafer surface. In particular, for an ion beam having an angle of non-parallelism of 1°, the beam has an incident angle of +1° at the left side of the wafer, an incident angle of 0° at the center of the wafer and an incident angle of −1° at the right side of the wafer. Thus, the angle of incidence varies by 1° over the wafer surface. In some applications, such variation in angle of incidence may be unacceptable.

An example of a technique for measuring ion beam parallelism is described with reference to FIGS. **7**A, **7**B, **8**A, and **8**B. FIGS. **7**A and **7**B are schematic diagrams which illustrate the measurement of different ion beams with a beam profiler and two beam detectors. FIGS. **8**A and **8**B are graphs that illustrate the outputs of the beam detectors as a function of profiler position.

As shown in FIGS. **7**A and **7**B, ion beam parallelism is measured using a moving beam profiler **150** and spaced-apart beam detectors **152** and **154**, which correspond to beam parallelism and direction measuring system **80** (FIG. **1**). Beam profiler **150** may be any element that partially blocks the ion beam and is laterally movable relative to the ion beam. Detectors **152** and **154**, for example, may be Faraday cups, which produce an electrical output signal in response to an incident ion beam. As the profiler **150** is moved across the ion beam, it blocks a portion of the ion beam and produces an ion beam shadow. The beam shadow moves across detectors **152** and **154** and produces output signals in the form of negative going output current pulses.

As shown in FIG. **7**A, a parallel scanned ion beam **160** has normal incidence on a wafer plane **170**. Detectors **152** and **154** produce output pulses as shown in FIG. **8**A when the profiler is positioned in alignment with each detector. The profiler positions at which detector output pulses are generated can be used to determine that ion beam **160** has parallel trajectories and is normal to wafer plane **170**.

Referring to FIG. **7**B, a diverging ion beam **162** has normal incidence on wafer plane **170**. In this case, detector **152** produces an output pulse as shown in FIG. **8**B when profiler **150** is positioned to the right of detector **152**, and detector **154** produces an output pulse when profiler **150** is positioned to the left of detector **154**. The profiler positions at which output pulses are generated can be used to determine the

angle of divergence of ion beam **162**. In response to a converging ion beam (not shown), detector **152** produces an output pulse when profiler is positioned to the left of detector **152**, and detector **154** produces an output pulse when profiler **150** is positioned to the right of detector **154**. The profiler positions at which detector output pulses are generated can be used to determine the angle of convergence of the ion beam. Additional details regarding techniques for measuring ion beam parallelism are provided in U.S. application Ser. No. 09/588,419, filed Jun. 6, 2000, which is hereby incorporated by reference.

It will be understood that different techniques may be used for measuring beam parallelism within the scope of the invention. In addition, the invention is not limited to use with a scanned ion beam. For example, the invention may be used with a ribbon ion beam as disclosed in U.S. Pat. No. 5,350,926, issued Sep. 27, 1994 to White et al.

The bi-mode implant technique described above permits the specification on beam parallelism to be relaxed without degrading ion implantation uniformity over the surface of the semiconductor wafer. Depending on the architecture of the ion implanter, ion implantation uniformity may be achieved without requiring an ion optical element to for parallelizing the ion beam. In ion implanter architectures which include an ion optical element for parallelizing the ion beam, the requirement for adjusting the parallelism of the ion beam may be relaxed, in some cases permitting a fixed parallelizing ion optical element to be used.

While there have been shown and described what are at present considered the preferred embodiments of the present invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the scope of the invention as defined by the appended claims.

What is claimed is:

1. A method for implanting ions into a workpiece, comprising the steps of:

generating an ion beam;

measuring an angle of non-parallelism of the ion beam;

performing a first implant with the workpiece oriented at a first angle; and

performing a second implant with the workpiece oriented at a second angle, wherein the first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

2. A method as defined in claim **1** wherein the steps of performing said first and second implants are controlled to provide substantially equal ion doses in the workpiece.

3. A method as defined in claim **1** wherein the angle of non-parallelism is less than about 5°.

4. A method as defined in claim **1** wherein the angle of non-parallelism comprises a half angle of divergence of the ion beam.

5. A method as defined in claim **1** wherein the angle of non-parallelism comprises a half angle of convergence of the ion beam.

6. A method as defined in claim **1** further comprising the step of generating the ion beam utilizing a parallelizing device.

7. A method as defined in claim **1** further comprising the step of generating the ion beam without utilizing a parallelizing device.

8. A method as defined in claim **1** wherein the reference direction comprises a direction of the ion beam at the workpiece.

9. A method as defined in claim **1** wherein the reference direction comprises a selected implant angle relative to a direction of the ion beam at the workpiece.

10. A method as defined in claim **1** wherein the first and second angles are equal in magnitude.

11. A method for implanting ions into a semiconductor wafer, comprising the steps of:

generating an **[**in**]** *ion* beam;

measuring an angle of non-parallelism of the ion beam;

tilting the wafer at a first angle;

performing a first implant at the first angle;

tilting the wafer at a second angle; and

performing a second implant at the second angle, wherein the first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

12. A method as defined in claim **11** wherein said first and second implants are controlled to provide substantially equal ion doses in the wafer.

13. A method as defined in claim **11** wherein the angle of non-parallelism of the ion beam is less than about 5°.

14. A method as defined in claim **11** wherein the angle of non-parallelism of the ion beam comprises a half angle of divergence of the ion beam.

15. A method as defined in claim **11** wherein the angle of non-parallelism of the ion beam comprises a half angle of convergence of the ion beam.

16. A method as defined in claim **11** further comprising the step of generating the ion beam utilizing a parallelizing device.

17. A method as defined in claim **11** further comprising the step of generating the ion beam without utilizing a parallelizing device.

18. A method as defined in claim **11** wherein the reference direction comprises a direction of the ion beam at the wafer.

19. A method as defined in claim **11** wherein the reference direction comprises a selected implant angle relative to a direction of the ion beam at the wafer.

20. A method as defined in claim **11** wherein the first and second angles are equal in magnitude.

21. Apparatus for implanting ions into a semiconductor wafer, comprising:

means for generating an ion beam;

means for measuring an angle of non-parallelism of the ion beam;

means for tilting the wafer at a first angle;

means for performing a first implant at the first angle;

means for tilting the wafer at a second angle; and

means for performing a second implant at the second angle, wherein the first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism.

22. A method for implanting ions into a semiconductor wafer, comprising the steps of:

generating an ion beam;

tilting the wafer at a first angle with respect to the ion beam;

performing a first implant with the wafer tilted at the first angle;

tilting the wafer at a second angle that is equal in magnitude and opposite in sign with respect to said first angle; and

performing a second implant with the wafer tilted at the second angle*, wherein the step of tilting the wafer at the first angle comprises tilting the wafer at a half angle of divergence of the ion beam*.

[**23**. A method as defined in claim **22** wherein the step of tilting the wafer at a first angle comprises tilting the wafer at a half angle of divergence of the ion beam.]

[**24**. A method as defined in claim **22** wherein the step of tilting the wafer at a first angle comprises tilting the wafer at a half angle of convergence of the ion beam.]

25. Apparatus for implanting ions into a semiconductor wafer, comprising:

an ion beam generator;

a measuring system for measuring an angle of non-parallelism of the ion beam; and

a tilt mechanism for tilting the semiconductor wafer at first and second angles, wherein the first and second angles are opposite in sign with respect to a reference direction and in magnitude are equal to or greater than the measured angle of non-parallelism, wherein first and second implants are performed at the first and second angles, respectively.

26. Apparatus as defined in claim **25** wherein said measuring system comprises a movable beam profiler and one or more beam detectors.

27. Apparatus as defined in claim **25** further comprising an ion optical element for parallelizing the ion beam.

28. Apparatus as defined in claim **25** wherein the first and second angles are equal in magnitude.

29. A method for implanting ions into a workpiece, comprising:

generating an ion beam;

performing a first implant with the workpiece oriented at a first angle relative to a reference direction; and

performing a second implant with the workpiece oriented at a second angle relative to the reference direction, wherein the first and second angles are opposite in sign with respect to the reference direction, and wherein the reference direction is a selected implant angle with respect to the workpiece.

30. A method as defined in claim 29, wherein the first and second implants are controlled to provide substantially equal ion doses in the workpiece.

31. A method as defined in claim 29, further comprising generating the ion beam utilizing a parallelizing device.

32. A method as defined in claim 29, further comprising generating the ion beam without utilizing a parallelizing device.

33. A method as defined in claim 29, wherein the first and second angles are equal in magnitude.

34. A method as defined in claim 29, wherein generating an ion beam comprises generating a scanned ion beam.

35. A method as defined in claim 29, wherein generating an ion beam comprises generating a ribbon ion beam.

36. A method as defined in claim 30, further comprising measuring an angle of non-parallelism of the ion beam, wherein the magnitudes of the first and second angles are equal to or greater than the measured angle of non-parallelism.

37. A method as defined in claim 29, wherein the first and second angles are equal in magnitude and wherein the first and second implants are controlled to provide substantially equal ion doses in the workpiece.

38. A method for implanting ions into a semiconductor wafer, comprising:

generating an ion beam;

tilting the wafer at a first angle relative to a reference direction;

performing a first implant at the first angle;

tilting the wafer at a second angle relative to the reference direction; and

performing a second implant at the second angle, wherein the first and second angles are opposite in sign with respect to the reference direction, and wherein the reference direction is a selected implant angle with respect to the wafer.

39. A method as defined in claim 38, wherein the first and second implants are controlled to provide substantially equal ion doses in the wafer.

40. A method as defined in claim 38, further comprising generating the ion beam utilizing a parallelizing device.

41. A method as defined in claim 38, further comprising generating the ion beam without utilizing a parallelizing device.

42. A method as defined in claim 38, wherein the first and second angles are equal in magnitude.

43. A method as defined in claim 39, further comprising measuring an angle of non-parallelism of the ion beam, wherein the magnitudes of the first and second angles are equal to or greater than the measured angle of non-parallelism.

44. A method as defined in claim 38, wherein the first and second angles are equal in magnitude and wherein the first and second implants are controlled to provide substantially equal ion doses in the wafer.

45. Apparatus for implanting ions into a semiconductor wafer, comprising:

an ion beam generator; and

a tilt mechanism for tilting the semiconductor wafer at first and second angles, wherein the first and second angles are opposite in sign with respect to a reference direction, wherein first and second implants are performed at the first and second angles, respectively, and wherein the reference direction is a selected implant angle with respect to the wafer.

46. Apparatus as defined in claim 45, further comprising an ion optical element configured to parallelize the ion beam.

47. Apparatus as defined in claim 45, further comprising a measuring system for measuring an angle of non-parallelism of the ion beam, wherein the magnitudes of the first and second angles are equal to or greater than the measured angle of non-parallelism.

48. Apparatus as defined in claim 45, wherein the first and second angles are equal in magnitude.

49. Apparatus as defined in claim 45, wherein the ion beam generator is configured to generate a scanned ion beam.

50. Apparatus as defined in claim 45, wherein the ion beam generator is configured to generate a ribbon ion beam.

51. Apparatus for implanting ions into a semiconductor wafer, comprising:

means for generating an ion beam;

means for tilting the wafer at first and second angles; and

means for performing first and second implants at the first and second angles, respectively, wherein the first and second angles are opposite in sign with respect to a reference direction, and wherein the reference direction is a selected implant angle with respect to the wafer.

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