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(54) Title: A METHOD OF IMPLANTING A SUBSTRATE AND AN ION IMPLANTER FOR PERFORMING THE METHOD

(57) Abstract: An implanter provides two-dimensional scanning of a substrate relative to an implant beam so that the beam draws a raster of scan lines on the substrate. The beam current is measured at turnaround points off the substrate and the current value is used to control the subsequent fast scan speed so as to compensate for the effect of any variation in beam current on dose uniformity in the slow scan direction. The scanning may produce a raster of non-intersecting uniformly spaced parallel scan lines and the spacing between the lines is selected to ensure appropriate dose uniformity.

A METHOD OF IMPLANTING A SUBSTRATE AND AN ION IMPLANTER FOR PERFORMING THE METHOD

Field of the Invention

This invention relates to a method of implanting a substrate in which the relative movement between the substrate and an implant beam is controlled to maintain a desired and uniform dose of implanted species over the surface of the substrate. The invention also relates to ion implanters adapted for performing the method.

Background of the Invention

In a typical ion implanter, a relatively small cross-section beam of ions of a desired atomic species is scanned relative to a substrate to be implanted, typically a semi-conductor wafer.

The beam may be scanned transversely in two dimensions relative to the stationary wafer, or the wafer may be scanned in two dimensions relative to a stationary beam. There are also hybrid scanning techniques when the beam is scanned in one dimension whilst the wafer is mechanically scanned in a second typically orthogonal direction.

The various techniques have advantages and disadvantages. For batch processing of semi-conductor wafers, the wafers of a batch can be mounted on a rotating wheel and the axis of rotation of the wheel can then be scanned to and fro to provide two-dimensional mechanical scanning of the wafers across a stationary beam. An example of batch implanter of this kind is described in US Patent No. 5,389,793.

Single wafer implanters can employ the hybrid mechanical and electrostatic or electromagnetic beam

scanning outlined above. Such an arrangement is described in our commonly assigned US Patent No. 5,898,179. Here, the ion beam is electromagnetically scanned in a first direction perpendicular to the beam axis in the ion implanter, whilst the wafer is mechanically moved in a second generally orthogonal direction.

It is important in implanting to ensure that the total dose of desired species implanted into the semi-conductor wafer or other substrate has the desired level of dose uniformity over the entire substrate surface. In the above-described batch-type of implanters, this is achieved by spinning the implant wheel at high speed and scanning the wheel axis to and fro so that the wafers mounted on the wheel pass across the beam many times during an implant process. In the hybrid single-wafer implanters also mentioned above, dose uniformity is maintained by performing the electrostatic or electromagnetic beam scanning at a relatively high rate compared to the mechanical movement of the wafer to be implanted. Dose uniformity over the wafer surface in the direction of mechanical movement of the wafer is ensured by controlling the rate of this mechanical movement, but the rate of mechanical movement is always much slower than the beam scanning rate.

Summary of the Invention

It is an object of embodiments of this invention to provide novel scanning algorithms which can provide particular advantages as will be apparent from the following.

Accordingly, the invention provides a method of implanting a substrate, comprising a) generating an implant beam having a measurable flux of a desired atomic

species and b) producing relative movement between the substrate and the beam both (i) in a first direction transverse to the beam direction to produce at least one pass of the beam over the substrate and (ii) in a second direction transverse to the beam direction and said first direction to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which have predetermined spacing in said first direction. The scans are arranged to extend beyond an edge of the substrate to positions at which no beam flux is absorbed by the substrate. The beam flux is measured at these positions and the speed of the next said scan over the substrate is adjusted in response to the previously-measured beam flux. The speed adjustment may be sufficient to compensate fully for beam current changes during the pass, so that the adjustment maintains a desired rate of implanting in the substrate of said atomic species per unit length of the scan over the substrate. However the speed adjustment may compensate only partly, and other adjustments may be made as well, such as to the spacing between line mid-points and/or to the beam current itself.

In this method, the movement in the first direction can be called a slow scan between the beam and the substrate and the movement in the second direction can be called a fast scan. Preferably, the slow scan movement is maintained to ensure the raster lines drawn on the substrate by the fast scans have mid-points which are uniformly spaced. The amount of dose per unit length delivered by each of the fast scans is then controlled from scan to scan in accordance with the measured beam flux by adjusting the speed of the fast scans.

The invention may be employed using a continuous relative movement between beam and substrate in the slow scan direction, producing a zig-zag or saw-tooth scan pattern on the substrate. However, better results are obtained if the scans draw a raster of non-intersecting uniformly spaced substantially parallel lines on the substrate.

Good dose uniformity over the substrate can then be obtained, even for a single pass of the beam over the substrate in said first direction.

Importantly also, good dose uniformity is possible even if the fast scans of the beam in said second direction are themselves relatively slow compared to the scanning rates achievable with electromagnetic/electrostatic beam scanning systems. As a result, the method has particular application in single wafer mechanical scanning systems where the fast scanning of the wafer relative to the beam is achieved by a reciprocating mechanical movement of the wafer on a wafer holder. With reciprocating mechanical scanning systems, the highest rate at which the wafer can be reciprocated across the implant beam is limited. As a result, with an implant beam having a predetermined flux of the desired atomic species to be implanted, the amount of dose delivered to each unit area of the substrate in the scan path, as the beam makes a single traverse over that area, is much higher. Therefore, the spacing between successive fast scans, and in particular the spacing between the lines of the raster formed by the scanning system, tends to be greater.

Controlling the speed of each fast scan in such a scanning system, in accordance with the beam flux measured just before the scan, ensures that each fast scan delivers

dose to the wafer at the same rate per unit length of the scan so that the uniformly spaced scans deliver a uniform dose over the slow scan.

Preferably, said relative movement between the substrate and the beam in said second direction is produced by mechanically scanning the substrate parallel to said second direction, and said relative movement in said first direction is produced by mechanically translating said substrate parallel to said first direction by a uniform distance between scans.

The invention also provides a method of implanting a substrate comprising the steps of a) generating an implant beam having a predetermined beam flux of a desired atomic species, b) mechanically translating the substrate parallel to a first direction transverse to the beam direction to produce at least one pass of the beam over the substrate, c) mechanically reciprocating the substrate parallel to a second direction, transverse to the beam direction and said first direction, to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which have predetermined spacing in said first direction, and d) controlling said mechanical translating step to select said spacing of said mid-points of the raster lines so that said raster provides a desired uniformity, in said first direction, of implanted dose of said atomic species over the substrate.

A two-dimensional mechanical scanning procedure of this kind enables wafers to be implanted singly (i.e. not in a batch process) using a relatively simple beam line without the beam scanning systems employed in hybrid scanning single-wafer implanters such as those discussed

above. Because reciprocating mechanical scanning of a wafer is likely to be relatively slow compared to electrical beam scanning, relatively few scans of the beam over the substrate are required to deliver to the substrate the dose of required atomic species specified by the process recipe. This implies that the individual lines of the raster produced by the scanning process may be spaced apart by a significant fraction of the width of the ion beam. Also the complete implant may require only a small number of passes of the beam over the substrate (in the above-mentioned first direction transverse to the mechanical reciprocation direction, the second direction).

The method of the invention set out above ensures that the spacing of the raster lines is nevertheless such as to provide the desired dose uniformity over the substrate. Again, best results are obtained if the scans draw a raster of non-intersecting uniformly spaced substantially parallel lines in the substrate, which can be achieved by employing a plurality of translation steps in said first direction between respective pairs of successive scans.

The controlling step set out above may include measuring the cross-sectional profile of the ion beam at least in said first direction, calculating from said profile a maximum value of said spacing of said mid-points which provides said desired uniformity, and adjusting the mechanical translating step to select a value of said spacing which does not exceed said maximum value.

Techniques for calculating from the measured profile the maximum value of raster line spacing to provide the desired uniformity will be explained in greater detail in the following description of examples of this invention.

Alternatively, or additionally, the controlling step may include measuring the cross-sectional profile as above, calculating a desired value of said uniform raster line spacing from data including said beam flux, the speed of said mechanical reciprocation and the desired dose per unit area of substrate to be implanted, then using said measured cross-sectional profile of the ion beam to calculate the dose uniformity which would be obtained at the calculated desired spacing value, and selecting said desired spacing value as the uniform spacing to be employed, only if said calculated uniformity is not worse than said desired uniformity.

It will be understood that, given a predetermined beam flux of the desired atomic species, and a known rate of scanning, the raster line spacing needed to provide the implant recipe dose to the substrate using, for example, four passes of a substrate over the beam, can be calculated. However, this desired raster line spacing to achieve the desired recipe dose can be used for implanting only if it results in the desired dose uniformity. If the calculated uniformity is worse than the desired uniformity, the beam flux and consequently the line spacing can be reduced to a level at which the calculated dose uniformity is no longer worse than the desired uniformity. Alternatively, or as well, steps may be taken to improve the spatial blending quality of the measured beam profile, as will be explained later in greater detail.

In the summary above and the detailed description which follows, the term "raster" is used to denote a set of scan lines drawn by an ion beam on a substrate being implanted. The scan lines of a single raster may be drawn in a single pass of the beam over the wafer (in the slow

scan direction), or may be drawn by two or more successive passes. It should also be noted that a single scan line of the raster could be drawn by multiple overlying scans of the beam over the substrate (in the fast scan direction).

Brief Description of the Drawings

Examples of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of an ion implanter illustrating an embodiment of the present invention;

Figure 2 is a schematic illustration of the mechanical scanning pattern performed by the implanter of Figure 1 to produce a desired raster;

Figure 3 illustrates an alternative scanning pattern which may be performed;

Figure 4 illustrates a further scanning pattern;

Figure 5 is a graphical representation of an arbitrary ion beam intensity profile function in one dimension;

Figure 6 is an illustration of a semi-conductor wafer to be implanted showing the scanning raster over the substrate, and illustrating an arbitrary beam shape;

Figure 7 is a graphical representation of dose uniformity against the spatial frequency of the scanning raster lines on the substrate wafer, calculated by means of Fast Fourier Transform (FFT);

Figure 8 is a similar graphical representation of dose uniformity against spatial frequency showing additional points plotted by using the scaling property of a Fourier transform;

Figure 9 is a further graphical representation of the dose uniformity against spatial frequency of raster lines calculated more precisely;

Figure 10 is a graphical representation of an idealised beam profile in the form of a Gaussian function; and

Figure 11 is a graphical representation of calculated dose uniformity against the spatial frequency of scanning raster lines for the Gaussian profile of Figure 10.

Description of the Preferred Embodiments

Referring to Figure 1, the illustrated ion implanter comprises an ion source 10 from which a beam 11 of ions is extracted by means of extraction electrodes 12. The ion beam 11 then passes through a mass analyser magnet 13 and ions in the beam emerging from the mass analyser magnet 13 which have a desired mass, corresponding to ions containing the atomic species to be implanted, are selected from the beam by means of a mass resolving slit 14.

These components of the ion implanter are standard and well known to workers in the field of ion implantation. Together these components form an ion beam generator which generates a beam of ions containing a desired atomic species for implantation in a semi-conductor wafer.

The mass selected ion beam from the beam generator described above enters an evacuated process chamber having a chamber wall of which part is illustrated at 15. A wafer scanning arrangement illustrated generally at 16 is mounted on the wall 15 of the process chamber and is operable to scan a wafer 17 held on a wafer holder 18 in two directions transversely of the mass selected ion beam

19. The wafer holder 18 is mounted at a distal end 20 of a scan arm 21 which extends through a vacuum seal 22 from the interior to the exterior of the process chamber. The vacuum seal 22 is formed in a slide plate 23 which is mounted for linear movement transversely of the longitudinal axis of the scan arm 21, on a rotary carrier plate 24, which is in turn mounted for rotatable movement in a plane transverse to the scan arm 21 relative to the process chamber wall 15.

The scan arm 21 is mounted for longitudinal movement on the slide plate 23 and can be driven longitudinally to and fro by a motor 25. The slide plate 23 carrying the scan arm 22 can itself be driven transversely of the scan arm 21 by a drive motor 26. Suitable operation of the drive motors 25 and 26 produce a combined scanning movement of the wafer holder 18 and any semi-conductor wafer thereon in a two-dimensional scan pattern across the ion beam 19.

In a convenient example, the rotary support plate 24 of the scanning system is mounted on the process chamber wall 15 by an air bearing and vacuum seal combination such as disclosed in US Patent No. 5,898,179 and GB-A-2360332. Similarly, the slide plate 23 is mounted for linear motion on the rotary support plate 24 again by means of an air bearing and vacuum seal combination as disclosed in the above-referred US patent specification. The scan arm 21 is preferably mounted for longitudinal motion through the vacuum seal 22 in the slide plate 23 by the linear motor and compliant air bearing vacuum seal arrangement disclosed in our copending United States Patent Application Serial No. 10/119290, the contents of the specification of which are incorporated herein by reference in their entirety.

In the process chamber of the implanter, a Faraday is located downstream of the wafer holder 18 in a position to absorb the entire ion beam 19 whenever the wafer holder 18 is positioned such that no part of the beam 19 impinges on a wafer 17 on the holder 18, or on the scan arm 21. The total charge absorbed from the ion beam by the Faraday 30 provides a measure of the flux in the beam 19 of ions containing the atomic species to be implanted. A controller 31 receives a signal from the Faraday 30 on a line 32, and is operative to derive from this signal a value for the total beam flux of the desired species. The controller 31 is also operative to control the operation of drive motors 25 and 26 so as to control the scanning motion of the scan arm 21.

In a preferred arrangement, the controller 31 is operative to move the wafer holder 18 in a sequence of linear movements across the beam 19 in the plane of the paper of Figure 1, with each linear movement separated by a stepwise movement normal to the plane of the paper. The resulting scan pattern is illustrated in Figure 2 in which the dashed line 35 is the locus of the centre 36 of wafer 17 as it is reciprocated to and fro by the scan arm 21 in the X-coordinate direction, and indexed downwardly, parallel to the Y-coordinate direction, at the end of each stroke of reciprocation.

In Figure 2, the ion beam 19 is illustrated as having a substantially circular cross-section with a diameter which is substantially less than the diameter of the wafer 17. In practice, the wafer 17 may have a diameter of 300 mm, whereas the diameter of the ion beam is typically 50 mm. As can be seen, the reciprocating scanning action of the wafer 17 ensures that all parts of the wafer 17 are exposed to the ion beam 19. The movement of the wafer 17

causes the beam 19 to make repeated scans over the wafer 17 with the individual scans being parallel and equally spaced apart, until the beam makes a full pass over the wafer.

Although the line 35 in Figure 2 represents the motion of the wafer 17 on the holder 18 relative to the stationary ion beam 19, the line 35 can also represent a visualisation of the scans of the ion beam across the wafer. For this purpose, the wafer 17 is represented in dashed outline 17a at the centre of the illustrated scan pattern, and the ion beam is represented at 19a. Obviously, the motion of the ion beam 19a relative to the wafer 17a is in the reverse direction compared to the actual motion of the wafer 17 relative to the ion beam 19.

In this example, the controller 31 scans the wafer 17 so that the ion beam 19a draws a raster of non-intersecting uniformly-spaced parallel lines on the substrate. Each line 37 corresponds to a single scan of the ion beam over the substrate. As illustrated, these ion beam scans extend beyond an edge of the wafer 17 to positions 38 at which the beam cross-section is completely clear of the wafer 17a so that no beam flux is absorbed by the wafer. At these positions, the full flux of the beam 19a reaches the Faraday 30 located downstream of the wafer holder 18, so that the full beam current of desired species can then be determined by the controller 31 from the signal on line 32. It will be appreciated that in the visualisation represented in Figure 2 in which the beam 19a scans over the wafer 17a, Faraday 30 effectively moves with the beam 19a. In practice, of course, the beam 19 and Faraday 30 are fixed and it is the wafer 17 which is moved.

Assuming the beam flux of atomic species to be implanted is constant over time, the dose of the desired species delivered to the wafer 17a is maintained constant over the wafer in the coordinate direction X of the raster lines 37 by maintaining a constant speed of movement of the wafer 17 along the raster lines. Also, by ensuring that the spacing between the individual raster lines 37 is uniform, the dose distribution along the coordinate direction Y is also maintained substantially constant.

In practice, however, there may be some progressive variation in the beam flux during the time taken for the wafer 17 to perform a complete pass over the ion beam 19, i.e. to complete the full raster of lines 37 as illustrated in Figure 2.

In order to reduce the effect of such beam flux variations during a scanning raster, the controller is arranged to measure the beam flux at the positions 38 when the entire beam flux is absorbed by the Faraday 30 and then use the measured flux to adjust the speed at which the wafer holder 18 is moved over the next scan or raster line 37. If the beam flux measurement at the positions 38 indicates that the beam flux has become less, then the controller ensures that the wafer holder is driven along the next scan line 37 at a slower speed so as to maintain a desired rate of implant of the required atomic species per unit distance of travel of the wafer holder 18 along the scan line. In this way, any variations in the beam current during the course of the formation of a complete raster of scan lines over the wafer does not result in a variation in the dose delivered to the substrate in the scan line spacing direction.

In the example described so far, the relative movement between the semi-conductor substrate or wafer and

the ion beam is provided by mechanically scanning the semi-conductor wafer in two directions transverse to the ion beam. This obviates the need to employ ion beam deflection systems to scan the ion beam itself. However, in different examples, the beam may be scanned, by means of beam deflectors, in at least one of the two transverse directions providing the two-dimensional relative scanning between the wafer and the beam. In all cases, however, the scanning system produces multiple scans of the beam over the wafer in each of one or more passes, whereby the scans draw a raster of non-intersecting uniformly-spaced parallel lines on the substrate. Also the beam flux is measured at positions where the scans extend beyond the edge of the wafer and the speed of the next scan is adjusted to maintain the dose rate per unit length of scan at a desired value.

In the mechanical scanning system described above with reference to Figures 1 and 2, the wafer 17 is translated by a uniform distance between each individual scan, that is to say each individual stroke of the reciprocating motion of the scanning arm 21 along its axis, in order to produce the zig-zag raster pattern illustrated in Figure 2. However, the scanning mechanism may be controlled so that multiple scans are performed along the same line of the raster. For example, each raster line may represent a double stroke or reciprocation of the scanning arm 21 and the wafer holder 18 is then translated by the uniform distance only between each double stroke. The resulting scanning pattern is illustrated in Figure 3.

Also, Figure 2 illustrates only a single pass of the beam over the wafer parallel to the Y-coordinate direction, but the complete implant procedure may include

multiple passes. Then each such pass of the implant process may be arranged to draw a respective independent raster of uniformly-spaced parallel lines. However, the scan lines of the multiple passes may be combined to draw a composite raster effectively drawn from the scans of a plurality of passes. For example, the scans of a second pass could be drawn precisely mid-way between the scans of the first pass to produce a composite raster having a uniform raster line spacing which is half the spacing between the successive scans of each pass.

As mentioned previously, using a purely mechanical scanning system normally results in the maximum speed of travel of the ion beam over the semi-conductor wafer being limited by the maximum speed of mechanical scanning of the wafer holder. In a mechanical scanning system of the kind illustrated in Figure 1 and described in more detail in the above-mentioned United States Patent Application Serial No. 10/119290, the maximum rate of reciprocation of the scan arm 21 along its longitudinal axis may be of the order of 1 Hz. For a given ion beam current, or flux of the desired atomic species to be implanted, the time during which the semi-conductor wafer can be exposed to the ion beam during the ion implanting process is dictated by the recipe dose of the atomic species to be implanted. Assuming that over-scanning of the wafer relative the ion beam is limited to the amount necessary to ensure an even distribution of dose over the wafer, i.e. a square raster pattern such as illustrated in Figure 2, it can be seen that the limited total time for the implant in combination with the limited mechanical scan speed dictates the spacing for the raster lines drawn by the scans over the wafer surface, assuming each scan draws a separate line.

Clearly, in order to ensure adequate uniformity of dose delivered to the wafer in the direction of the raster line spacing, this spacing or line pitch must be less than the cross-sectional dimension of the ion beam in the line spacing direction (Y-coordinate direction of Figure 1). In practice, the dose uniformity is improved with a smaller raster line pitch.

The recipe dose could be delivered to the wafer by performing a single pass drawing a raster of scan lines at the line pitch dictated by the beam current, the mechanical reciprocation rate of the scanning mechanism, and the required recipe dose. However, it may be preferable to deliver the same recipe dose to the wafer in multiple passes of the wafer across the ion beam, in order to reduce the thermal loading of the wafer caused by the impinging ion beam. Then, in order to maximise dose uniformity, the scan lines drawn during each pass are preferably arranged to interleave scan lines of the previous pass to produce a composite raster with a reduced line pitch.

For example, if the line pitch dictated by the recipe dose requirements as explained above is T, then each of four passes could be made with scans separated by 4T. Each of the passes is arranged to spatially phase shift the scans of the pass by the amount T, so that the composite raster drawn by the four passes has lines with the pitch T. In this way, the thermal loading of the wafer is reduced whilst ensuring the raster line pitch is maintained at the desired value T. Figure 4 illustrates a part of the scanning pattern of four interleaved passes as described above.

Although the raster line spacing which can be used with a mechanical scanning system is dictated by the

recipe dose and beam current, as explained above, it is nevertheless important to ensure that the line spacing or pitch is small enough to provide the desired dose uniformity in the spacing direction. This uniformity is a function of the shape of the beam profile and the raster line pitch. A smaller pitch results in a more uniform dose distribution over the wafer. The following is a mathematical description of how the uniformity varies as a function of scan pitch for a parallel line scanning pattern. Fourier transformation is used as a tool since the analysis involves periodic patterns in dose distribution.

In this study, it is assumed that beam current and profile do not change during an implant. Time dependency is not treated, although that is very similar. Notations τ, t, u, υ and T are used as spatial variables, and likewise, ω and 1/T as spatial frequencies.

In a parallel line scanner, implant dose h(t) at a location t on a wafer can be written using a periodic δ-function as:-

$$h(t) = \int_0^1 b(\tau)\cdot\delta_T(t-\tau)d\tau, \qquad (\delta_T(t-\tau) = \sum_{n=-\infty}^{\infty}\delta(t-\tau-nT)) \qquad 1)$$

where $b(\tau)$ is the beam profile in the slow scan direction (y in Figure 2) and $\delta_T(\tau)$ is a periodic δ-function of period T. T corresponds to one translation step or the spacing between raster lines in a composite raster. Figure 5 illustrates the functions and Figure 6 illustrates the raster scanning pattern. The wafer 17 is scanned in front of the beam 19 in parallel lines spaced apart by a constant distance T. For simplicity, $b(\tau)$ is

defined within a range [0, 1]. In other words, the step T is normalized to the actual beam size. Equation 1 gives the accumulated dose at a location t after one complete slow scan or one complete raster with 1/T fast scans. Dose h(t) is also a periodic function with a period T.

Fourier transforms of the functions of Equation 1 are defined as follows:

$$b(t) \xrightarrow{FT} B(\omega)$$
$$\delta_T(t) \xrightarrow{FT} \Delta_{\omega_0}(\omega)$$
$$h(t) \xrightarrow{FT} H(\omega)$$

The Fourier transform of a periodic δ-function is also a periodic δ-function.

$$\Delta_{\omega_0}(\omega) = \omega_0 \cdot \sum_{n=-\infty}^{\infty} \delta(\omega - n\omega_0), \qquad \omega_0 = 2\pi / T \qquad 2)$$

Using the convolution theorem and notations above, Equation 1 is transformed as:

$$H(\omega) = B(\omega)\Delta_{\omega_0}(\omega) = \omega_0 \cdot B(\omega) \cdot \sum_{n=-\infty}^{\infty} \delta(\omega - n\omega_0)$$
$$= \omega_0 \cdot \sum_{n=-\infty}^{\infty} B(n\omega_0) \cdot \delta(\omega - n\omega_0) \qquad 3)$$

This is a significant result. Equation 3 shows that the Fourier transform of dose h(t) consists of a series of impulses with a constant interval $\omega_o = 2\pi/T$, and that the amplitude of each impulse at $\omega = n\omega_o$ is equal to $\omega_o B(n\omega_o)$, that is ω_0 times the spectral density of beam profile at $\omega = n\omega_0$.

Variance, σ^2, of the implant is defined as

$$\sigma^2 = 1/T \cdot \int_0^T (h(t) - \overline{h(t)})^2 dt \qquad 4)$$

where $\overline{h(t)}$ is the average dose. The integration is performed in the region of [0, T] since h(t) is a periodic function of period T.

$$\overline{h(t)} = 1/T \cdot \int_0^T h(t)dt = H(0) = \omega_0 \cdot B(0) \cdot \delta(\omega) \qquad 5)$$

If the dose deviation is written as $f(t) = h(t) - \overline{h(t)}$ and $f(t) \xrightarrow{FT} F(\omega)$, then from Equation 4,

$$\sigma^2 = 1/T \cdot \int_0^T f(t)^2 dt$$

This is the definition of the power of f(t). Using Parseval's theorem this can be expressed as:

$$\sigma^2 = \sum_{n=-\infty}^{\infty} |F_n|^2$$

where $|F_n|$ is the amplitude of the n-th term of F.

From Equations 3 and 5,

$$F(\omega) = H(\omega) - H(0) = \omega_0 \cdot \sum_{n=-\infty}^{\infty} B(n\omega_0) \cdot \delta(\omega - n\omega_0) - \omega_0 \cdot B(0) \cdot \delta(\omega)$$

$$= \omega_0 \cdot \sum_{n=-\infty}^{-1} B(n\omega_0) \cdot \delta(\omega - n\omega_0) + \omega_0 \cdot \sum_{n=1}^{\infty} B(n\omega_0) \cdot \delta(\omega - n\omega_0)$$

Since b(t) is real, $|B(n\omega_0)| = |B(-n\omega_0)|$.

Therefore,

$$\sigma^2 = 2 \cdot \omega_0{}^2 \cdot \sum_{n=1}^{\infty} |B(n\omega_0)|^2$$

and the standard deviation, σ is

$$\sigma = \omega_0 \cdot \sqrt{2 \cdot \sum_{n=1}^{\infty} |B(n\omega_0)|^2} \qquad 6)$$

The relative standard deviation, σ_r, normalized to the average dose, $\overline{h(t)}$ (see Equation 5), is

$$\sigma_r = \sigma / \overline{h(t)} = \sqrt{2 \cdot \sum_{n=1}^{\infty} \left| B(n\omega_0) \right|^2} / B(0) \qquad 7)$$

Equations 6 and 7 describe how dose non-uniformity depends on ω_0, thus on the slow scan step T. The standard deviation of the dose implanted at a frequency 1/T consists of the amplitudes of $B(n\omega_0)$, ($\omega_0=2\pi/T, n=1,2,\cdots$) in the spectral density of the beam function. σ does not contain an amplitude $B(\omega)$ for $\omega \neq n\omega_0$ nor for $\omega=0$. Equations 6 and 7 are mathematically accurate only when the infinite summation is performed. However, $B(\omega)$ is usually a fast diminishing function of ω, and a fairly good approximation of σ and σ_r is obtained by summing only a few lower harmonic terms in the series.

Calculating $B(\omega)$ in the continuous frequency domain is time consuming. Instead, one can use Fast Fourier transform (FFT) and derive values of $B(\omega_n)$ for the discrete frequencies, $\omega_n=2n\pi (n=0,1,2,\cdots)$. FFT of a beam profile that consists of 2^I data points yields $B(\omega)$ only up to $\omega_{I-1}=2\pi \cdot 2^{I-1}$. If the beam profile function is measured and known as a vector each element of which corresponds to $b(\Delta\tau \cdot m)$, $m=0,1,2,\cdots,2^7$), for instance, one can achieve $B(\omega)$ up to a frequency of $2^{7-1}=64$Hz. Equations 6 and 7 then provide fairly accurate values of σ and σ_r, respectively, up to a frequency of $2^{7-2}=32$Hz. $B(\omega)$ can be derived at non-integer frequencies by using the scaling property of the Fourier transform. With $\alpha>1$ being a scaling factor, the Fourier transform of a function $b(\alpha t)$ yields $B(\omega)/\alpha$ for a series of frequencies, $\omega_n=2n\pi/\alpha (n=0,1,2,\cdots)$.

Figure 7 shows the calculated σ_r as a function of frequency, 1/T, for the arbitrary beam profile function shown in Figure 5. FFT is performed for b($\Delta\tau$.m) up to a length 2^7. A typical requirement is for σ_r to be smaller than 0.5% after an implant.

From the graph, one can choose 1/T>8 as the implant scan spatial frequency. Thus the slow scan step or normalised scanning raster line spacing T should be less than 1/8th of the beam dimension in the spacing direction (Y) to meet the required dose uniformity σ_r<0.5%.

In Figure 8, a plot of σ_r is shown after applying the scaling property to B(ω) with two different values of α.

In Figure 9, the FFT result is compared to that of exact calculation by Equation 4. The FFT agrees with the exact curve well despite that the beam profile b(t) was sampled at only 2^7=128 points. It may be noticed that σ_r has a periodic pattern in addition to a fast diminishing trend as frequency rises.

If the beam profile function is a Gaussian, as illustrated in Figure 10, σ_r diminishes very quickly as scan pitch decreases. This is because Fourier transform of a Gaussian function is also a Gaussian, as shown below:

$$b(t)=\exp(-\alpha^2 t^2)\xrightarrow{FT}B(\omega)=1/(\sqrt{2}\cdot\alpha)\cdot\exp(-\omega^2/4\alpha^2) \qquad 8)$$

It can be seen that σ approaches 0 fast due to the term $|B(n\omega_0)|^2=1/(2\cdot\alpha^2)\cdot\exp(-n\omega_0^2/2\alpha^2)$. A smaller value a in Equation 8 gives a broader profile and faster decrease in σ.

The graph shown in Figure 11 illustrates the case where a=5.7. σ_r falls below 0.5% at 1/T=4.3Hz. This is

almost half the frequency of the arbitrary beam profile of Figure 5.

Summarising the above, a fast Fourier transform method can be used to calculate the variation in dose uniformity across the wafer in the raster line spacing direction with raster line pitch, for a particular beam profile function in the spacing direction. In operation, the above calculations can be performed quickly by a computer, such as a computer used for other implanter control functions. Known FFT processors or software applications may be used for this purpose. Instead of FFT techniques, the uniformity calculations may be performed in other ways, such as by use of computer simulation.

When performing an implant using the above-described scanning process, the value for the raster line spacing of the scanning is selected which is sufficiently small relative to the beam dimension in the spacing direction to ensure that the dose uniformity in this direction meets the required standard, <0.5% in the above-described examples.

A number of different procedures may be used for determining the profile function of the ion beam in the raster line spacing direction for use in the above calculations of dose uniformity. For example, the arrangement disclosed in the above-referred United States Patent Application Serial No. 10/119290 may be employed. In this arrangement a small Faraday having an opening of typically 1 cm^2, is mounted on the scanning arm 21, so that it can be scanned across the ion beam by appropriate operation of the motors 25 and 26 to drive the scanning arm 21 in its two component directions. A full two-dimensional map can then be made of the beam cross-sectional profile, in both X- and Y-directions and the

effective profile function in the Y-direction can be calculated.

Using the measured profile function in the Y-direction, the maximum value can be calculated as outlined above of raster line spacing or pitch which can provide the desired dose uniformity. When performing the implant, the scanning mechanism is then controlled to ensure that the raster line spacing employed does not exceed the calculated maximum.

In practice, it is often desirable to use a raster line spacing for the scanning which has been calculated from the beam current available, the dose of ions to be implanted per unit area of wafer, according to the implant recipe, and the speed at which the scanning mechanism can complete the desired number of passes across the beam (which is in turn dependent on the maximum scan speed in the X-direction. Accordingly, before performing an implant, this desired value of the raster line spacing is calculated, having measured the beam cross-sectional profile and the beam current available. Then, this desired line spacing is compared with the calculated variation of dose uniformity obtained for different line spacings to ensure that the calculated desired spacing value will give the required dose uniformity. The implant proceeds only if the calculated spacing value provides satisfactory uniformity.

If the calculated uniformity using the desired spacing value is worse than the desired uniformity, the beam flux may be reduced. Reducing the beam flux results in the calculated line spacing also being reduced. The beam flux is reduced to a level at which the calculated dose uniformity meets the required standard. The beam flux may be reduced by adjusting one or more of the

operating parameters of the ion source including the rate of supply of the feed gas to the arc chamber of the source, the arc supply power, the cathode power, the extraction voltage and the spacing of the extraction electrodes from the ion source. Appropriate adjustments will be known by the skilled person. Alternatively, beam flux can be adjusted by altering a beam aperture at a selected location along the beam path, so as to reduce the current of beam passing through the aperture.

Alternatively, or as well, the calculated uniformity can be improved by modifying the beam profile. As demonstrated above, if the beam profile is closer to a Gaussian shape, the blending properties of the beam can be substantially improved so that good dose uniformity is obtainable with larger raster line spacings. Retuning of the beam, in ways which are well understood by the workers in this field, can improve the beam profile. Retuning can minimize clipping of the beam as it passes from ion source to process chamber, and thereby remove undesirable asymmetries or peaks in the beam profile. The beam could be retuned, for example, by adjusting the lateral position of ion source extraction electrodes relative to the arc chamber of the source, to ensure the extracted beam is directed centrally along the optimum flight path along the beam line of the implanter. Beam profile may also be modified by introducing a single magnetic quadrupole in the beam line to produce a desired spreading of the beam in the Y-direction.

In this procedure, the beam profile is remeasured and the resulting uniformity using the desired line spacing is recalculated with a view to meeting the required uniformity specification.

In the examples of the invention described above, the scanning mechanism is controlled to provide a stepped slow scan, with a uniform step movement between successive fast scans, to produce parallel scan lines on the wafer. In other embodiments of the invention, a continuous slow scan action may be employed with simultaneous fast scans, to produce a zig-zag like scan pattern on the wafer, e.g. as illustrated in Figure 12. Tolerable dose uniformity in the slow scan direction 40 can still be obtained for example if the mid-points 41,42 of successive scans are uniformly spaced in the slow scan direction. It can be seen however that dose uniformity is increasingly compromised towards the edges of the wafer 43 on either side of the centre line 44 where the spacing between successive line pairs becomes increasingly different. Nevertheless, if the pitch (between line mid-points) is sufficiently small compared to the beam size in the slow scan direction, adequate uniformity over the whole wafer can be obtained. It is still important to control the slow scan speed relative to the fast scan repetition rate to achieve a line mid-point spacing which is small enough to provide the desired uniformity. Dose uniformity in the slow scan direction can be calculated at locations near the edge of the wafer where uniformity will be most compromised by the zig-zag scan pattern. These calculations can be performed using Fourier transform techniques similar to those discussed above for parallel line scanning. Alternatively, computer simulation techniques may be employed.

In order to ensure good overall uniformity in the slow scan direction, a minimum pitch size (between line mid-points) is determined by calculation from knowledge of the beam profile shape. Then subsequent scanning of the

wafer must maintain a pitch size no greater than this calculated minimum.

As with parallel line scanning, it may be necessary to reduce beam current or improve beam profile, to achieve the required minimum pitch size without exceeding the required recipe dose on the wafer.

To compensate for any variation in beam current during a pass, this is measured at turnaround points between successive fast scans and the speed of subsequent fast scans controlled accordingly. The repetition rate of fast scans is preferably maintained constant, so that changes in fast scan speed do not effect the pitch between scan line mid-points. This may require some dead time available at each fast scan turnaround to accommodate the increased fast scan time consequent on a reduced fast scan speed for example.

In the above-described examples, the mechanical system disclosed is based on the structure described in the above-referred United States Patent Application Serial No. 10/119290. Any other form of mechanical scanning arrangement may also be used to provide the desired equally spaced and parallel raster lines. For example, the articulated arm scanning mechanism disclosed in United Kingdom Application No. 0214384.0 filed 21st June, 2002 may be employed.

Also, the scans of the substrate holder forming the parallel raster lines need not be precisely linear but could, for example, be formed as arcs of concentric circles.

Many other arrangements may be employed for providing the essential features of the invention as set out in the following claims.

CLAIMS:

1. A method of implanting a substrate, comprising

a) generating an implant beam having a measurable flux of a desired atomic species,

b) producing relative movement between the substrate and the beam both (i) in a first direction transverse to the beam direction to produce at least one pass of the beam over the substrate and (ii) in a second direction transverse to the beam direction and said first direction to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which have predetermined spacing in said first direction, said scans extending beyond an edge of the substrate to positions at which no beam flux is absorbed by the substrate,

c) measuring said beam flux at said positions, and d) adjusting the speed of the next said scan over the substrate in response to the previously measured beam flux to compensate at least partly for the effect of beam current changes during a said pass on dose uniformity in said first direction.

2. A method as claimed in claim 1, wherein said relative movement is continuous in said first direction over said pass.

3. A method as claimed in claim 2, wherein said relative movement is produced by mechanically scanning the substrate parallel to said second direction and simultaneously mechanically translating said substrate parallel to said first direction with a continuous motion.

4. A method as claimed in claim 1, wherein said scans draw a raster of non-intersecting uniformly spaced substantially parallel lines on the substrate.

5. A method as claimed in claim 4, wherein said relative movement between the substrate and the beam in said second direction is produced by mechanically scanning the substrate parallel to said second direction, and said relative movement in said first direction is produced by mechanically translating said substrate parallel to said first direction by a uniform distance between scans.

6. A method as claimed in claim 5, wherein said substrate is translated by said uniform distance between each scan.

7. A method as claimed in claim 5, wherein said mechanical scanning is continued and said substrate is mechanically translated to produce a plurality of said passes of the scanned beam over the substrate.

8. A method as claimed in claim 7, wherein the scans of each said pass draw a respective said raster.

9. A method as claimed in claim 7, wherein said raster is drawn from the scans of a plurality of said passes.

10. A method as claimed in any preceding claim, wherein the spacing of said mid-points of the lines of the raster is selected to provide a desired uniformity in the

spacing direction of implanted dose of said atomic species over the substrate.

11. A method of implanting a substrate comprising the steps of

a) generating an implant beam having a predetermined beam flux of a desired atomic species,

b) mechanically translating the substrate parallel to a first direction transverse to the beam direction to produce at least one pass of the beam over the substrate,

c) mechanically reciprocating the substrate parallel to a second direction, transverse to the beam direction and said first direction, to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which have predetermined spacing in said first direction,

and

d) controlling said mechanical translating step to select said spacing of said mid-points of the raster lines so that said raster provides a desired uniformity, in said first direction, of implanted dose of said atomic species over the substrate.

12. A method as claimed in claim 11, wherein said controlling step includes measuring the cross-sectional profile of the ion beam at least in said first direction, calculating from said profile a maximum value of said spacing of said mid-points which provides said desired uniformity and adjusting the mechanical translating step to select a value of said spacing which does not exceed said maximum value.

13. A method as claimed in claim 11, wherein said controlling step includes measuring the cross-sectional profile of the ion beam at least in said first direction, calculating a desired value of said spacing from data including said beam flux, the speed of said mechanical reciprocation and the desired dose per unit area of substrate to be implanted, then using said measured cross-sectional profile of the ion beam to calculate the dose uniformity which would be obtained at the calculated desired spacing value, and selecting said desired spacing value as the spacing to be employed, only if said calculated uniformity is not worse than said desired uniformity.

14. A method as claimed in claim 13, wherein, if the calculated uniformity is worse than said desired uniformity, the beam flux is reduced to a level at which said calculated dose uniformity is no longer worse than said desired uniformity.

15. A method as claimed in claim 13, wherein, if the calculated uniformity is worse than said desired uniformity, the ion beam is modified to improve the spatial blending quality of said beam profile, such that the calculated uniformity is improved.

16. A method as claimed in any of claims 11 to 15, wherein the substrate is mechanically translated parallel to said first direction in a continuous movement over said pass.

17. A method as claimed in any of claims 11 to 15, wherein the substrate is mechanically translated parallel

to said first direction in a plurality of translation steps between respective pairs of successive scans of the beam, to complete a said pass of the substrate across said beam, whereby said scans draw a raster of non-intersecting uniformly spaced substantially parallel lines on the substrate.

18. A method as claimed in claim 17, wherein said translation steps are of uniform size.

19. A method as claimed in claim 17, wherein said uniform size of the translation steps is selected so that the uniform spacing of the raster lines drawn in said pass provides said desired dose uniformity.

20. A method as claimed in claim 18, wherein the substrate is mechanically translated parallel to said first direction to complete a plurality n of said passes across said beam, and the translation steps of different said passes have the same uniform size and are spatially phased so that the composite raster drawn by the plurality of passes has raster lines with a uniform spacing which is 1/m times said uniform size of said translation steps, where m is an integral factor of n.

21. An ion implanter comprising an ion beam generator producing an implant beam with a measurable flux of a desired atomic species to be implanted, a substrate holder for holding a substrate to be implanted, scanning apparatus producing relative movement between the substrate holder and the beam both (i) in a first direction to produce at least one pass of the beam over a substrate on the holder, and (ii) in a second direction

transverse to the beam direction and said first direction to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which have predetermined spacing in said first direction, said scans extending beyond an edge of the substrate to positions at which no beam flux is absorbed by the substrate,

a Faraday to absorb the beam and measure said beam flux at said positions, and a controller for said scanning apparatus which is responsive to the previously measured beam flux to adjust the speed of the next said scan over the substrate to compensate at least partly for the effect of beam current changes during a said pass on dose uniformity in said first direction.

22. An ion implanter as claimed in claim 21, wherein said scanning apparatus is operative such that said relative movement is continuous in said first direction over said pass.

23. An ion implanter as claimed in claim 21, wherein said scanning apparatus is operative to produce said relative movement such that said scans draw a raster of non-intersecting uniformly spaced substantially parallel lines on the substrate.

24. An ion implanter comprising an ion beam generator producing an implant beam having a predetermined beam flux of a desired atomic species,

a substrate holder for holding a substrate to be implanted,

mechanical scanning apparatus operable to translate a substrate on the holder parallel to a first direction transverse to the beam direction to produce at least one pass of the beam over the substrate, and to mechanically reciprocate the substrate parallel to a second direction, transverse to the beam direction and said first direction, to produce a plurality of scans of the beam over the substrate during each said pass, whereby said scans draw on the substrate a raster of lines having mid-points which are uniformly spaced in said first direction, and a controller for said scanning apparatus to control said translation of the substrate to select said uniform spacing of said mid-points so that said raster provides a desired uniformity, in said first direction, of implanted dose of said atomic species over the substrate.

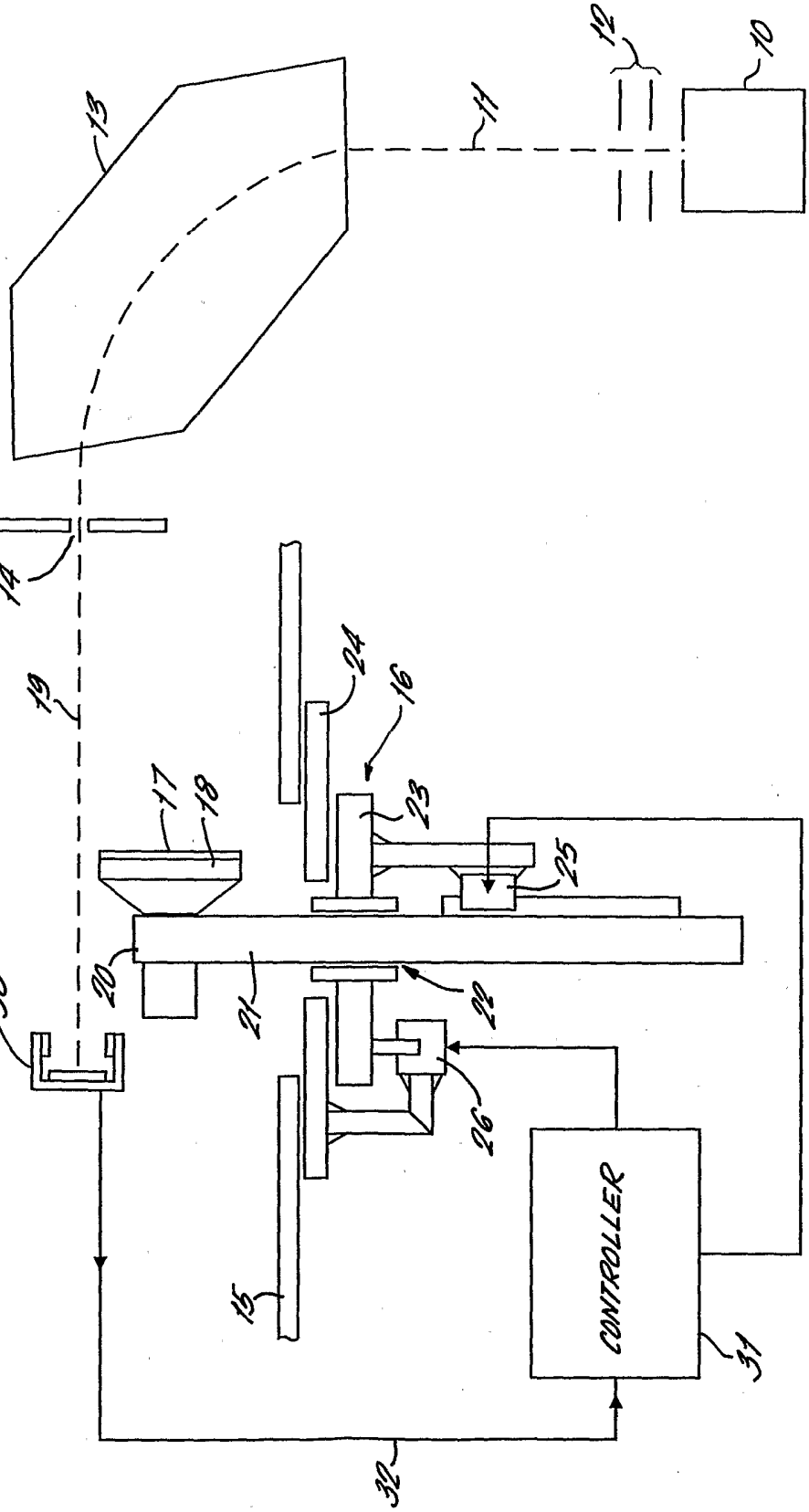
25. An ion implanter as claimed in claim 24, wherein said mechanical scanning apparatus is operative to translate a substrate on the holder parallel to said first direction in a continuous movement over said pass.

26. An ion implanter as claimed in claim 24, wherein said mechanical scanning apparatus is operative to translate a substrate on the holder parallel to said first direction in a plurality of translation steps between respective pairs of successive scans of the beam, to complete a said pass of the substrate across said beam, whereby said scans draw a raster of non-intersecting uniformly spaced substantially parallel lines on the substrate.

27. An ion implanter as claimed in claim 26, wherein said translation steps are of uniform size.

28. An ion implanter as claimed in claim 27, wherein said controller is operative to select the uniform size of the translation steps so that the uniform spacing of the raster lines drawn in said pass provides said desired dose uniformity.

29. An ion implanter as claimed in claim 27, wherein said mechanical scanning apparatus is operative to translate the substrate to complete a plurality n of said passes across said beam, and said controller is operative to maintain the translation steps of different said passes to have the same uniform size and to be spatially phased, so that the composite raster drawn by the plurality of passes has raster lines with a uniform spacing which is 1/m times said uniform size of said translation steps, where m is an integral factor of n.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32
CONTROLLER

FIG. 1.

FIG. 2.

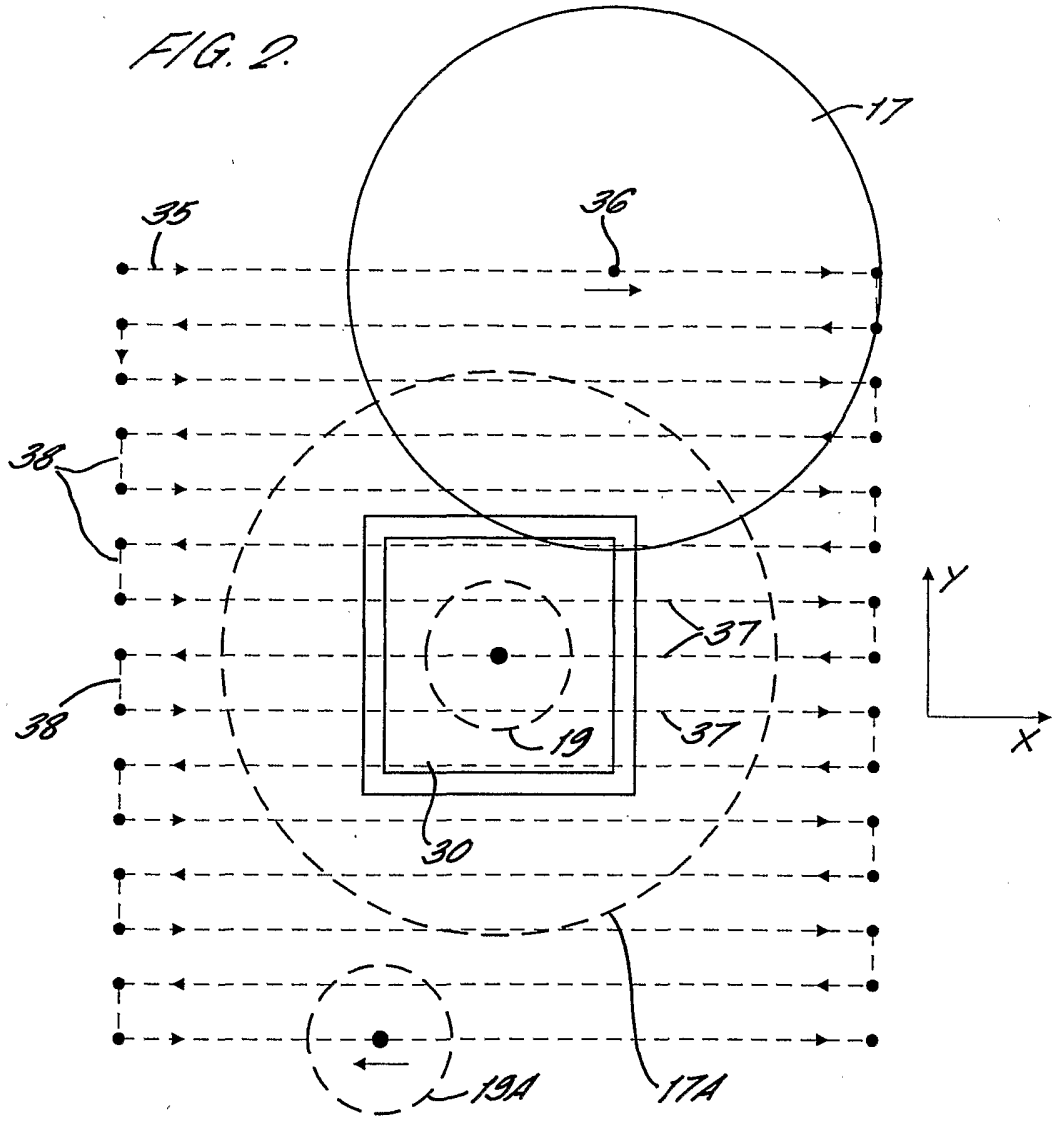


FIG. 3.

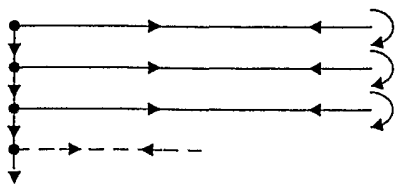
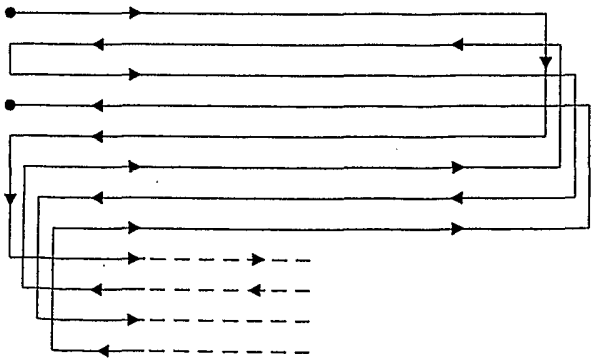


FIG. 4.



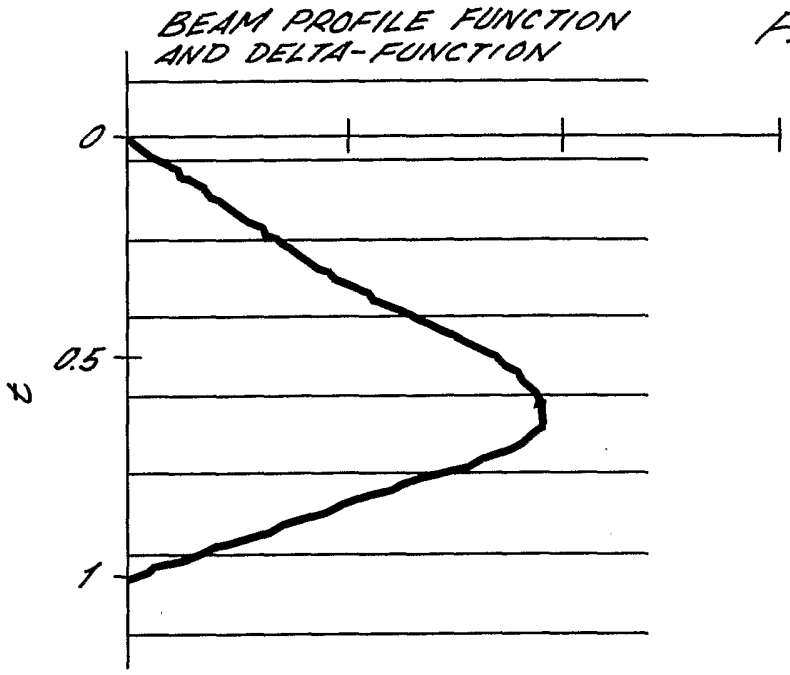


FIG. 5.

FIG. 6.

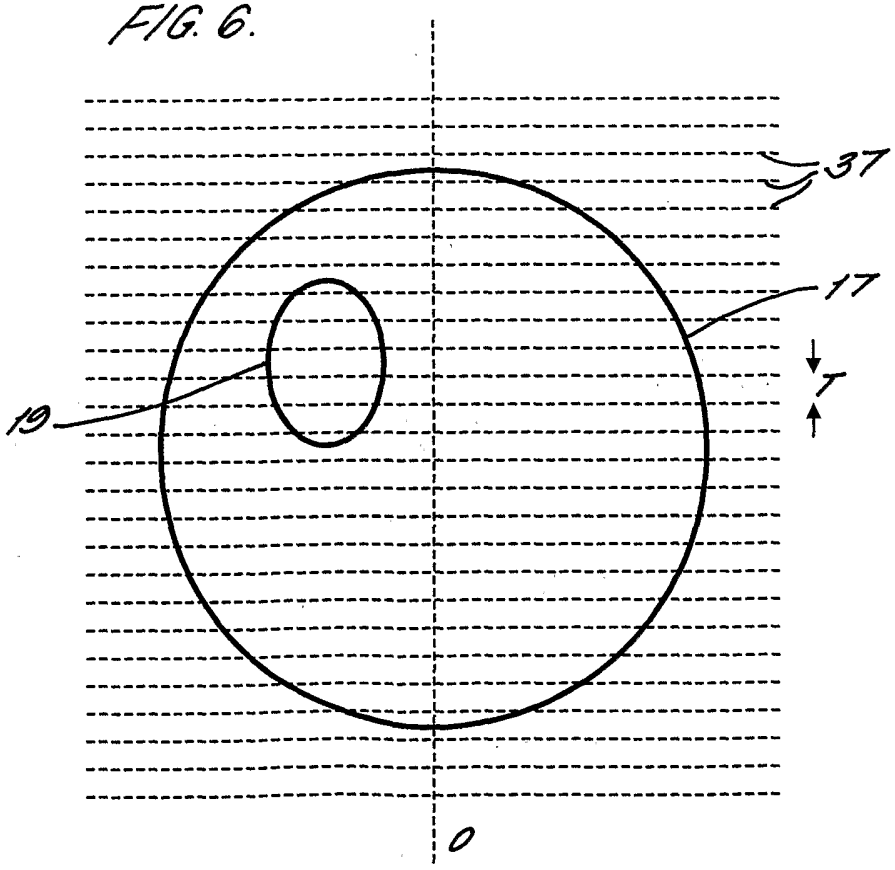
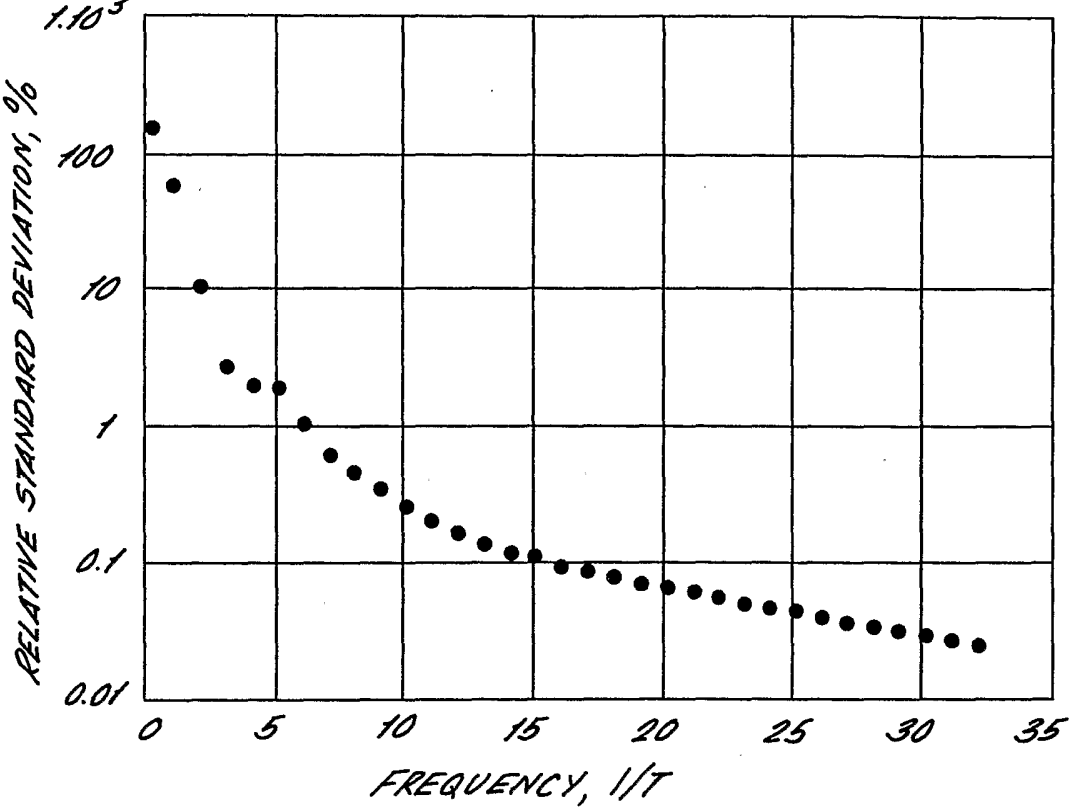


FIG. 7.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0.1
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FREQUENCY, 1/T

FIG. 8.

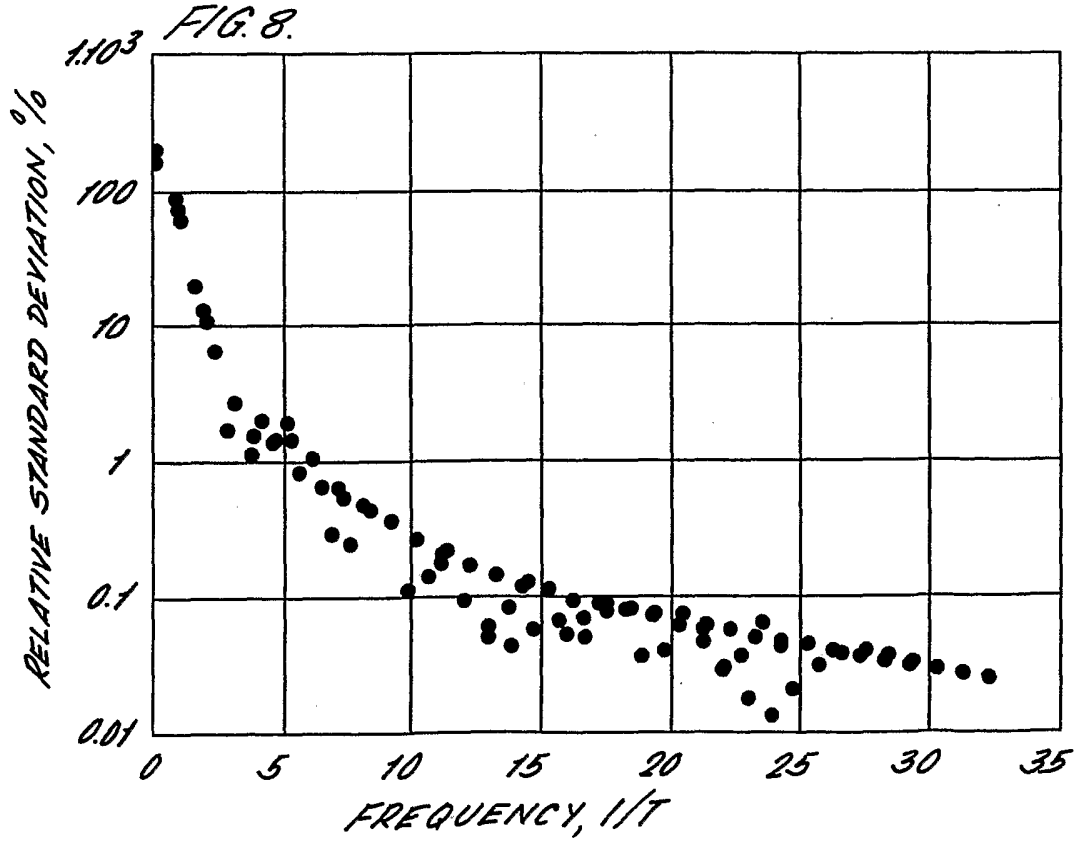
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FIG. 9.

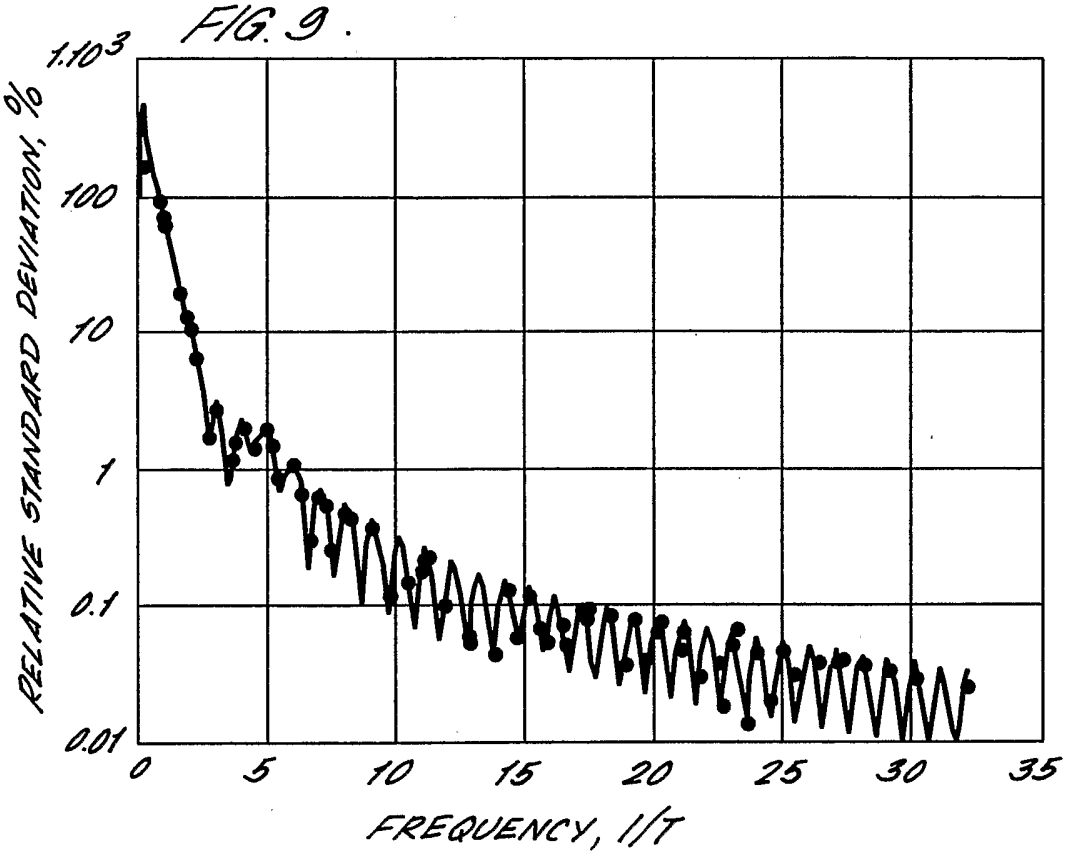
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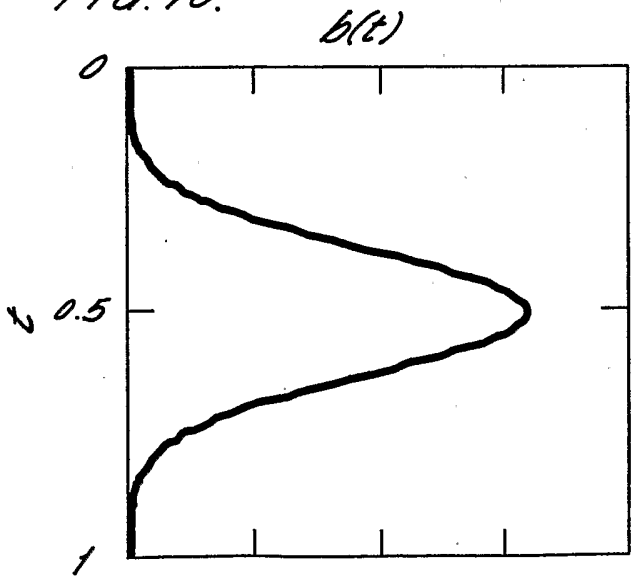
FIG. 10.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t

FIG. 11.

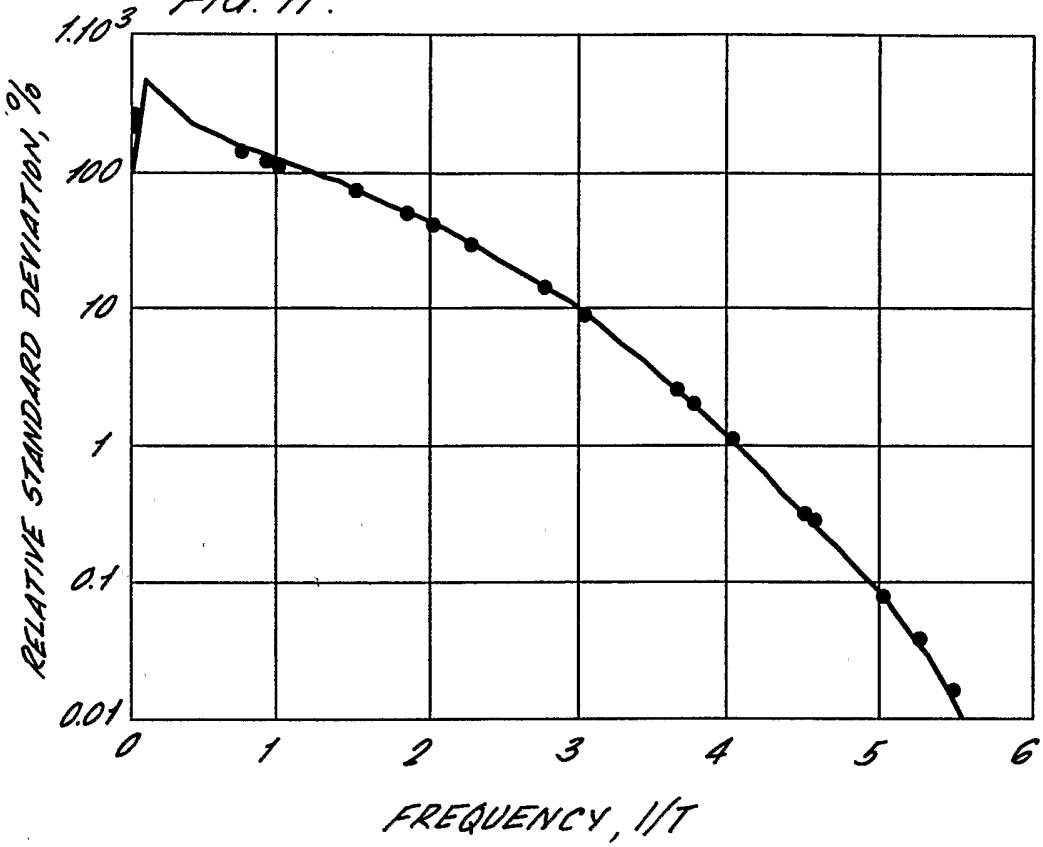
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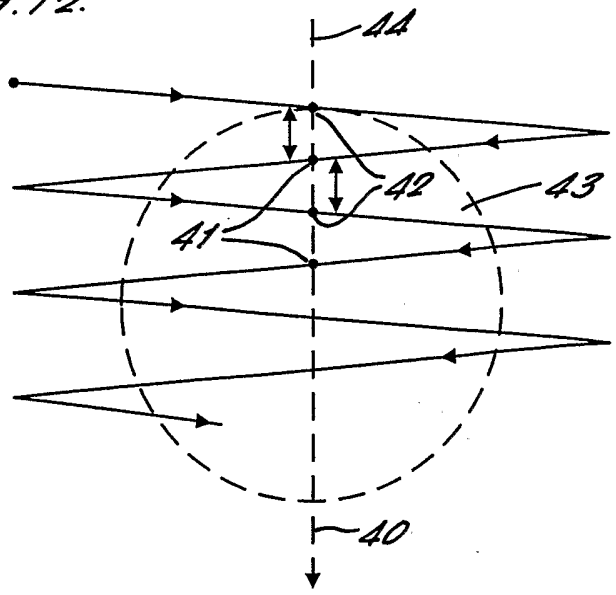
FIG. 12.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