

[54] ELECTRON BEAM APPARATUS

[75] Inventor: Denis Frank Spicer, Putnoe, Bedford, England

[73] Assignee: Texas Instruments Incorporated, Dallas, Tex.

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[52] U.S. Cl. 315/31 R, 250/49 C, 250/49 D, 315/27 GD

[51] Int. Cl. H01j 29/56

[58] Field of Search 315/31 R, 27 GD; 250/49.5 C, 49.5 D

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Primary Examiner—Benjamin A. Borchelt

Assistant Examiner—H. A. Birmiel

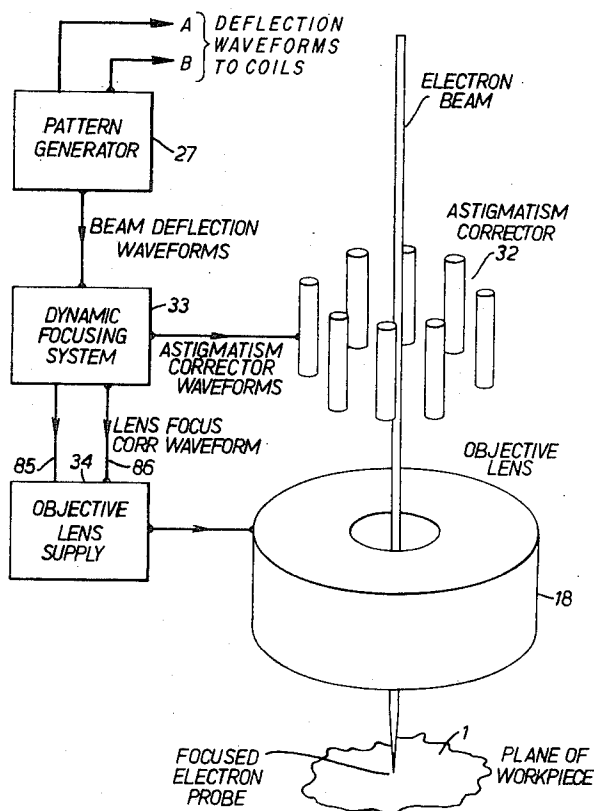
Attorney—Samuel M. Mims, Jr., James O. Dixon, Andrew M. Hassell, Harold Levine, Melvin Sharp, Michael A. Sileo, Jr., Gary C. Honeycutt, Henry T. Olsen and John E. Vandigriff

[57]

ABSTRACT

An electron beam apparatus is provided, including means for producing an electron beam in combination with an electron lens for focussing the beam and means for deflecting the beam in two directions. A signal derived from the deflecting signals is applied to the lens for correcting for the curvature of the surface described by the focus of the beam during deflection, and is also applied to means for correcting astigmatism of the electron lens.

19 Claims, 24 Drawing Figures



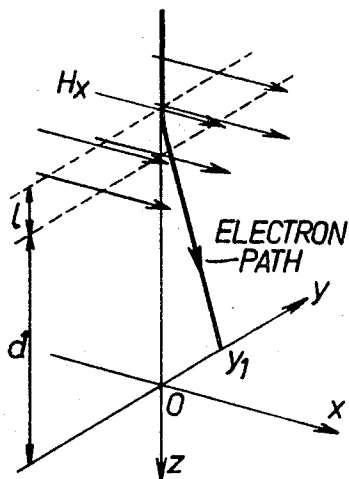


FIG. 1a.

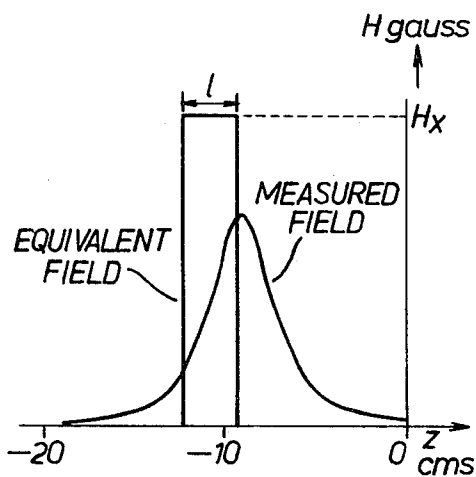


FIG. 1b.

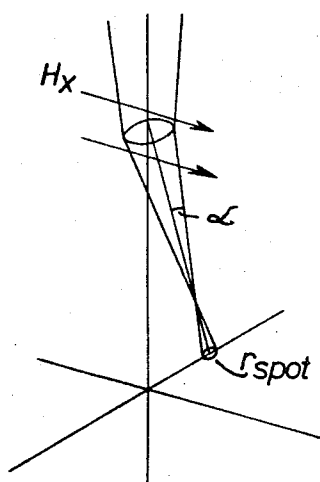


FIG. 1c.

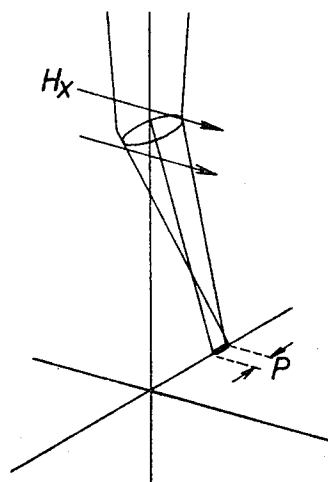


FIG. 1d.

INVENTOR
Denis F. Spicer
 BY *Gary C. Hough*
 ATTORNEY

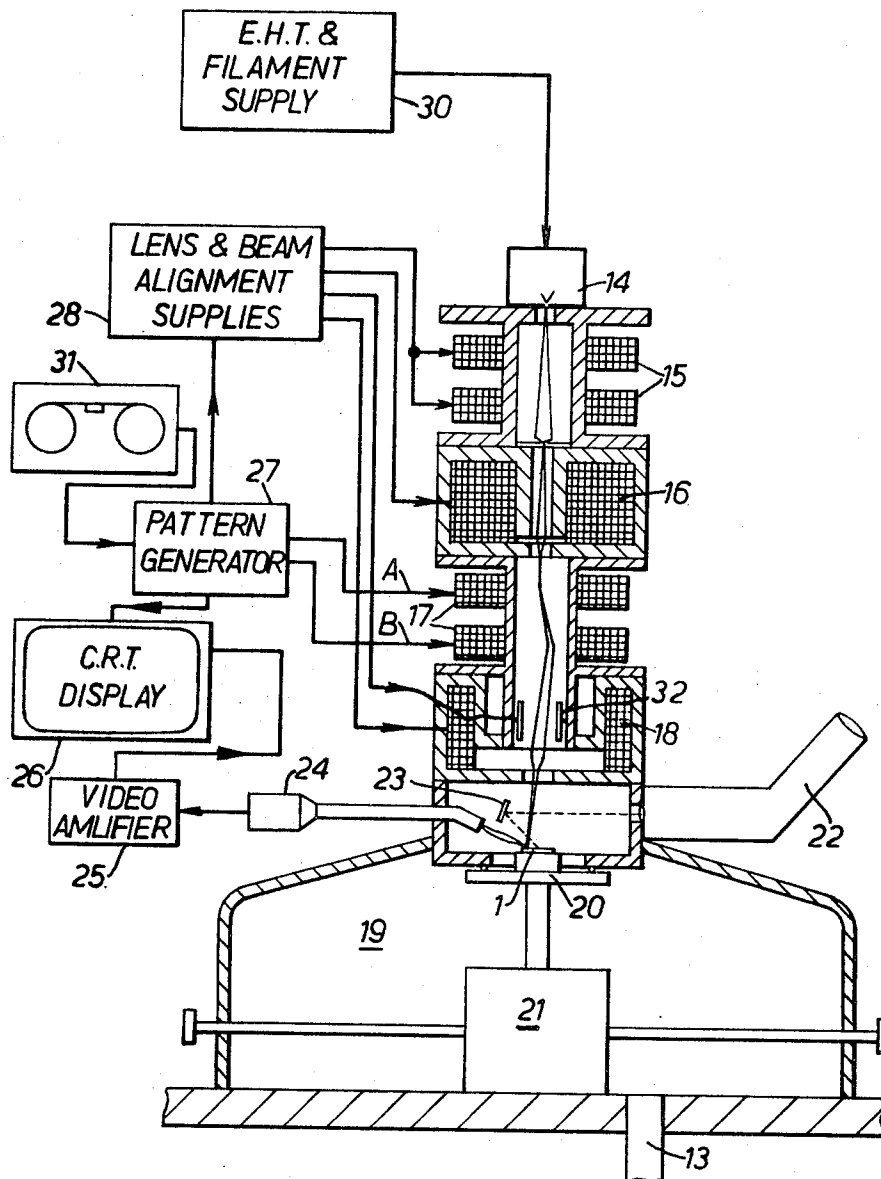


FIG. 2.

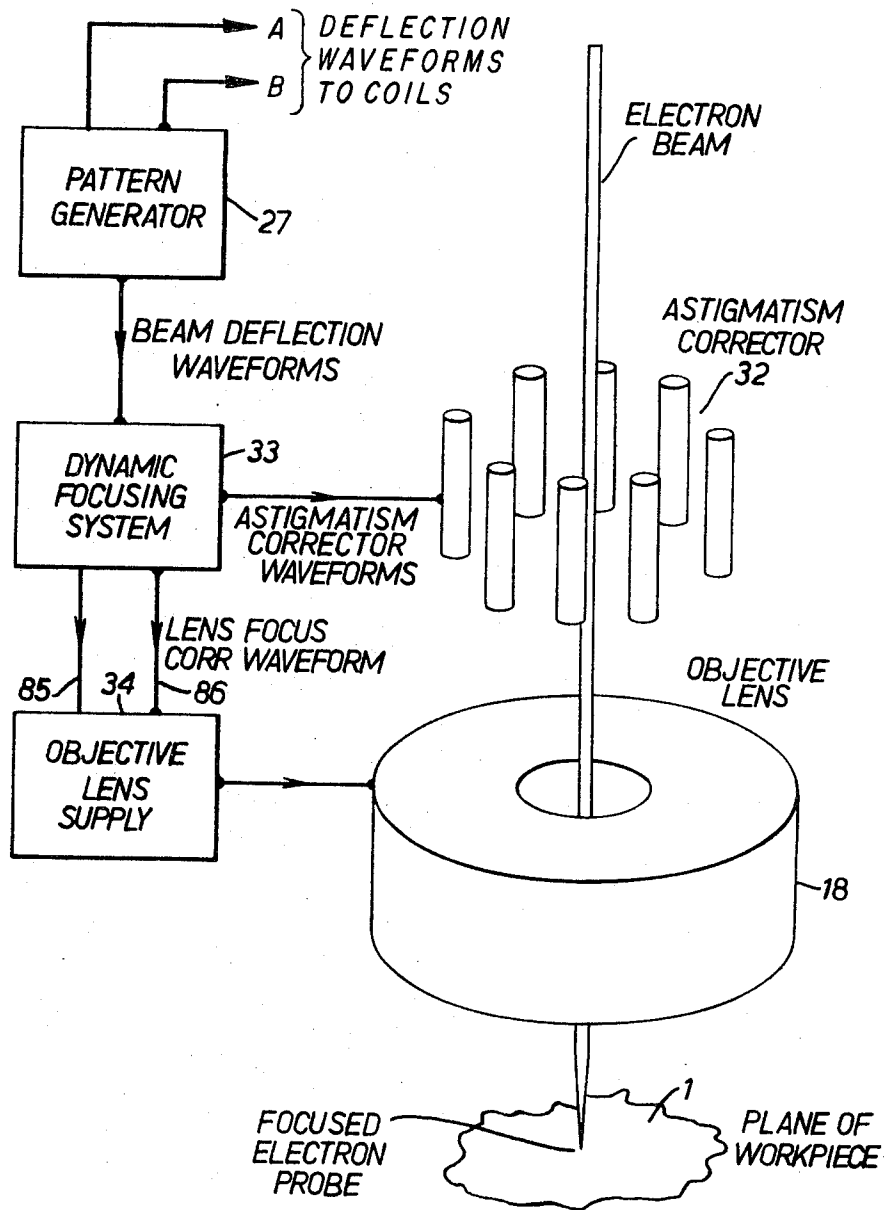
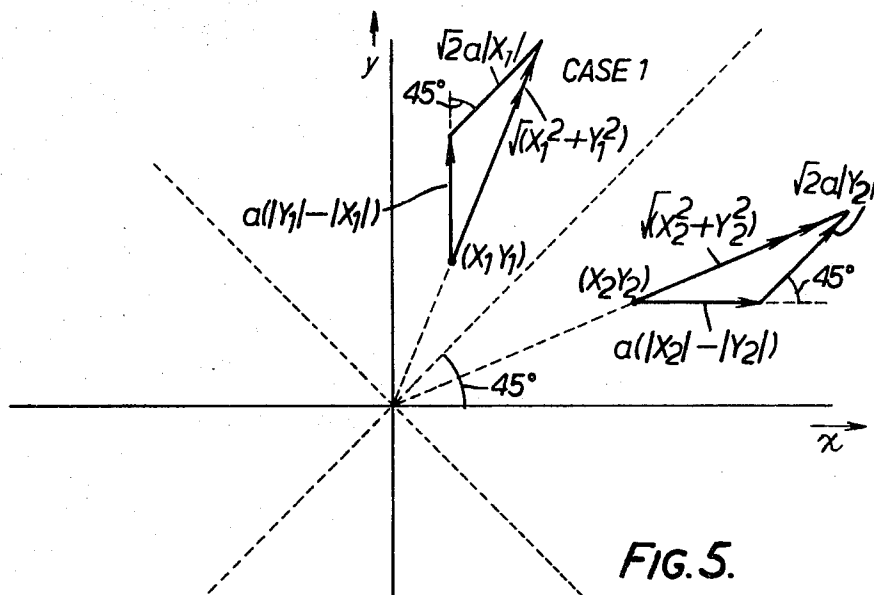
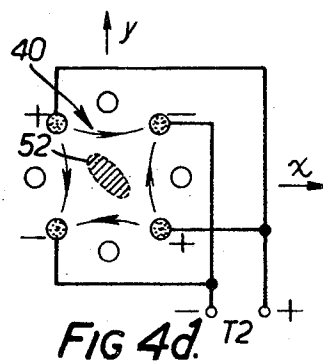
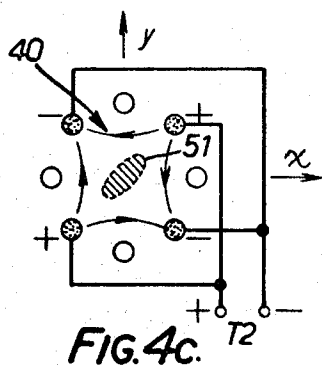
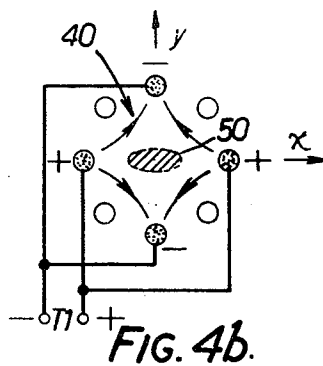
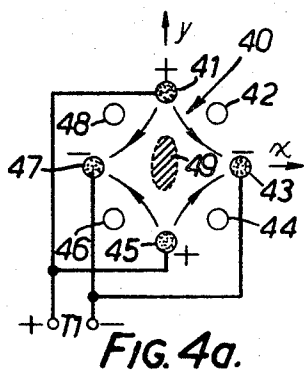
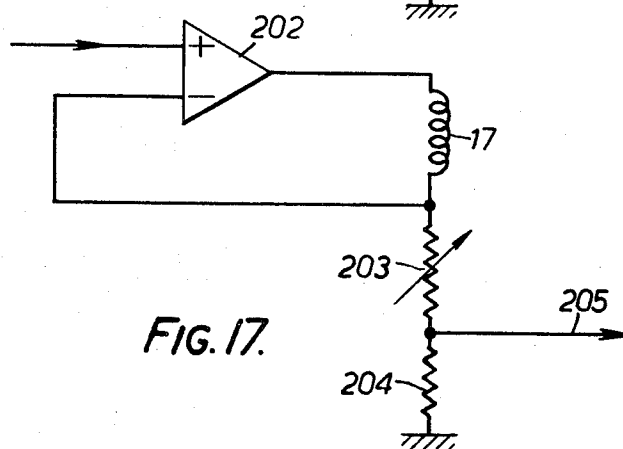
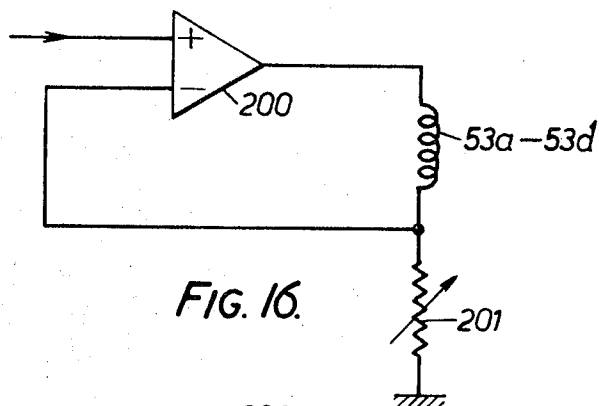
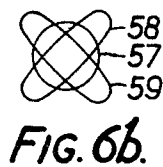
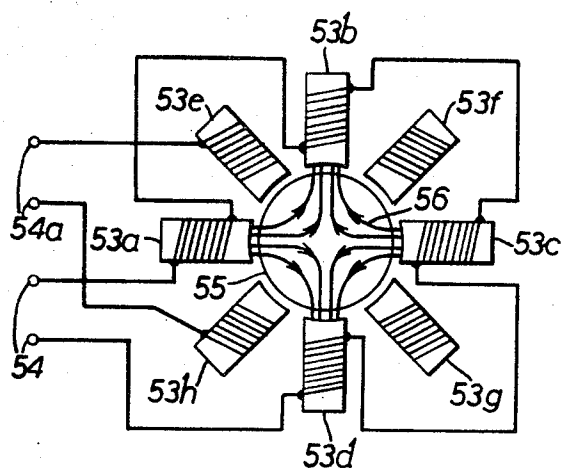


FIG. 3.





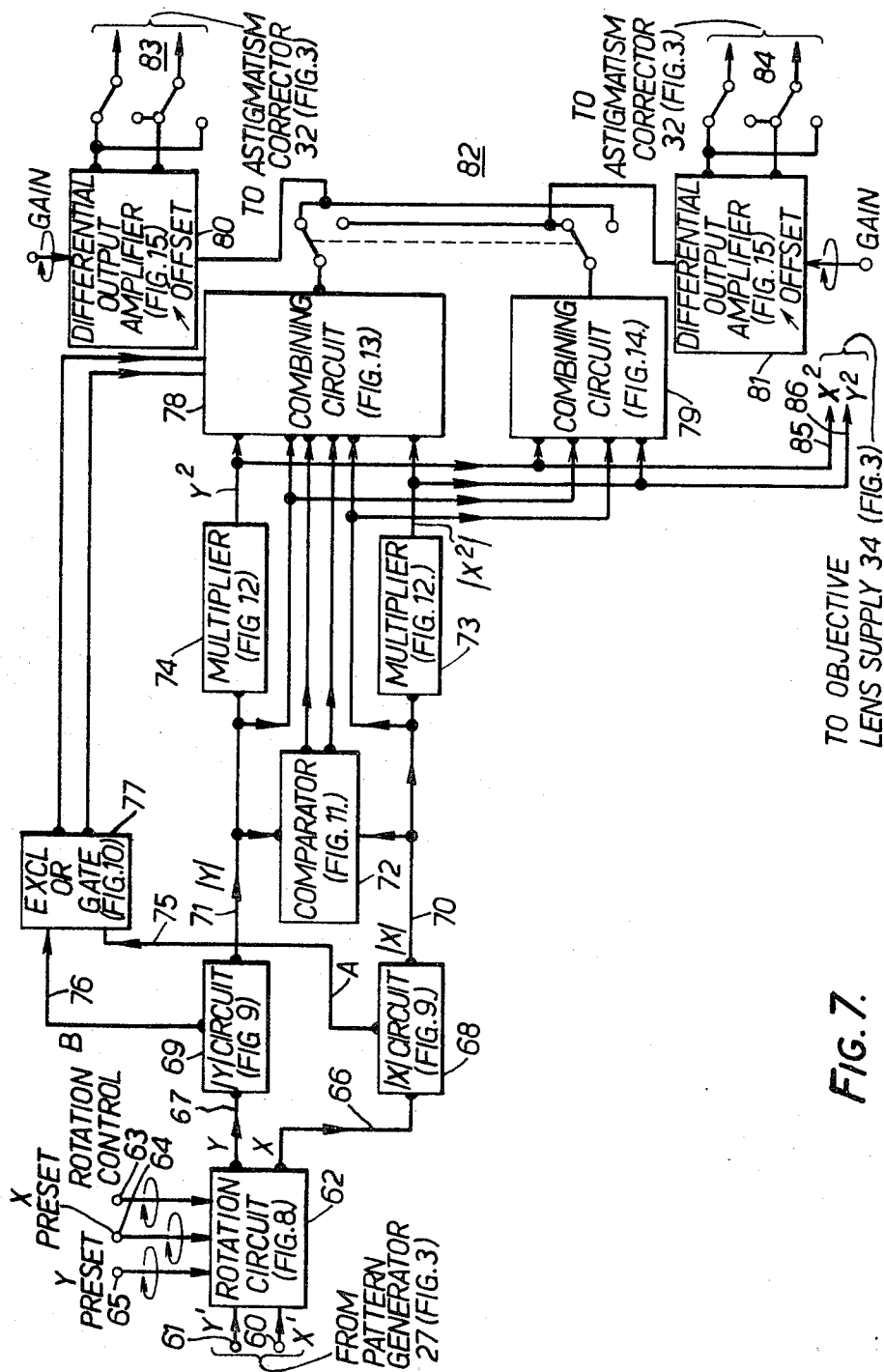


FIG. 7.

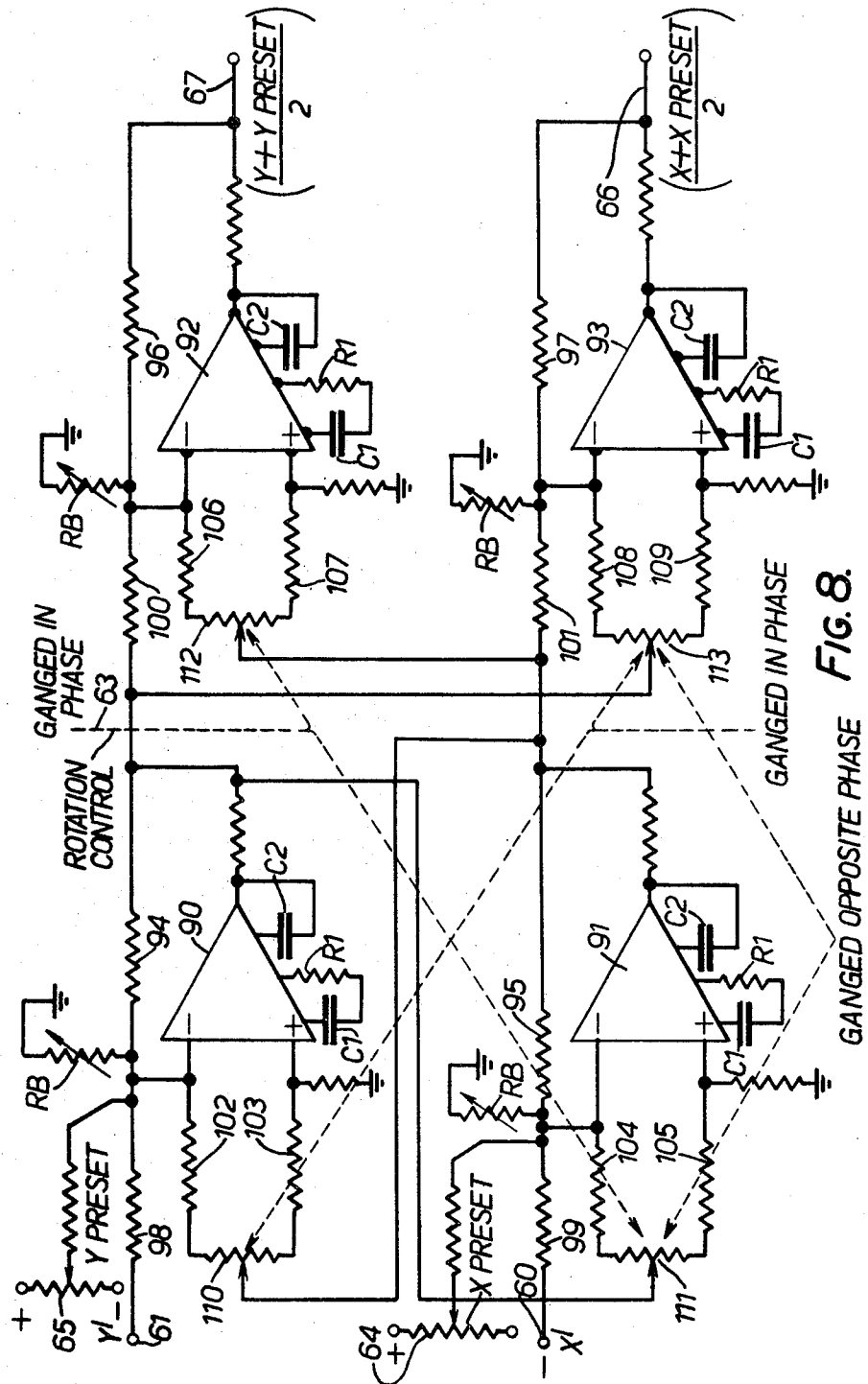


FIG. 8.

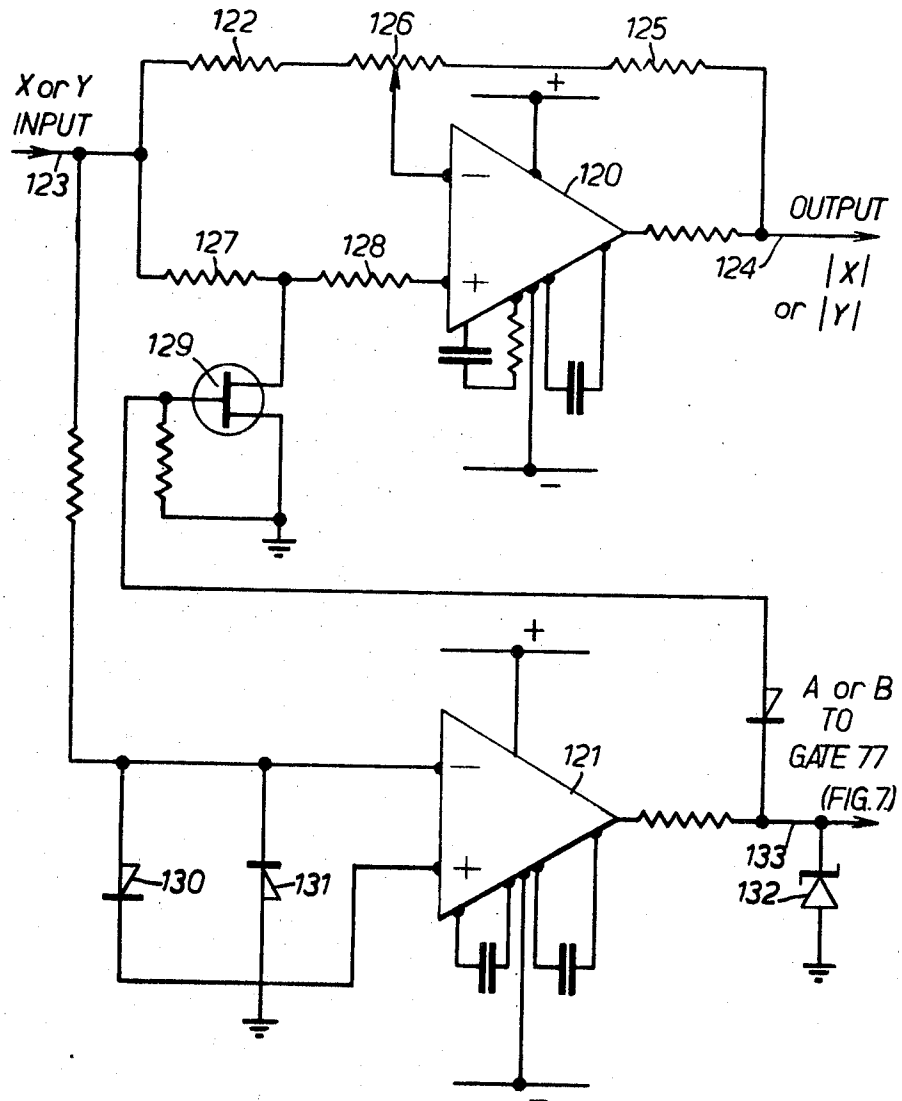
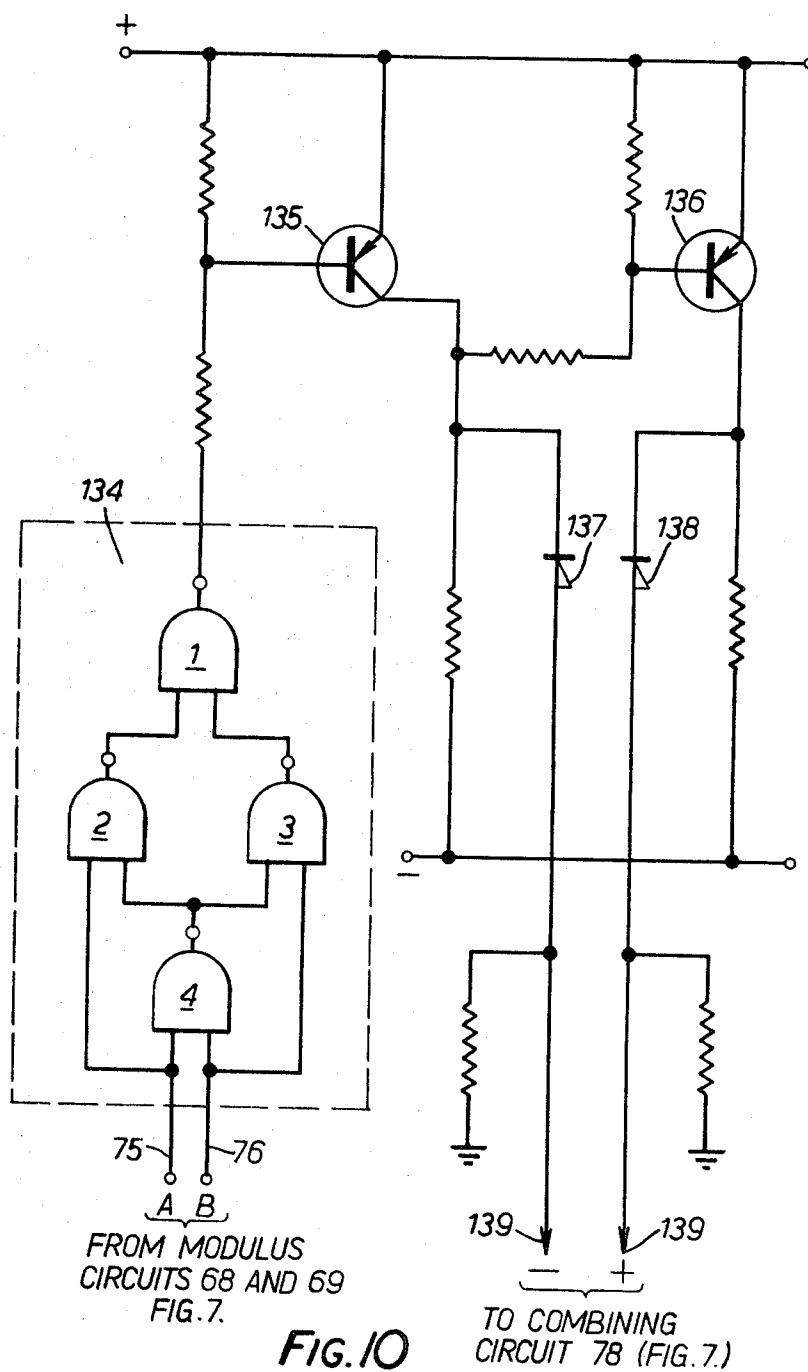


FIG. 9



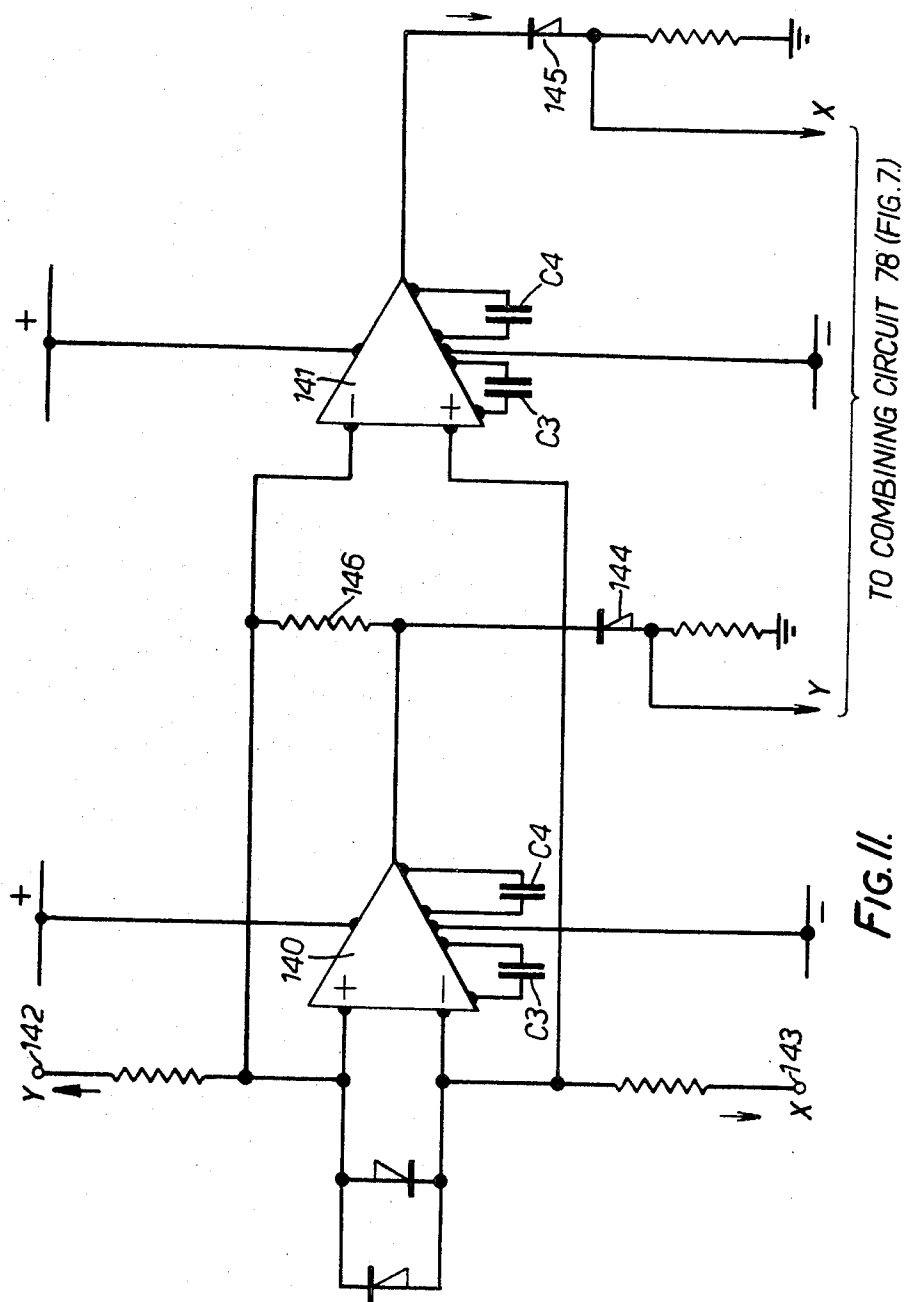
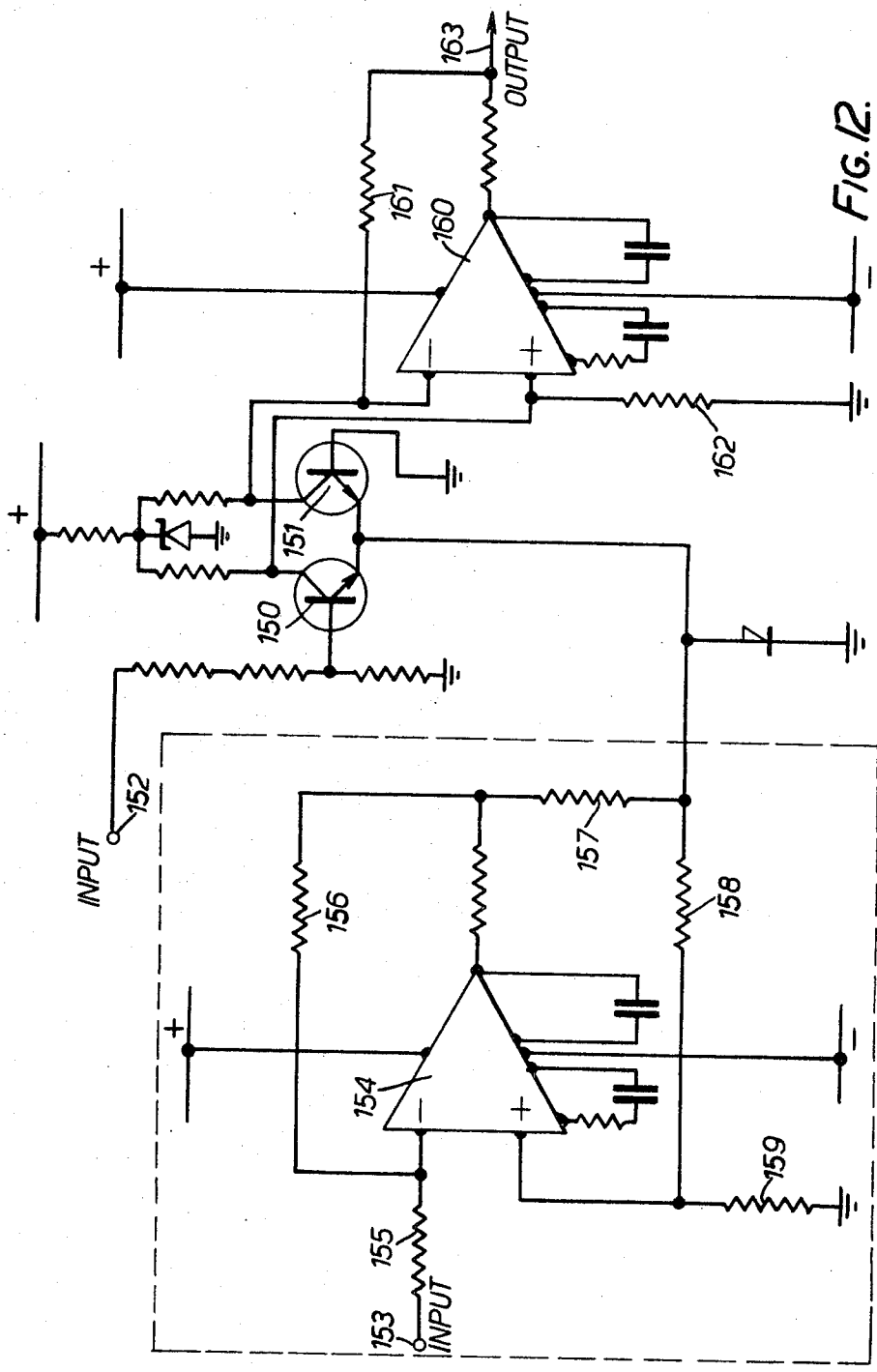
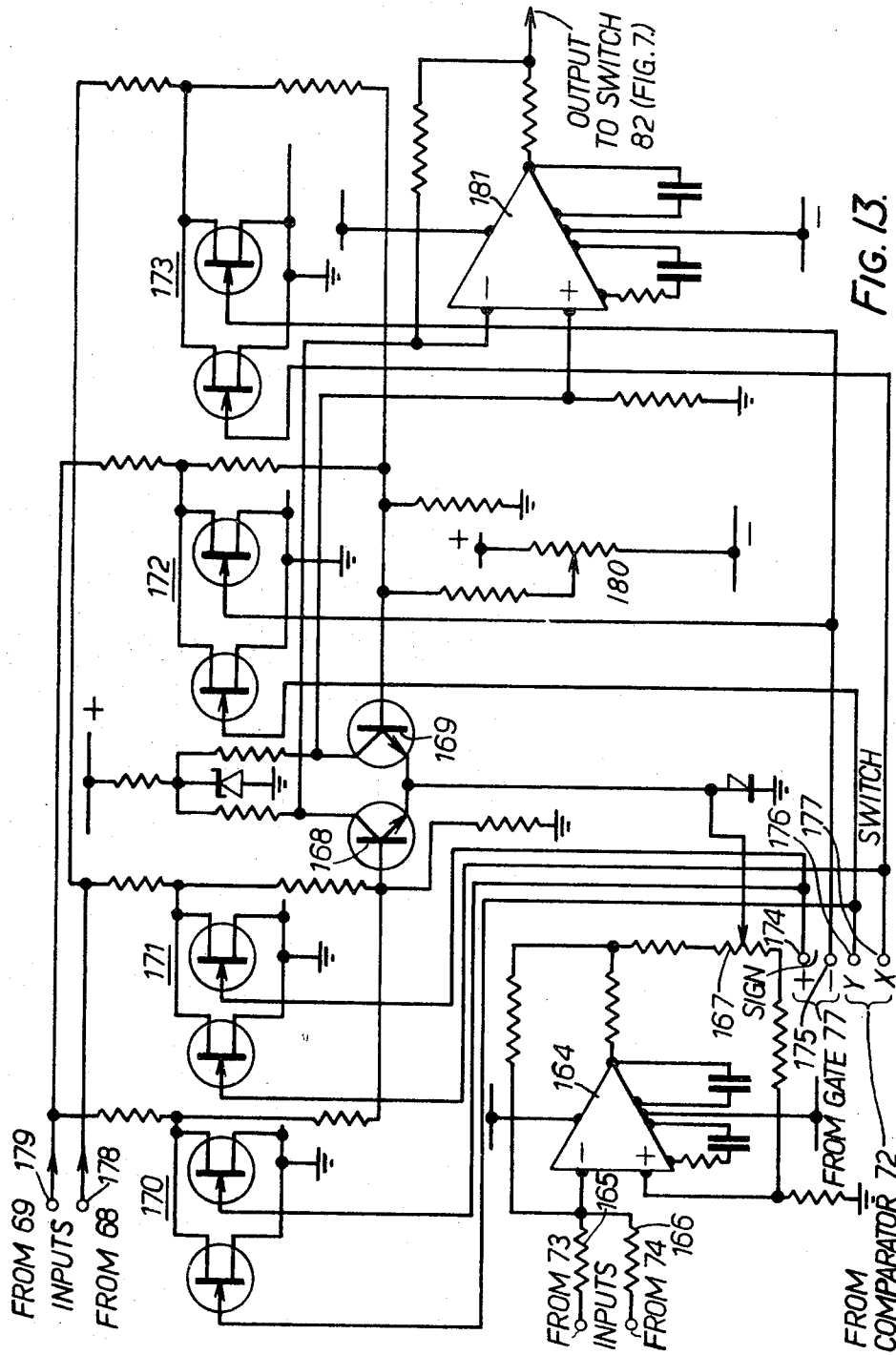


FIG. II.





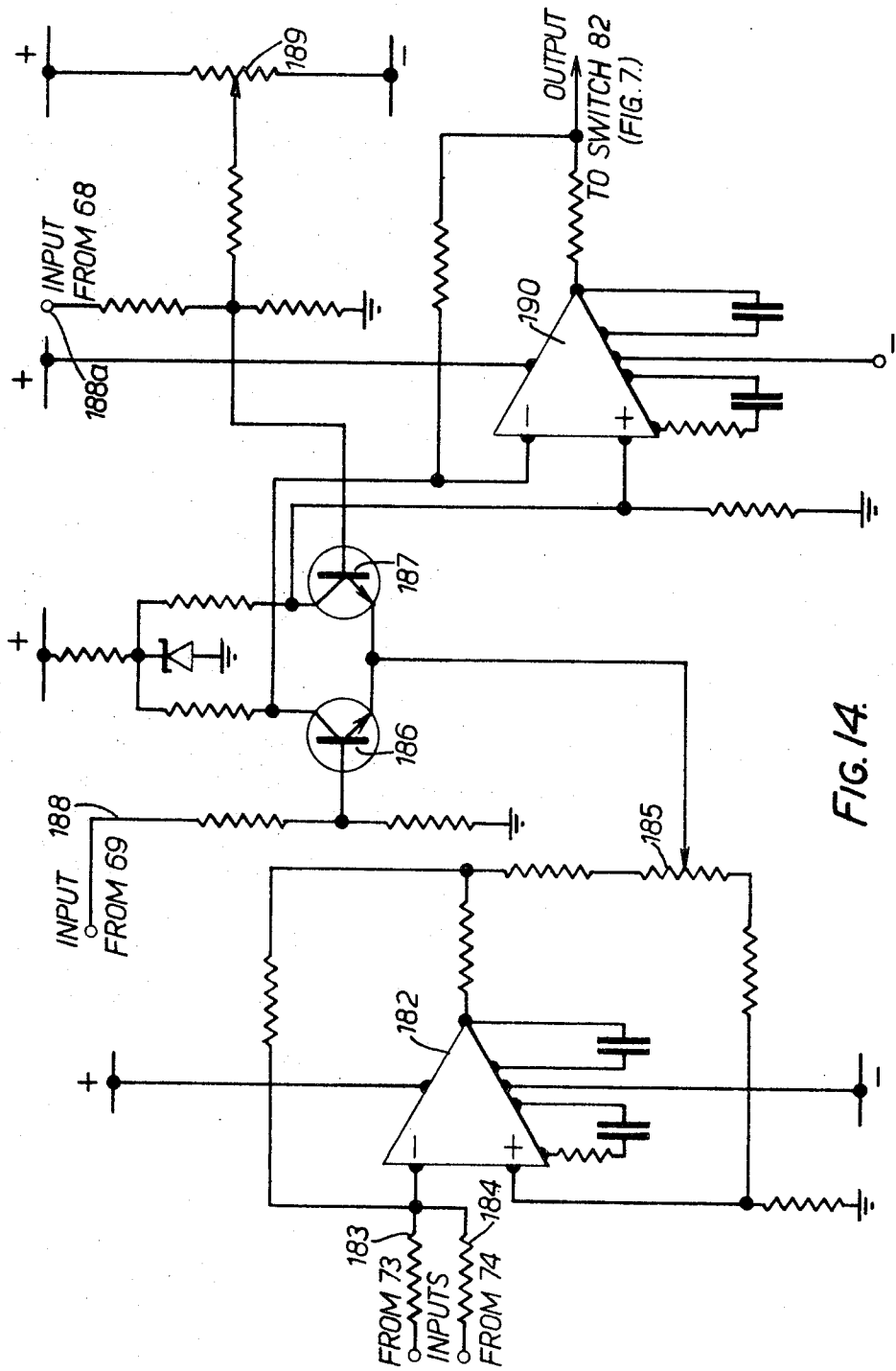


FIG. 14.

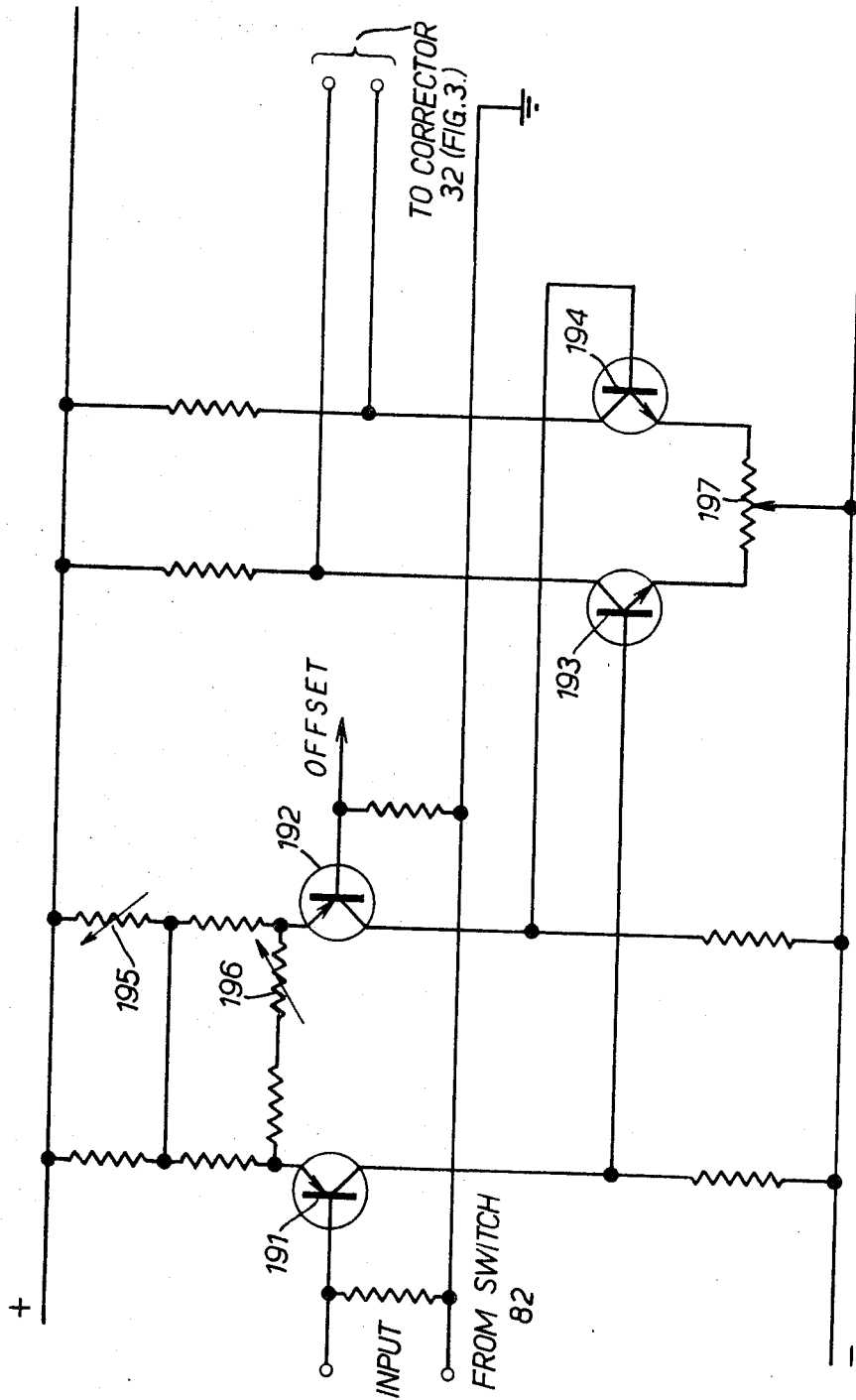


FIG. 15.

ELECTRON BEAM APPARATUS

This invention relates to electron beam apparatus and especially but not exclusively to such apparatus as might be used for producing an exposed pattern on a resist, the pattern being delineated by deflection of the electron beam.

In co-pending patent application TI-3906 there is described a system for using an electron beam to expose a sensitive resist for the purposes of manufacturing integrated circuits and other semiconductor devices. It has been found that the use of an electron beam in this way can provide more accurate patterning in the exposure of the resist with the result that improved integrated circuits may be produced. However, in the electron beam generating columns used for this work it is usual to deflect the beam before the final focussing stage and it has been found that it is usually possible to deflect the beam by about 1,000 times the diameter of the focussed spot before serious defocussing takes place. While this is satisfactory for scanning electron microscopes and similar instruments, it would be desirable to be able to deflect the beam up to 10,000 times the spot diameter in the patterning required in the manufacture of integrated circuits. However, with such large deflections some correction of the electron optics is necessary to achieve the sharply defined patterning over the whole area scanned by the beam.

It is an object of the present invention to provide a system for focussing the electron beam so that a spot is better focussed at relatively larger deflections than before.

According to the present invention there is provided electron beam apparatus including means for producing an electron beam having an electron lens for focussing the beam, and means for deflecting the beam in two directions in response to respective deflection signals, wherein there are provided means for applying a signal derived from the deflecting signals to the electron lens for correcting for curvature of the surface described by the focus of the beam during deflection and means for applying signals derived from the deflecting signals to means for correcting astigmatism introduced by the deflection of the beam.

In order that the invention may be fully understood and readily carried into effect it will now be described with reference to the accompanying drawings in which:

FIGS. 1a, 1b, 1c and 1d illustrate distortion of the spot produced by an electron beam which it is required to correct;

FIG. 2 is a diagram showing one example of a system using an electron beam for producing exposure patterns on a resist for the manufacture of integrated circuits;

FIG. 3 is a diagram showing the arrangement used in the electron beam generating column of FIG. 2 for electrostatically correcting astigmatism;

FIGS. 4a, 4b, 4c and 4d show the effect of the astigmatism corrector shown in FIG. 3;

FIG. 5 shows how two types of astigmatism correction can be combined to produce correction of astigmatism in any direction;

FIG. 6a shows a system of coils for correcting astigmatism magnetically;

FIG. 6b shows the effect of one set of the coils shown in FIG. 6a;

FIG. 7 is a block diagram of one example of apparatus for effecting dynamic focus correction suitable for use with the apparatus of FIG. 2;

FIG. 8 shows in more detail the rotation circuit of FIG. 7;

FIG. 9 shows a circuit for producing an output equal to the modulus of the signal suitable for use in the arrangement of FIG. 7;

FIG. 10 shows an EXCLUSIVE OR circuit suitable for use in FIG. 7;

FIG. 11 shows one example of a comparator for FIG. 7;

FIG. 12 is the circuit of the analog multiplier of FIG. 7;

FIG. 13 is the circuit of one combining circuit of FIG. 7;

FIG. 14 is the circuit of another combining circuit of FIG. 7;

FIG. 15 is the circuit of one form of the output amplifier of FIG. 7;

FIG. 16 shows an alternative to the amplifier of FIG. 15 for driving a magnetic astigmatism corrector; and

FIG. 17 shows one way in which a voltage proportional to deflection can be derived from the deflection circuits.

FIG. 1a shows an electron ray directed along the z-axis passing through a magnetic field parallel to the x-axis which field deflects the electron ray away from the z-axis so that it meets the y-axis at Y_1 . This magnetic field shown in FIG. 1a occupies a region of length L along the z-axis spaced a distance d from the origin of the system of axes and is of uniform strength H_x within the region. However, this is an ideal magnetic field and in practice the magnetic field is likely to be as shown in FIG. 1b indicated by the curved outline labelled "measured field" where it can be compared with the ideal "equivalent field" indicated by the rectangular outline. Although the magnetic field cannot be constrained to the rectangular outline of the ideal equivalent field, this equivalent field can be calculated so that the defocussing of an electron beam passing through the deflecting field which occurs in practice can be calculated from the equivalent field and correction applied on this basis.

FIG. 1c shows the defocussing of a focussed electron beam produced by deflection of the beam by a magnetic field due to curvature of the focal surface. The result of this curvature is that on parts of the plane on which the beam is being focussed, it is not focussed to a point but to a circle of radius of r_{spot} .

Astigmatism introduced by the deflection of the beam causes the electron beam to be focussed into a line of length P as shown in FIG. 1d. This line is radial to the origin, that is to say the astigmatism is in the direction of deflection.

With a practical deflecting field, such as is shown in FIG. 1b, the calculation of the defocussing of the beam is more difficult and is also complicated by the fact that deflection is normally carried out before the objective lens.

However, the corrections necessary can readily be found by experiment and in the apparatus shown in FIG. 2 it was found that the correction for curvature of the focal surface varied with the square of the deflection distance, this being the same as for the simple deflecting field shown in FIG. 1b, and the correction required for astigmatism varies as the cube of the deflec-

tion distance, the sense of this correction being in the direction of deflection.

The electron beam machine shown in FIG. 2 itself is coupled by the pipe 13 to a vacuum pump, not shown. The machine has an electron gun 14 which may, for example, be thermionic, from which electrons pass aligning and blanking coils 15 to a magnetic condenser lens 16. From the condenser lens the beam passes through x-axis and y-axis deflection coils 17 to an astigmatism corrector 32 and a magnetic objective lens 18. The deflection coils and astigmatism corrector can be arranged in other configurations relative to the objective lens. In the work chamber 19 forming part of the evacuated space there is provided a worktable 20 on which a semiconductor wafer 1 is placed. The worktable 20 is mounted on a suitable mechanical stage 21 by which the worktable 20 can be moved by controls from outside the workchamber 19. The objective lens 18 serves to focus the electron beam onto the surface of the wafer 1. For the rough alignment of the wafer in the machine there is provided an optical microscope 22 through which the surface of the wafer 1 can be observed with the aid of the mirror 23. In order to obtain a video signal in response to markings formed on the surface of the wafer 1 there is provided a single channel electron multiplier 24 which picks up the secondary electrons emitted from the surface of the wafer 1; as is well known from the scanning electron microscope art, the secondary emission which takes place during the scanning of the electron beam over the surface varies in response to marks on the scanned surface. Thus there is produced from the multiplier 24 a video signal representing the surface marks on the wafer 1 which signal is applied to amplifier 25 and then to cathode-ray display tube 26. Pattern generator 27 provides a x-axis and y-axis deflection signals (X and Y) for the deflection coils 17 and also for the cathode-ray display tube 26, and also beam blanking signals and focus correction signals which are applied to the lens and beam alignment supply circuits 28. The circuits 28 provide the necessary currents and voltages for focussing the electron beam on the surface of the wafer 1, correcting astigmatism in the lenses, aligning the beam from the electron gun with the lenses and for blanking the beam. In view of the difficulty of turning off the beam by means of a control electrode, the beam blanking is effected by deflecting the beam away from the axis of the lens system so that it does not pass through an aperture in the lens but is cut off. Preferably the electron gun is arranged off the axis of the lens system so that light from the cathode cannot fall on the surface of the wafer 1 and cause photo-exposure of the resist; in addition ions emitted from the cathode are also prevented from entering the electron optical system. Unit 30 provides the EHT and filament supplies of the electron gun. Punched tape reader 31 is provided for applying in digital form signals to the pattern generated 27 to determine the deflection of the electron beam as described above.

The electron optical components used in the column shown in FIG. 2 for effecting the correction of the focussing of the beam are the objective lens 18 and the astigmatism corrector 32. These components are shown in FIG. 3. The objective lens 18 is a magnetic lens powered by a steady current derived from unit 34 and in order to correct for the curvature of its focal surface, the unit 34 receives from the dynamic focussing

system 33 — also part of unit 28 (FIG. 2) — a signal proportional to the square of the electron beam deflection, this signal being that required to correct the curvature as determined experimentally. For setting up the apparatus it is desirable for the magnitude of the correcting signal to be adjustable so that the correction can be accurately made.

The astigmatism corrector 32 as shown in FIG. 3 operates electrostatically and consists of eight rods equally spaced around the axis of the column which rods receive voltage waveforms derived from the dynamic focussing system 33. These rods are used as two interleaved sets of four electrostatic electrodes, each set being arranged at the corners of a square, and receive the voltages described below for connecting the astigmatism of the optical system which occurs along the direction of deflection.

FIGS. 4a, 4b, 4c and 4d show the method of applying the correction voltages to the eight rods of the astigmatism corrector 32. In FIGS. 4a and 4b the set of four rods used for correction of the astigmatism along the deflection axis x and y is shown and in FIGS. 4c and 4d the correction for astigmatism in diagonal directions is shown. The eight rods have references 41, 42, 43, 44, 45, 46, 47 and 48 respectively, the four rods 41, 43, 45 and 47 being used for the axis astigmatism correction and the four rods 42, 44, 46 and 48 being used for the diagonal astigmatism correction. Considering now the axis astigmatism correction as shown in FIGS. 4a and 4b the rods 41 and 45 are connected together and the rods 43 and 47 are connected together. In FIG. 4a a voltage applied across terminals T₁ maintains the rods 41 and 45 at a positive potential with respect to the rods 43 and 47 producing the electric field pattern shown and distorting an electron beam of circular cross-section to the elliptical form 49 having its major axis corresponding with the y-axis as shown. In FIG. 4b the voltage across the terminals T₁ is reverse of in polarity and the rods 41 and 45 are negative with respect to the rods 43 and 47, producing the electric field shown and distorting a circular electron beam to the elliptical form 50 shown having its major axis corresponding to the x-axis. For diagonal astigmatism correction, as shown in FIGS. 4c and 4d, the rods 42, 44, 46 and 48 are connected in pairs and to terminals T₂, in the same way as were the rods 41, 43, 45 and 47 for the axis astigmatism correction and the shapes to which a circular electron beam is distorted by making rods 42 and 46 positive and negative with respect to rods 44 and 48 are respectively shown at 51 and 52 in these figures. Thus with the eight rods of the astigmatism corrector fed with appropriate potentials differing amounts of axis and diagonal astigmatism can be provided.

These two types of astigmatism correction can be combined together as shown in FIG. 5 to produce correction of any desired magnitude and in any desired direction. From a study of FIG. 5 it will be apparent that the amount of diagonal astigmatism correction required is:

$$\pm a \sqrt{2} (X^2 + Y^2) \times (\text{the smaller of } |X| \text{ and } |Y|)$$

the sign of this correction being positive when X and Y are of the same sign and negative when X and Y have

different signs; and the axis astigmatism correction required is:

$$a (|Y| - |X|) (X^2 + Y^2)$$

where X and Y are signal amplitudes representing the amount of deflection of the beam along the x and y axes and where $a\sqrt{2}$ and a are the multiplying factors determining the amount of correction.

These expressions represent the astigmatism correction required but do not take into account the fact that the objective lens being magnetic rotates the deflection and because the astigmatism corrector lies partly in the field of the objective lens the deflection axes do not coincide with the axes of the astigmatism correction. In order to overcome this difficulty the deflection waveforms from which the correction waveforms are derived are "rotated" electrically, that is to say they are combined together in accordance with trigonometrical principles to simulate the effect of rotation of the deflection axes. This rotation of the deflection waveforms used for astigmatism correction is not required if the astigmatism corrector is placed outside the field of the objective lens and on the same side of it as the deflection coils 17.

As an alternative to electrostatic astigmatism correction, magnetic astigmatism correction can be used using a set of eight coils 53a, 53b, 53c, 53d, 53f, 53g and 53h having their axes disposed radially relative to the axis of the electron beam column as shown in FIG. 6a. The coils are divided into two sets of four, 53a, 53b, 53c and 53d, and 53e, 53f, 53g and 53h, the coils of each set being spaced at 90° intervals around the axis of the electron beam column and connected in series in the manner shown in FIG. 6a for coils 53a, 53b, 53c and 53d connected to terminals 54; the coils 53e, 53f, 53g and 53h are connected to terminals 54a but the connections between those coils are omitted for clarity in the drawing. The coils 53a through 53h are preferably mounted outside the electron beam column wall represented by the circle 55, although they could be within it. The column wall is preferably of glass with a coating 0.010 inch thick of stainless steel. Coils 53a, 53b, 53c and 53d when energized produce a magnetic field indicated by lines of force 56. The effect of the magnetic field produced by coils 53a to 53d is to distort a circular electron beam as represented by 57 in FIG. 6b in directions diagonal to the axes of the coils 53a to 53d to produce a beam of elliptical shape such as 58 or 59 of FIG. 5b depending on the polarity and magnitude of the voltage applied to terminal 54. The coils 53e to 53h when energized produce a similar field to that shown for coils 53a to 53d which cause distortion of a circular electron beam in directions along the axes of coils 53a to 53d. Thus by suitable regulation of the energization of the coils 53a to 53h correction for astigmatism can be achieved in a similar way to that described above with reference to FIGS. 4a to 4d and 5, bearing in mind differences in the effects of electrostatic and magnetic correction.

The use of magnetic astigmatism correction has several advantages over electrostatic correction, among which are the fact that the magnetic corrector requires lower voltages for its operation than the electrostatic corrector so that it can more easily be driven by transistors, and the fact that the magnetic corrector can be

placed outside the electron beam column wall so that it is accessible and cannot become contaminated as can the electrostatic corrector which must be inside the column wall and therefore must be cleaned periodically to ensure reliable and consistent behavior of the electron beam.

The astigmatism correction coils or rods may be located at any of several positions along the electron beam column; for example, between the deflection coils and the objective lens (as shown in FIGS. 2 and 3), between the condenser lens and the deflection coils, (the deflection coils being placed close to the objective lens), or between the condenser lens and the objective lens, with the deflection coils following the objective lens. Preferably the electron beam passes through the astigmatism corrector before deflection, as otherwise the astigmatism corrector can cause distortion of the deflection because the electron beam is not passing through the center of the corrector. It should be kept in mind that no "rotation" of the deflection signals is required if the astigmatism corrector and the deflection coils are adjacent and neither is within a lens field.

FIG. 7 is a block diagram of a system for correcting the focus of an electron beam in accordance with the outline above, producing from the deflection waveforms for the electron beam (a) the correction signal for the objective lens to correct for curvature of the focal surface and the axis and (b) diagonal astigmatism correction signals for the astigmatism corrector. The X and Y deflection waveforms are applied (from unit 27, FIG. 2) to terminals 60 and 61 respectively from which they are transmitted to a rotation circuit 62 which effects the electrical rotation of these signals in accordance with the setting of a control 63. Before rotation in circuit 62 the deflection waveforms are referred to as X' and Y'. The rotation circuit 62 is also provided with X and Y preset controls 64 and 65 respectively for the purpose of compensating for any offset in the symmetry along the x and y axes of the electron optical system. From the circuit 62 signals representing the rotated X and Y waveforms are applied via conductors 66 and 67 to respective modulus circuits 68 and 69 which produce as outputs on conductors 70 and 71 respectively signals representing the moduli of the respective rotated X and Y deflections, which signals are applied to a comparator 72 and also to respective multipliers 73 and 74 for producing signals proportional to the squares of the moduli signals. The sign (+ or -) of the input signal to the modulus circuits 68 and 69 appear on conductors 75 and 76 respectively by which they are applied to an EXCLUSIVE OR gate 77 which produces an output indicating whether the signs of the rotated X and Y deflection waveforms are the same or different. The outputs of the modulus circuits 68 and 69, the gate 77, the comparator 72 and the multipliers 73 and 74 are applied to combining circuits 78 and 79 which respectively produce output signals representing the diagonal and axis astigmatism correction signals in accordance with the expressions (1) and (2) set out above. These correction signals are applied to respective output amplifiers 80 and 81 which apply the correction as voltages to the terminals T₁ and T₂ associated with the rods of the electrostatic astigmatism corrector (FIG. 3) as described above with reference to FIG. 4 or as currents to the terminals 54 and 54a associated with the magnetic astigmatism corrector of FIG. 6a. Changeover switches 82, 83 and 84 are provided for

effectively rotating the connection of the astigmatism correction signals round the ring of eight rods or coils forming the astigmatism corrector; these switches together with the rotation circuit 62 permit the correction signals to be rotated through 360°, so that any amount of rotation produced by the objective lens can be accommodated.

The outputs of the multiplier 73 and 74, which represent the squares of the moduli of the rotated X and Y deflection signals, are also applied via respective conductors 85 and 86 to the voltage supply (34, FIG. 3) for the objective lens for the purpose of correcting for the curvature of the focal surface.

The rotation circuit 62 is shown in detail in FIG. 8. This circuit uses four differential operational amplifiers 90, 91, 92 and 93 connected as summing circuits with respective feedback resistors 94, 95, 96 and 97. As shown each of the operational amplifiers 90, 91, 92 and 93 is the same and is formed by an integrated circuit element with additional coupling components in the form of a capacitor C_1 and a resistor R_1 in series and a separate capacitor C_2 . The operational amplifiers have respective main input resistors 98, 99, 100 and 101 and respective pairs of subsidiary input resistors 102 and 103, 104 and 105, 106 and 107, 108 and 109. The ends of the subsidiary input resistors remote from their connections to the corresponding operational amplifiers are connected to the ends of respective potentiometers 110, 111, 112, 113. The output of the amplifier 90 is connected to the input resistor 100 of amplifier 92 and also to the wipers of potentiometers 111 and 113. The output of amplifier 91 is connected to the input resistor 111 of amplifier 93 and also to the wipers of potentiometers 110 and 112. The outputs of amplifiers 92 and 93 respectively are connected to conductors 67 and 66 on which they set up the "rotated" X and Y waveforms. The rotation control 63 is connected to adjust the wipers of potentiometers 111 and 112 in one direction and the wipers of potentiometers 110 and 113 to an equal extent in the opposite direction. From simple trigonometrical analysis it will be apparent that adjustment of the rotation control will have the effect of modifying the signals set up on conductors 67 and 66 in a way which corresponds to a rotation of the deflection axes through the same angle relative to a set of fixed axes. The feedback connections from the outputs of amplifiers 90 and 91 to the inputs of amplifiers 91 and 90 respectively serve to correct for the error of scale which arises from simulating rotation by adding to the signal representing the deflection in one coordinate direction, (e.g., x axis) a proportion of the signal in the other coordinate direction (e.g., y axis) (that is at 90° to the first direction). The X and Y preset controls 65 and 64 serve to shift the zero values of the X and Y waveforms to compensate for lack of symmetry of the objective lens in the two coordinate directions. Adjustable balancing resistors R_B are also provided connected from the inputs of the four amplifiers 90 to 93 to earth to enable differences in the values of the resistors in the circuit to be compensated. Note that because the values of the input resistors of the amplifiers 90 and 91 are twice those of the feedback resistors 94 and 95 so that the output signals are based on half the magnitude of the input signals. The other components (C_1 and C_2 , and R_1) connected to the amplifiers are provided for the purpose of stabilizing them because the amplifiers are in the form of integrated circuits and are general

purpose amplifiers intended for a wide range of applications. The amplifiers in this example are Texas Instruments type SN 72709N.

The modulus circuits 68 and 69 are the same and one such circuit is shown in detail in FIG. 9. The circuit shown in FIG. 9 consists of two differential operational amplifiers 120 and 121. The amplifier 120 has its inverting input connected through input resistor 122 to input conductor 123 (66 or 67, FIG. 7) of the circuit. The output of the amplifier 120 is connected to output conductor 124 (70 or 71, FIG. 7) of the circuit and also via feedback resistor 125 to the inverting input of the amplifier 120. A balancing potentiometer 126 is provided for correcting for differences between the values of resistors 122 and 125 and compensating for the finite gain of the amplifier 120. The input conductor 123 is also connected through resistors 127 and 128 connected in series to the non-inverting input of the amplifier 120, the junction of the resistors 127 and 128 being connected to earth through a field effect transistor 129. The output of amplifier 121 is connected to the gate of the transistor 129 to control its conductive state. The input signal on the conductor 123 is also applied to the inverting input of amplifier 121 which has no overall feedback path so that this amplifier, being of high gain, responds in a trigger-like fashion to the input signal with the result that the transistor 129 is conducting for all negative values of input signal and non-conducting for all positive values of that signal. When the transistor 129 is conducting the junction of resistors 127 and 128 is effectively shorted to earth so that the amplifier 120 together with resistors 122 and 125 acts as an inverting circuit of unity gain. When the transistor 129 is not conducting, however, the voltage applied to the non-inverting input of the amplifier 120 is equal to the input voltage with the result that the potential at the inverting input of the amplifier 120 also tends to the input voltage, which condition is only achieved when the voltage on the conductor 124 is also equal to the input voltage. It will be appreciated, therefore, that the transistor 129 effectively determines whether the circuit including the amplifier 20 and its associated resistors has a gain of +1 or -1. The diodes 130 and 131 in the input circuit of amplifier 121 are provided to prevent it being overloaded by the input signal and the zener diode 132 serves to restrict the swing at the output of the amplifier 121. Note that the additional components connected to the side of the amplifier 121 differ from those connected to the amplifier 120; this is because the amplifier 121 is in an open loop where the amplifier 120 has negative feedback across it. The amplifiers 120 and 121 are formed by integrated circuits, which may be of the same type as amplifiers 90 to 93, and the components connected to the sides of these amplifiers provided coupling within the amplifiers. A signal representing the sign of the input signal appears on the conductor 133 (75 or 76, FIG. 7) connected to the output of amplifier 121.

FIG. 10 shows how an integrated circuit 134 including four two-input NAND gates may be connected to form the EXCLUSIVE OR gate 77. The output of the interconnected gates of the integrated circuit is connected to an amplifier having two transistors 135 and 136, the amplifier having two output conductors 139 on one of which a signal appears when the output produced represents "1" and on the other of which the signal appears when the output produced represents

“0. The output conductors 139 (which apply an input to the combining circuit 78, FIG. 7) are fed through respective diodes 137, 138 from the collector electrodes of the transistors 135 and 136 respectively. Transistor 135 amplifies the output of the integrated circuit and transistor 136 inverts the output of transistor 135.

The circuit of the comparator 72 is shown in FIG. 11 and includes two differential operational amplifiers 140 and 141 both connected in open loops. The amplifiers 140 and 141 are formed from integrated circuits, and couplings within the amplifiers are provided by the capacitors of C_3 , C_4 as shown. The input signals to the comparator are applied at terminals 142 and 143 (71, 70 FIG. 7), one of which is connected to the inverting input of one amplifier and the non-inverting input of the other amplifier, and the other of which is connected to the non-inverting input of the one amplifier and the inverting input of the other amplifier, so that if one input signal is higher than the other, the amplifier 140 produces an output of a given sense and if the other input signal is higher than the stated one input signal, the amplifier 141 produces an output of the said given sense. These outputs are fed through respective diodes 144 and 145 to output conductors 146 and 147 of the comparator for application to the combining circuit 78 (FIG. 7). A resistor 146 of high value (e.g., 20MQ) is connected from the output of amplifier 140 to its inverting input and to the non-inverting input of amplifier 141 for the purpose of providing a small dead space on both sides of the equality position of the input signals which reduces the sensitivity of the circuit to variations in the input signals due to noise.

The multipliers 73 and 74, which in this application are used to square the respective signals applied to them, are substantially the same and a circuit of one of them is shown in FIG. 12. This multiplier consists of a long-tailed pair of transistors 150 and 151 to the base electrode of one of which the input signal is applied via terminal 152 (from line 70 or 71, FIG. 7), and a current is applied up the tail of this pair of transistors of magnitude proportional to the second input signal by means of a current driving circuit including a differential operational amplifier 154. The amplifier 154 is formed from an integrated circuit and has an input resistor 155 connected to its inverting input from the terminal 153 (from line 70 or 71, FIG. 7), for the input signal; a negative feedback resistor 156 is connected between the output and the inverting input of the amplifier. A positive feedback path of the same resistance as the negative feedback path including resistors 157 and 158 is provided between the output and the non-inverting input of the amplifier. The non-inverting input of amplifier 154 is connected to ground through resistor 159 of the same value as the input resistor 155. The junction of resistors 157 and 158 from which the current proportional to the input signal at terminal 153 is derived is connected to the emitter electrodes of the transistors 150 and 151. From the collectors of these transistors a balanced output signal representing the square of the input signal to the amplifier 154 is derived and applied to the inputs of a second differential operational amplifier 160 provided with negative feedback resistor 161 making it into a summing circuit. The non-inverting input of amplifier 160 is connected to earth through resistor 162 of value equal to that of feedback resistor 161. The output signal representing the square of the input signal is derived from the output of ampli-

fier 160 at conductor 163 and applied to the combining circuits 78, 79 of FIG. 7 and to one of the output lines 85 and 86 of FIG. 7). The amplifier 160 is formed by an integrated circuit having as coupling components a capacitor and a series combination of a resistor and a capacitor. A zener diode is provided to stabilize the voltage applied to the collector electrodes of transistors 150 and 151.

The combining circuits 78 and 79, which produce the diagonal and axis astigmatism correction signals respectively, are shown in FIGS. 13 and 14. They include multipliers similar to that of FIG. 12 for the purpose of multiplying the two component signals of the correction function together. In the combining circuit 78, shown in FIG. 13, input signals respectively representing $(X^2 + Y^2)$ from the multipliers 73 and 74 (FIG. 7) are applied to amplifier 164 connected as a summing amplifier through signal input resistors 165 and 166, and there is derived from the wiper of potentiometer 167 a current proportional to the sum of the input signals, i.e., representing $(X^2 + Y^2)$. The current from the amplifier 164 is applied to the common emitter connection of a long-tailed pair of transistors 168 and 169, the voltages on the base electrodes of each of which are switched by two pairs of field effect transistors; 170 and 171 for transistor 168 and 172 and 174 for transistor 169. Adjustment of the potentiometer 180, the wiper of which is connected to the base electrode of transistor 169 adjusts the offset of the long-tailed pair. The four pairs 170, 171, 172 and 173 of field effect transistors are provided to change the sign of the output signal depending on whether the deflection signals X and Y have the same or different signs; this is achieved in response to signals on terminals 174 and 175 from the exclusive OR gate 77 on conductor 139 (FIG. 10). The pairs of field effect transistors are also controlled by signals on terminals 176 and 177 depending on whether the modulus of X or the modulus of Y is the lesser, to apply the matter of $|X|$ and $|Y|$ to the base of transistor 168 or 169 the signals on terminals 176 and 177 being produced by the comparator 72 on conductors 146 and 147 (FIG. 11). The signals representing $|X|$ and $|Y|$ are applied to terminals 178 and 179 respectively from the modulus circuits 68 and 69 respectively and conductors 70 and 71 (FIG. 7). The collector electrodes of transistors 168 and 169 are connected to the inverting and non-inverting inputs of an amplifier 181 connected as a summing amplifier from which the combining circuit output as given by expression (1) and that of FIG. 14 is obtained for application via switch 82 to one of the output amplifiers 80 and 81, FIG. 7). The operation of this combining circuit will be apparent from a brief consideration of the circuits bearing in mind the description of FIG. 12.

The combining circuit 79 is shown in FIG. 14 and is generally similar to that of FIG. 12 having a long-tailed pair of transistors 186 and 187, to the commoned emitter electrodes of which is applied a current from the wiper of a potentiometer 185. Input signals representing X^2 and Y^2 from multipliers 73 and 74 (FIG. 7) are respectively applied via conductors 183 and 184 to a summing amplifier 182. The amplifier 182 has positive and negative feedback paths of approximately equal resistance, the positive feedback path including the potentiometer 185. Other input signals representing Y and X from modulus circuits 69 and 68 are respectively applied via conductors 188 and 188a to the base elec-

trodes of transistors 186 and 187 respectively, the base electrode of transistor 187 also receiving an adjustable offset voltage from the wiper of potentiometer 189. The output signals derived from the collector electrodes of the transistors 186 and 187 are connected respectively to the inverting and non-inverting inputs of an amplifier 190. The amplifier 190, which like the amplifier 182 is an integrated circuit, serves to produce an output voltage proportional to the difference between the collector currents of the transistors 186 and 187, i.e., given in expression (2). The output from amplifier 190 is applied via switch 82 to one of the output amplifiers 80 and 81, FIG. 7).

FIG. 15 shows the circuit of the differential output amplifier 80 or 81 (FIG. 7) and consists of two balanced grounded emitter stages in cascade with means for adjusting the gain and offset of the signals.

The first stage includes transistors 191 and 192 the collector electrodes of which are connected directly to the base electrodes of the second stage transistors 193 and 194 respectively. The input signal (from the switch 83, FIG. 7) is applied to the base electrode of transistor 191 and an offset voltage is applied to the base of transistor 192. The emitter electrodes of transistors 191 and 192 are connected to a conductor maintained at a suitable positive potential volts via respective resistive chains, that of transistor 192 including an adjustable resistor 195 for balancing out common mode interference. The emitter electrodes of transistors 191 and 192 are also connected together through a fixed resistor and a variable resistor 196, which provides a gain control for the amplifier. The emitter electrodes of transistors 193 and 194 are connected together via a potentiometer 197, the wiper of which is connected to a conductor maintained at a suitable negative potential, the potentiometer providing differential gain balance. Balanced output voltages are derived from the collector electrodes of the transistors 193 and 194 (output 83 or 84, FIG. 7).

If a magnetic astigmatism corrector is used instead of an electrostatic one, the correction signals must be provided as currents rather than voltages and FIG. 16 shows a replacement for the amplifier of FIG. 15 to produce a current output. In FIG. 16 a differential d.c. amplifier 200 is used, the output of which is applied through one set of coils of the astigmatism corrector (53a to 53d as shown) to the inverting input of the amplifier 200. The inverting input of the amplifier 200 is also connected to earth through a variable resistor 201 which provides a gain control for the amplifier.

FIG. 17 illustrates one way in which a voltage proportional to the amount of deflection required in FIG. 7 on conductors 60 and 61 for producing the focus correction signals can be obtained from the deflection circuits of the electron beam apparatus. Amplifier 202 is the driver amplifier for one of the deflection coils 17 (FIG. 2) of the apparatus, the coils being connected from the output to the inverting input of the amplifier 202, which is a differential d.c. amplifier. The inverting input of the amplifier 202 is connected to earth through variable resistor 203, providing amplitude control for the deflection signal, and fixed resistor 204. The voltage set up across resistor 204 is proportional to the deflection current and is applied via conductor 205 to conductor 60 or 61 (FIG. 7). Two such circuits are required, one for the x-axis deflection producing the

waveform X^1 and one for the y-axis deflection producing the waveform Y^1 .

In operation, the system is adjusted in gain and rotation and so on to give the best focus over the whole field of deflection required of the electron beam. While these parameters are being adjusted, different parts of the field may be observed by deriving a television signal from the secondary electron detector 24 (FIG. 2) and producing an image on the cathode-ray display tube 26 from it. Preferably the technique of simultaneously displaying side by side on the cathode-ray tube, images of small areas distributed over the field as described in co-pending patent application Ser. No. 051,257 is used.

It will be appreciated that the arrangements described above are examples of the invention and many alternative embodiments will be evident to those skilled in the art.

What is claimed is:

1. Electron beam apparatus utilizing dynamic focusing in correcting astigmatism and lens curvature conditions comprising in combination:

- a. means for producing an electron beam;
- b. first deflecting means responsive to deflecting signals for deflecting the beam in a selected pattern;
- c. second deflecting means responsive to first correcting signals which are proportional to the cube of the distance the electron beam is deflected from a central axis for correcting astigmatism conditions;
- d. an electron lens responsive to a second correcting signal for focusing the electron beam;
- e. first correcting means responsive to said deflecting signals for providing said first correcting signal; and
- f. second correcting means responsive to said deflecting signals for providing said second correcting signals.

2. The electron beam apparatus of claim 1 wherein said deflected distance is provided by said first deflecting means.

3. Apparatus according to claim 2, in which the second deflecting means includes a first field-producing means effective to compress or expand the electron beam in directions corresponding to the axes of deflection of the beam, and second field producing means effective to compress or expand the electron beam in directions corresponding to diagonals to the axes of deflection of the beam.

4. Apparatus according to claim 3, in which the field producing means are operative to produce an electrostatic field.

5. Apparatus according to claim 4, in which the field producing means together includes eight electrodes equally spaced around a central axis of the apparatus; the first field producing means consisting of four electrodes each at a respective corner of a square and the second field producing means consisting of four electrodes interleaved between those of the first field producing means.

6. Apparatus according to claim 3, in which the field producing means are operative to produce a magnetic field.

7. Apparatus according to claim 6, in which the field producing means together includes eight coils equally spaced around a central axis of the apparatus with the axes of the coils radial, the first field producing means consisting of four coils spaced at 90° intervals around the axis of the apparatus, and the second field produc-

ing means consisting of four coils between those of the first field producing means.

8. Apparatus according to claim 3, in which the first and second field producing means are effective to compress or expand the electron beam in directions respectively parallel to the deflection axes and diagonal to the deflection axes.

9. Apparatus according to claim 3, in which the electron lens is magnetic and at least one of the deflecting means lies in the magnetic field of the lens, wherein the first and second field producing means are placed so as to be effective to compress or expand the electron beam in directions equally inclined to the deflection axes, to thereby compensate for rotation of the electron beam due to the field generated by the magnetic electron lens.

10. Apparatus according to claim 8, in which the electron lens is magnetic and at least one of the deflecting means lies in the magnetic field of the lens, wherein the deflection signals are combined electrically to simulate rotation of the deflection axes relative to the directions of the astigmatism correction thereby to compensate for rotation of the electron beam due to the field generated by the electron lens.

11. Apparatus according to claim 10, in which the signal applied to the first field producing means is $a(X^2 + Y^2)(|Y| - |X|)$ and the signal applied to the second field producing means is $\pm z \sqrt{2}(X^2 + Y^2)$ smaller of $|X|$ and $|Y|$ where X and Y are the amplitudes of the respective deflection signals or signals derived therefrom and a is a constant of proportionality, the signs of the signal applied to the second means being positive when X and Y are the same sign and negative when they are of different signs.

12. The electron beam apparatus of claim 2 wherein said second deflecting means is outside the field generated by said lens and is on the same side of said lens as is said first deflecting means.

13. Electron beam apparatus utilizing dynamic focusing in correction astigmatism and lens curvature conditions comprising in combination:

- a. means for producing an electron beam;
- b. first deflecting means responsive to deflecting signals for deflecting the beam in a selected pattern;
- c. second deflecting means responsive to first correcting signals for correcting astigmatism conditions;
- d. an electron lens responsive to a second correcting

signal for focusing the electron beam, wherein at least one of the deflecting means lie within the field generated by said electron lens;

- e. first correcting means responsive to said deflecting signals for providing said first correcting signal;
- f. second correcting means responsive to said deflecting signals for providing said second correcting signals; and
- g. rotation circuit means for providing said deflecting signals representing a rotated waveform to thereby compensate for the rotation due to the field of electron lens.

14. The electron beam apparatus of claim 13 wherein said second correcting signal is proportional to the square of the distance the electron beam is deflected from a central axis.

15. The electron beam apparatus of claim 14 wherein said second correcting signal is proportional to the sum of the squares of said deflecting signals.

16. The electron beam apparatus of claim 13 wherein said first correcting signal is proportional to the cube of the distance the electron beam is deflected by said first deflecting means.

17. The electron beam apparatus of claim 16 wherein said second correcting signal is proportional to the square of the distance the electron beam is deflected by said first deflecting means.

18. Electron beam apparatus utilizing dynamic focusing in correcting astigmatism comprising:

- a. means for producing an electron beam;
- b. first deflecting means responsive to deflecting signals for deflecting the beam a selected distance in a selected pattern;
- c. second deflecting means responsive to a correcting signal, indicative of the cube of said distance which said first deflecting means deflects the electron beam, thereby correcting astigmatic conditions; and
- d. correcting means for generating said correcting signal operatively responsive to said first deflecting means.

19. The apparatus of claim 18 wherein said deflecting signals consist of a first deflecting signal X and a second deflecting signal Y and said correcting signal is described by

$$a(|Y| - |X|)(X^2 - Y^2)$$

wherein a is a constant of proportionality.

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