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A. R. MOORE

2,600,373

SEMICONDUCTOR TRANSLATING DEVICE

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Fig. 1.

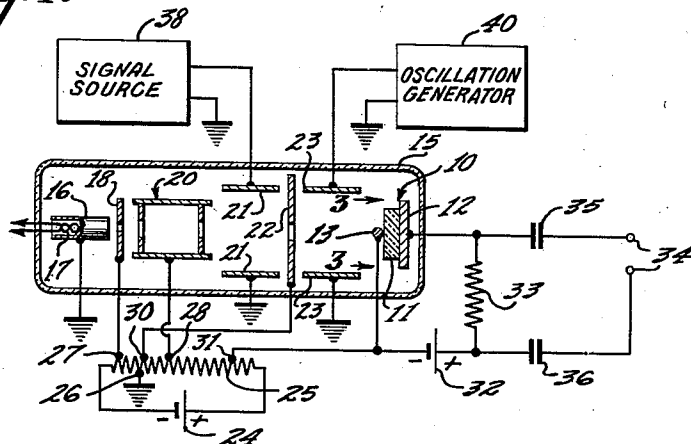


Fig. 2.

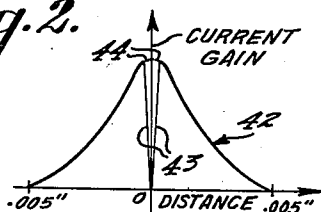


Fig. 3.

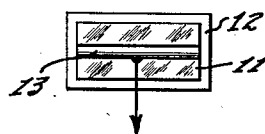
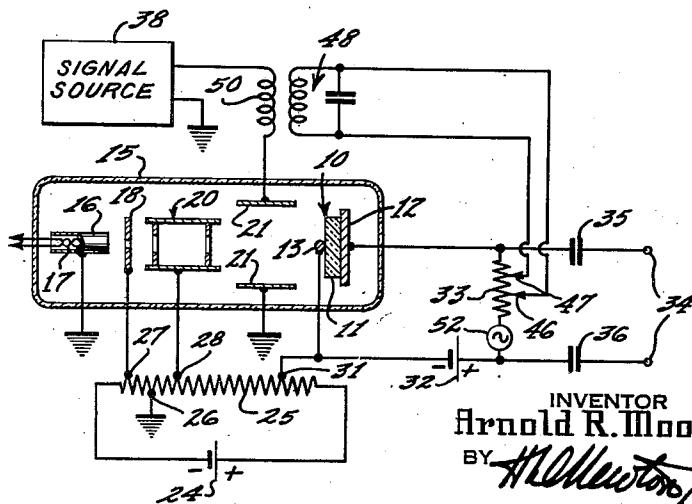


Fig. 4.



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SEMICONDUCTOR TRANSLATING DEVICE

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Application January 18, 1951, Serial No. 206,586

8 Claims. (Cl. 332—58)

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This invention relates generally to signal translating devices, and particularly relates to amplifier, modulator, oscillator or the like systems which incorporate a semi-conductor device.

The interaction of radiation and matter, and the interaction of energized particles with the matter through which they pass, have been studied extensively in the past. It is found that the conducting properties of insulating and semi-conducting materials are modified when subjected to irradiation or corpuscular bombardment. The changes in conducting properties may be transient, with the material returning to its normal condition very soon after the irradiation or bombardment ceases, or the changes in conducting properties are more lasting, though not permanent, and are found to be subsequently affected by heat treatment, or, finally, the changes in the conducting properties are of a permanent nature, being unaffected by heat treatment.

These effects have recently been utilized extensively in the development of crystal counters. The main emphasis has been on the development of materials and associated circuit means which enables the passage of a nuclear particle, such as an alpha, beta, or gamma ray, to be detected by the current pulse produced by the interaction of the nuclear particle or photon with the crystal through which it passes. Insulating crystals, semi-conductors and semi-conductor-point contact rectifiers (McKay) Phys. Rev., November 15, 1949, page 1537, vol. 76 have been used for this purpose.

The permanent changes in the material limit the useful life of crystal counters.

The effects of electron bombardment on thin insulating films using electrons in the kilovolt range have been studied by Pensak (Phys. Rev., vol. 75, February 1, 1949, pages 472-478). He finds that under the influence of the electron beam, the conductivity of the film is increased. It is believed that the increased conductivity can be attributed to the production of internal secondary electrons by the primary electron beam. The primary electron loses energy as it passes through the insulating film, and this energy is presumably used, in part, to raise electrons from the filled to the conduction band. Thus, the production of additional current carriers is reflected in an increased conductivity of the film.

McKay has bombarded diamond crystals with kilovolt electrons and observed electron bombardment induced conductivity. Here too, the

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production of internal secondary electrons by the action of the primary electron beam is believed to be, in part, responsible for the induced conductivity. The conductivity may also be enhanced by the production of holes, which result from the transfer of electrons from the filled to the conduction band. He also observed space charge effects due to the trapping of electrons and holes which reduced his electron bombardment conductivity after the initial excitation by the electron beam.

Thus we see that one method of varying the conducting properties of an insulating or semi-conducting material may be regarded as due to the production of internal secondary electrons and of holes, which provide additional current carriers. Another method of varying the conducting properties of an insulating or semi-conducting material involves the interaction of electrons and holes with a potential barrier which may happen to exist in the material. A potential barrier may be described as a region, extending over many inter-atomic distances, which has a higher resistivity than the bulk material.

The larger resistance, or impediment to current flow, that a barrier provides, is caused by the fact that a charge carrier such as a hole or an electron possessing a certain amount of total energy gains potential energy and loses a corresponding amount of kinetic energy as it attempts to surmount the potential barrier; if all the kinetic energy is expended before the charge carrier reaches the peak of the barrier, it is unlikely that the charge carrier will pass through.

The potential barrier may be approximately symmetrical; that is, it may have the same shape as seen from either side. Such a symmetrical potential barrier does not exhibit rectifying properties. On the other hand, unsymmetrical barriers do exhibit rectifying properties. The resistance of a potential barrier can be changed by causing charge of sign opposite to that of the normal carriers to be introduced into the region of the barrier. The space charge produced by the introduced charge lowers the barrier, and enables more of the normal current carriers to pass through. Thus, the presence of the charge of opposite sign in the barrier region lowers the effective resistance of the barrier.

The variation or modulation of the conducting properties of a barrier in this manner is utilized in the transistor. In the type A transistor, using N type germanium, for example, the normal current carriers are electrons. The emitter point

introduces holes, which diffuse to the barrier existing at the germanium-collector point junction and modify the conductivity of the junction. In the photo-transistor, visible light or infra-red radiation produces hole-electron pairs in the semi-conducting crystal. The quantum energy of light in the visible and infra-red is such that not more than one electron-hole pair can be produced per incident light quantum or photon. If the semi-conducting crystal is N type for example, the holes produced by the irradiation in the neighborhood of the metallic point contact can migrate into the junction and modulate the conductivity of the junction.

It has also been suggested in the patent of Kock 2,522,521 that the conductivity of an intrinsic semi-conductor be modulated by changing the temperature of the semi-conductor, thus provided an electrothermal transducer.

It is the principal object of the present invention to provide novel signal translating systems including a semi-conductor device having a barrier, such, for example, as a crystal rectifier.

A further object of the invention is to provide novel amplifier, oscillator, modulator, mixer or the like systems wherein a semi-conducting device having a barrier cooperates with an electron beam or stream which is deflected in accordance with a signal to increase the transconductance of the tube by a large factor, thereby obtaining high current and power gains.

Another object of the invention is to provide a novel amplifier, signal mixer or oscillator system having a current or power gain higher than that which may be obtained with a conventional amplifier tube, with a cathode ray tube or with a beam deflection tube.

A still further object of the invention is to provide a signal translating system which has substantially no coupling between the input and output circuits thereof.

In accordance with the present invention, use is made of a deflected electron stream to modulate or vary the effective resistance represented by the potential barrier of a semi-conducting material. Such a barrier is present, for example, in a crystal rectifier which has one electrode in low-resistance contact with the body and another electrode in rectifying contact therewith. Such a barrier is also present in the boundary region separating a semi-conductor from a metal which may serve as an electrode. The metal electrode may be of many forms, including that represented by a thin film, a point-contact, or a surface contact with a bulk metal and it is immaterial whether the junction rectifies or not. Such a barrier is also present in the region of a crystal grain boundary, and may also be present in any region which differs in structural form from the bulk material.

The electron stream or beam is caused to impinge on the semi-conductor in the neighborhood of the potential barrier. Each primary electron, in penetrating the semi-conductor, loses its energy, and produces a great many electron-hole pairs. The actual number of electron-hole pairs or secondary particles produced per incident primary electron depends upon such factors as the primary energy of the beam and the semi-conductor material used. If the potential barrier exists mainly near the surface, such as that at a metallic point semi-conductor junction, an electron beam would be used with energy so adjusted that the major part of the energy loss of the beam would occur near the surface barrier.

For the sake of illustration, let it be assumed that the semi-conductor is N type. Then the electrons and holes produced will both contribute to the conductivity of the region where they are produced and migrate by increasing the number of available current carriers in these regions. In addition, the holes will migrate into the potential barrier, and, as described previously, modulate the conductivity of the barrier. Thus, by directing the electron beam to impinge in the neighborhood of the potential barrier, the conductivity of the semi-conductor is modulated in two distinct ways: first, by increasing the number of available current carriers, and, secondly, by modifying the space charge existing at the potential barrier and therefore modulating its effective height.

Thus, the electron beam, by modulating the conductivity of the semi-conductor, can modulate the current passing through the semi-conductor. The electron beam itself is modulated by deflecting it with respect to the region of the potential barrier. It will be evident that such a system may be utilized in an amplifier, modulator, mixer, or oscillator circuit.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, as well as additional objects and advantages thereof, will best be understood from the following description when read in connection with the accompanying drawing, in which:

Figure 1 is a sectional view and circuit diagram of an amplifier or modulator system in accordance with the present invention including a beam deflection tube;

Figure 2 is a graph showing the current gain of the device of Figure 1 as a function of the beam deflection;

Figure 3 is a side elevational view taken in the direction of arrows 3, 3 in Figure 1 of the target of the deflection tube of Figure 1; and

Figure 4 is a sectional view and circuit diagram of a modified amplifier, oscillator or signal mixing system embodying the present invention.

Referring now to the drawing, in which like components have been designated by the same reference numerals throughout the figures, and particularly to Figure 1, there is illustrated a signal translating system including a semi-conductor device 10 which may, for example, be a crystal rectifier. Device 10 includes a semi-conducting body 11 which may consist of any suitable semi-conducting crystal such, for example, as silicon or preferably germanium. As is conventional for a crystal rectifier, the device 10 has two electrodes 12 and 13. Electrode 12 is in low-resistance contact with crystal 11 and may, for example, consist of a plate or sheet of metal or end of a metallic rod soldered to the crystal. Electrode 13 is in rectifying contact with crystal 11 and may, for example, be a point electrode. Thus, electrode 13 may consist of a fine wire of tungsten or phosphor bronze, for example, having a sharp point in contact with the crystal. As shown in Figures 1 and 3 rectifying electrode 13 may also be in line contact with the crystal. As shown particularly in Figure 3 rectifying electrode 13 preferably consists of a fine wire which extends in a substantially straight line across the width of the upper surface of crystal 11.

In accordance with the present invention crystal rectifier 10 represents the target for an electron beam. To this end crystal rectifier 10 is en-

closed in an evacuated envelope 15 within which is provided a cathode ray tube. The cathode ray tube includes a cathode 16 which may be indirectly heated by a filament 17, a control grid 18 and a first anode or focussing electrode 20. Grid 18 preferably has a rectangular aperture to pass a beam of substantially rectangular cross section. The beam may then be focussed by the first anode 20 and deflected by a first pair of deflection plates 21, 21. A screen or shield 22 with a rectangular aperture is interposed between the first pair of deflection plates 21 and a second pair of deflection plates 23, 23. The details of construction of such a beam deflection mixer tube may be obtained from a paper by Herold and Mueller which appears in the May, 1949 issue of "Electronics," pages 76-80 and which is entitled "Beam Deflection Mixer Tubes for UHF." It is well known that such beam deflection tubes are particularly advantageous at high and ultra-high frequencies due to their large transconductance. In the device of the present invention the already large transconductance of a beam deflection tube is multiplied by the very high current multiplication which may be obtained in accordance with the invention.

Cathode 16 may be grounded as shown. A battery 24 may be provided to supply the accelerating potentials for the deflection tube. Potentiometer resistor 25 is connected across battery 24 and an intermediate tap 26 on resistor 25 may be grounded. Grid 18 is maintained at a negative potential by tap 27. The first anode 20 is maintained at a positive potential by tap 28. One of the first pair of deflection plates 21, 21 may be grounded. Shield 22 is maintained at a positive potential by tap 30 on resistor 25 which, however, is less positive than that of first anode 20. One of the second pair of deflection plates 23, 23 may also be grounded. Rectifying electrode 13 is maintained at a high positive potential by tap 31 on resistor 25. The two electrodes 12 and 13 are connected through battery 32 and load resistor 33. The output signal may be obtained from output terminals 34 which are coupled across load resistor 33 by coupling capacitors 35 and 36.

A first signal is impressed on one of the deflection plates 21, 21 by a signal source 38. A second signal which may be developed by oscillation generator 40 is impressed on one of the second pair of deflection plates 23, 23. It is, of course, to be understood that instead of impressing an oscillatory wave on deflection plates 23, 23 a second signal may be impressed thereon so as to mix the two signals impressed on deflection plates 21 and 23.

The operation of the frequency converter of Figure 1 may best be explained by reference to Figure 2. Curve 42 of Figure 2 indicates the current gain of the device of Figure 1 with respect to the distance of the electron beam from rectifying electrode 13. It will be observed that at a distance of 5 mils from either side of rectifying electrode 13, the current gain is substantially zero. Lines 43 indicate the reduction of the current gain which is caused when the electron beam impinges on electrode 13. If electrode 13 should be a point electrode of negligible area with respect to the area of the electron beam, the gain of the device of Figure 1 will substantially follow the dotted curve 44.

The current flowing through output load resistor 33 is accordingly determined by the distance of the electron beam from rectifying electrode 13. This distance in turn is a function of the signal

developed by source 38 and of that developed by generator 40. Thus the device of Figure 1 may be used as a frequency converter or signal mixer. It will be observed that curve 42 is non-linear which is essential to obtain signal mixing or frequency conversion.

As pointed out hereinabove the resistance represented by a barrier in a semi-conducting body is modulated in accordance with the present invention. Such a barrier may be obtained not only in a crystal rectifier such as illustrated, but also by a semi-conducting body having a distinct N zone and a P zone which are separated from each other by a barrier.

In accordance with the invention a source of bias voltage such as battery 32 is connected between the electrodes 12 and 13 of crystal rectifier 10. It is to be understood, however, that rectifying electrode 13 may be made either positive or negative.

The device of Figure 1 as described herein functions as a converter or signal mixer and its operation is believed to be as follows. For the following discussion it will be assumed that crystal 11 is of the N type and may be an N type germanium crystal. Furthermore, it will be assumed that rectifying electrode 13 is negative with respect to the low-resistance electrode 12. The rectifier is accordingly biased in the reverse or back direction. In order to bias the crystal in the forward direction, the rectifying electrode 13 should be positive with respect to the low-resistance electrode 12. If crystal 11 were a P type crystal, the rectifying electrode 13 must be positive or negative to bias the rectifier respectively in either the reverse or the forward direction.

The electron beam developed in tube 15 impinges in the immediate vicinity of rectifying electrode 13 and creates internal secondary electrons in crystal 11 and an equal number of holes which may be considered as charge carriers having a positive charge and a mobility slightly less than that of the electrons in the crystal. It has been found that an electron beam having a voltage of 10,000 volts will create approximately 1000 pairs of electrons and holes. Some of the excess electrons induced or created by the electron beam are dissipated rapidly over the electrical circuit. The holes start to travel in the direction of the electric field, that is, they are attracted by the negatively biased rectifying electrode 13. The holes accordingly form a space charge cloud which surrounds itself with negative charge carriers, that is, electrons to maintain statistical neutrality over a relatively large volume of the solid. It will be understood that both excess electrons and excess holes create excess conductivity.

The holes which drift with the electrical field eventually arrive in the barrier layer which exists in the crystal rectifier 10 so that a positive charge is provided at the barrier. As explained hereinbefore, it is believed that this positive charge reduces the barrier height which in turn permits more electrons to pass through the lowered potential of the barrier. Eventually the holes are collected by the rectifying electrode 13. Thus, the lowering of the barrier height caused by the holes will permit an additional multiplication of the current which is similar to the secondary photo effect above referred to.

It will now be obvious why it is essential that the primary electron beam impinges in the immediate vicinity of the rectifying electrode 13. Thus, if the holes created in the crystal are not

close to the rectifying electrode, they will not be able to move into the barrier. Nevertheless, since the holes still travel a certain distance determined by the recombination time and by their mobility, they will still be able to induce a current, but the additional current multiplication caused by the lowering of the barrier is not present if the holes cannot reach the barrier.

The explanation of the operation of the device of Figure 1 will be similar if the crystal 11 is of the P type. In that case, the function of the holes and electrons is reversed. Otherwise, the current multiplication for a P type crystal is substantially the same as that for an N type crystal. However, the frequency response of a P type rectifier is slightly better than for an N type rectifier because the current flow in a P type rectifier is essentially due to the electrons which have a slightly higher mobility than the holes.

For maximum current multiplication the voltage of battery 32 should be of the order of 10 volts. When rectifying electrode 13 is biased in the back or reverse direction, the current multiplication is higher than if the rectifying electrode were biased in the forward direction. For a smaller bias voltage the current multiplication is reduced.

The electron beam may have any accelerating voltage below an upper limit which is determined by that of an electron beam having such a high accelerating voltage that it will cause changes of the crystal lattice as explained hereinbefore. This is due to collisions of the beam electrons with the lattice atoms or molecules which produce lattice defects. These give rise to the same effects as does a change of the impurity concentrations. An electron beam having an accelerating voltage of the order of 500,000 volts or more will cause changes of the crystal lattice of a germanium crystal. For crystals of different materials, the minimum accelerating voltage of the electron beam which will cause lattice changes will, of course, have different values.

It may also be pointed out that when the velocity of the primary beam becomes too high, the specific ionization of the electrons is smaller than that of the electrons of a beam having a lower velocity. When the primary electron beam has too high an energy, it penetrates very far into the crystal so that not enough pairs of holes and electrons are created in the immediate vicinity of the barrier. Accordingly, the current multiplication decreases when the accelerating voltage of the primary beam exceeds an optimum value.

With a primary electron beam having a current of 0.05 microampere and a voltage of 10,000 volts, an output current multiplication of 20,000 has been observed experimentally. When the primary beam has a still higher accelerating voltage and a lower beam current, output current multiplications as high as 50,000 have been obtained. The primary beam currents which were used experimentally are between .001 microampere and .5 microampere. For these primary beam currents, the output current obtained across load resistor 33 was between 50 microamperes and 5 milliamperes. The accelerating voltage of the primary beam which has been used experimentally was of the order of several kilovolts.

The upper frequency limit of the device of Figure 1 is determined by the transit time dispersion or spread of the primary electron beam and particularly by the transit time dispersion of the

electrons and holes created in crystal 11. The experimental evidence indicates that the upper frequency limit of the device of Figure 1 is above 10 megacycles and that it has a flat response at least up to a frequency of 10 megacycles.

Figure 4 illustrates a modified beam deflection tube in accordance with the present invention. The tube of Figure 4 may, for example, be used as an amplifier. Accordingly, the second pair of deflection plates 23, 23 and the shield 22 of the tube of Figure 1 are superfluous and may, therefore, be omitted. In that case, the output signal obtained from output terminals 34 is an amplified version of the signal developed by signal source 38.

The tube of Figure 4 may also be used as an oscillator. To this end, a pair of taps 46, 47 are provided on the output load resistor 33 and are connected to the terminals of a parallel resonant circuit 48 which is magnetically coupled with a coil 50 provided between one of the deflection plates 21 and the signal source 38. The signal source 38 may also be omitted. If the tube of Figure 4 is used in this manner, a portion of the output energy is fed back through parallel resonant circuit 48 and coil 50 into deflection plates 21, 21. The tube of Figure 4 will accordingly oscillate at the frequency to which parallel resonant circuit 48 is tuned.

The tube of Figure 4 may also be used for the purpose of signal mixing. In that case, taps 46, 47, resonant circuit 48 and coil 50 may be omitted. A signal generator 52 which may also be an oscillation generator may be provided in series with battery 32 and output load resistor 33. In that case, the output signal contains both the signal developed by source 38 and that developed by generator 52. It will be understood, however, that if the signal generator or oscillation generator 52 is provided in the output circuit as shown in Figure 4, it must develop a higher signal voltage because its signal voltage is mixed with the signal developed by source 38 and amplified by the tube of Figure 4.

The device of the invention may be considered essentially as a current amplifier. It may be applied particularly where secondary electron multipliers are now used. It has the advantage of greater simplicity and it requires but a small bias voltage, yet has a very large current gain which, when a high velocity primary electron beam is used, is comparable to that which may be obtained from a ten stage electron multiplier. It may be used wherever beam deflection tubes are utilized. It has the advantage that its gain is a product of the transconductance of the beam deflection tube and the current multiplication obtained in the crystal rectifier. Furthermore, there is no inherent coupling between the input and output circuits.

What is claimed is:

1. A signal translating system comprising a semi-conducting body, a first electrode in low-resistance contact with said body, a second electrode in rectifying contact with said body, means for developing an electron beam and directing it to impinge on said body in the vicinity of said second electrode, means for deflecting said beam across said body in accordance with a signal, a source of voltage and a load impedance element connected serially between said electrodes, and means for deriving an amplified output signal across said load impedance element which is representative of said signal.

2. A signal modulating system comprising a

semi-conducting body having a first and a second surface, a first electrode in low-resistance contact with the first surface of said body, a second electrode in rectifying contact with the second surface of said body, means for developing an electron beam and directing it toward said second surface, means for deflecting said beam across said surface in accordance with a first signal, means for simultaneously deflecting said beam across said second surface in accordance with a second signal, a source of voltage and a load impedance element connected serially between said electrodes, and means for deriving an amplified output signal across said load impedance element which is representative of said first and second signal.

3. A signal translating system comprising a semi-conducting body having a first and a second surface, a first electrode in low-resistance contact with the first surface of said body, a second electrode in rectifying contact with the second surface of said body, said second electrode being in line contact with said second surface and extending in a substantially straight line across the width of said second surface, means for developing an electron beam of substantially rectangular cross section and directing it toward said second surface and substantially parallel to said second electrode, means for deflecting said beam across said surface in accordance with a signal, a source of voltage and a load impedance element connected serially between said electrodes, and means for deriving an amplified output signal across said load impedance element which is representative of said signal.

4. A signal modulating system comprising a semi-conducting body having a first and a second surface, a first electrode in low-resistance contact with the first surface of said body, a second electrode in rectifying contact with the second surface of said body, said second electrode being in line-contact with said second surface and extending in a substantially straight line across the width of said second surface, means for developing an electron beam of substantially rectangular cross section and directing it toward said second surface and substantially parallel to said second electrode, means for deflecting said beam across said surface in accordance with a first signal, means for simultaneously deflecting said beam across said second surface in accordance with a second signal, a source of voltage and a

load impedance element connected serially between said electrodes, and means for deriving an amplified output signal across said load impedance element which is representative of said first and second signal.

5. An oscillator system comprising a semi-conducting body having a first and a second surface, a first electrode in low-resistance contact with the first surface of said body, a second electrode in rectifying contact with the second surface of said body, means for developing an electron beam and directing it toward said second surface, a source of voltage and a load impedance element connected serially between said electrodes, means for deriving a signal across said load impedance element, and means for deflecting said beam in accordance with said signal.

6. An oscillator system comprising a semi-conducting body having a first and a second surface, a first electrode in low-resistance contact with the first surface of said body, a second electrode in rectifying contact with the second surface of said body, said second electrode being in line contact with said second surface and extending in a substantially straight line across the width of said second surface, means for developing an electron beam of substantially rectangular cross section and directing it toward said second surface and substantially parallel to said second electrode, a source of voltage and a load impedance element connected serially between said electrodes, means for deriving a signal across said load impedance element, and means for deflecting said beam in accordance with said signal.

7. A system as defined in claim 1 wherein a signal generator is provided in series with said source of voltage and said load impedance element.

8. A system as defined in claim 3 wherein a signal generator is provided in series with said source of voltage and said load impedance element.

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The following references are of record in the file of this patent:

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