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Weiner

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[54] **ELECTRON BOMBARDED SEMICONDUCTOR**

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[52] **U.S. Cl.** **330/44;** 330/46; 357/58
[51] **Int. Cl.^{2}** **H03F 3/54**
[58] **Field of Search** 330/46, 44; 352/29; 357/58

[56] **References Cited**

UNITED STATES PATENTS

3,676,716	7/1972	Hanrahan	357/29 X
3,725,803	4/1973	Yoder	330/46
3,761,711	9/1973	Hall	357/58 X
3,836,990	9/1974	Harth	357/58 X

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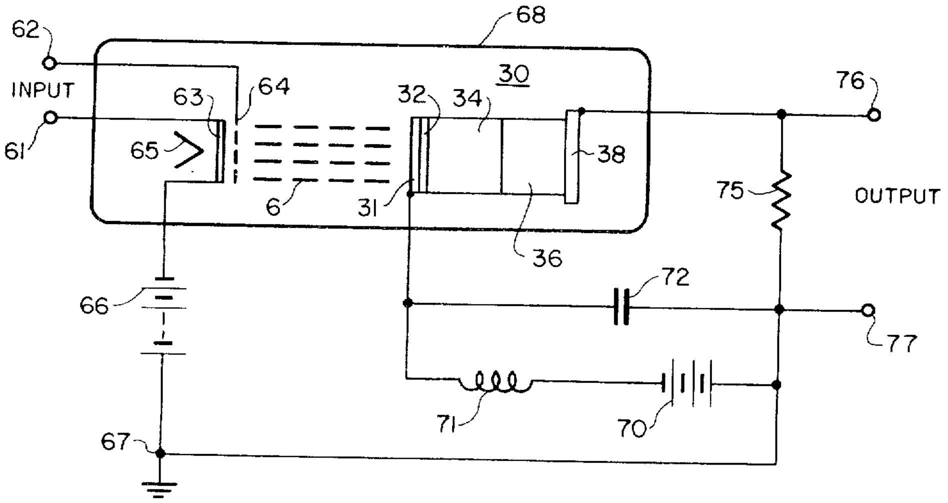
[57] **ABSTRACT**

A p^+-i-n^+ semiconductor diode is used as the target for an electron-bombarded semiconductor amplifier. In such amplifiers, a form of evacuated electron tube has a conventional cathode, heater, and grid. However, the tube has the semiconductor diode target in place of the more conventional anode. A high beam-accelerating potential between the cathode and the target causes a high-velocity electron beam to bombard the target, which has its outer layer thin enough to permit the electrons to pass through to the intrinsic region of the diode, where the electrons generate electron-hole pairs. The semiconductor diode target is connected in series with an output load and a source of target bias potential that draws a current of the newly-created electron-hole pairs across the output load. The grid modulates the electron beam, which, in turn controls the current across the output load.

4 Claims, 5 Drawing Figures



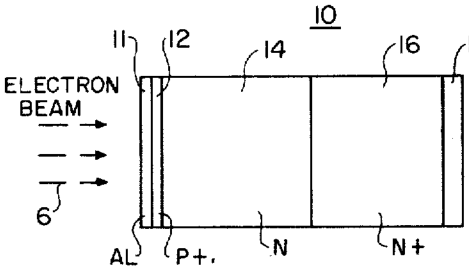


FIG. 1 (Prior Art)

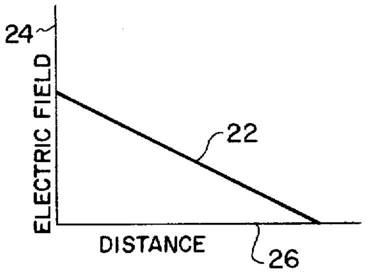


FIG. 2

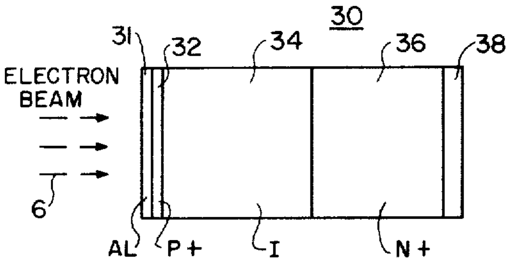


FIG. 3

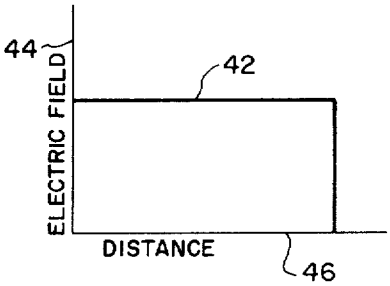


FIG. 4

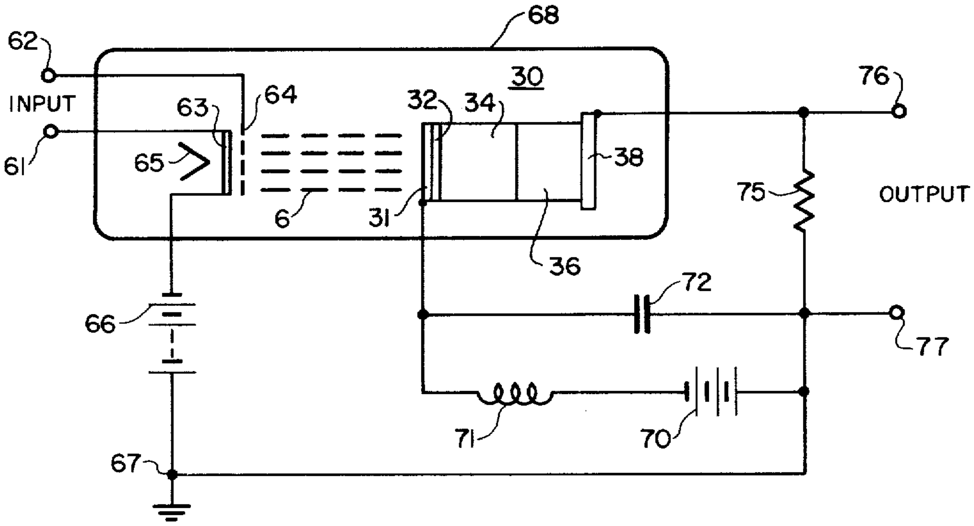


FIG. 5

ELECTRON BOMBARDED SEMICONDUCTOR

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

Prior-art amplifiers include both vacuum tubes and transistors that can be controlled to vary a current across a load in a well-known manner. Another device that is being developed as an amplifier is a vacuum tube that has a p^+-n-n^+ semiconductor diode as a target in place of a plate electrode. This target is bombarded by an electron beam emitted from the cathode of the vacuum tube under a high beam-accelerating potential. The electron beam traverses an outer conductive terminal layer, and a p^+ region, that have both been reduced to a minimum thickness for this purpose. The electrons then enter a lightly-doped n region—which is the depletion layer, or the drift space, of the semiconductor—to create electron-hole pairs by impact ionization.

When the terminals of the semiconductor diode target are connected in series with a source of bias voltage and an output load, the electron-hole pairs are rapidly swept out of the n region by an electric field created by the presence of the bias voltage, and a corresponding current appears across the output load. A modulating signal on the grid of the vacuum tube controls the electron beam and, ultimately, the current through the output load. Such an amplifier produces a higher gain-bandwidth product than either of the conventional prior-art amplifiers mentioned earlier.

However, the electric field profile for an n region — which is illustrated in the drawings — changes linearly with respect to distance through the n region, with the maximum field adjacent to the p^+ region and the minimum field adjacent to the n^+ region. Therefore, since the ionization caused by the bombarding electrons increases as the field strength increases, the ionization induced by the electric field is at its highest efficiency only in the n region immediately adjacent to the p^+ region.

For moderate electron beam energies, where the depth of electron penetration is minimal, the ionization efficiency may be relatively high. However, for higher electron beam energies, where the depth of penetration increases, the ionization efficiency will decrease. This will be more pronounced at higher frequencies — in the order of several gigahertz — where the depletion layer must be made thinner, to avoid the problems of electron-drift time, and the electron penetration is proportionately greater.

Furthermore the bias capable of being placed across a p^+-n-n^+ diode will be smaller than that of a diode in which the electric field is constant. This means that for a p^+-n-n^+ diode, the output power and efficiency will be less than that of a diode with a constant electric field in the drift space.

SUMMARY OF THE INVENTION

These and other disadvantages will be overcome by this invention of a novel semiconductor diode for use as the target in an electron-bombarded semiconductor amplifier. This novel semiconductor diode has an intrinsic layer instead of the usual n layer. The intrinsic layer is easier to fabricate since no n-type doping is required. The intrinsic layer is provided with the usual n^+ region, which is bonded to a conductive mounting terminal, on one side of the intrinsic layer. However, the p^+ region, on the other side of the intrinsic layer, is made very thin — in the order of a few tenths of a micron — to allow the passage of high-velocity bombarding electrons. The outer conductive terminal layer, which is bonded to the p^+ layer, is also made very thin — in the order of a tenth of a micron — to allow the passage of high velocity electrons.

When mounted in an electron-bombarded semiconductor amplifier, the usual bias voltage is connected in series with the terminals of the p^+-i-n^+ diode and a load impedance to utilize the variations in the charged pairs resulting from the variations in the electron bombardment caused by the grid.

In this case, the intrinsic region is now the depletion layer or drift space. However, since the electric field profile through the intrinsic region is constant, there is no preferential ionization region within the drift space, and the bombarding electrons will give a uniform density of ionized electron-hole pairs throughout the depth of penetration. This will provide relatively higher currents, and higher efficiency as the electron beam energy is increased. This is particularly valuable for higher modulating frequencies where a thinner depletion region must be used to reduce the drift time. The higher current across the output load will increase the effectiveness and the gain of an amplifier using a semiconductor diode of this type.

In addition, the constant electric field existing throughout the intrinsic region gives rise to greater power output and efficiency, since a larger bias voltage may be placed across a p^+-i-n^+ diode than can be placed across a p^+-n-n^+ diode. The p^+-i-n^+ diode is also ideal for manufacture as a large area semiconductor which is most effective for this purpose. Details on this can be found in "Output Capability of Electron Beam-Semiconductor Bandpass Amplifier Using Large Area Diodes," by Maurice Weiner and Martin Braun, IEEE Trans. on Electron Devices, May 1974.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross section of a typical, prior art, p^+-n-n^+ semiconductor junction diode target;

FIG. 2 shows the electric field profile of the n region of FIG. 1;

FIG. 3 shows a cross section of a p^+-i-n^+ semiconductor junction diode, in accordance with this invention, for use as a semiconductor target;

FIG. 4 shows the electric field profile of the i region of FIG. 3; and

FIG. 5 shows a typical orientation of, and circuitry for, an electron-bombarded semiconductor amplifier.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 is an enlarged cross-section of a typical p^+-n-n^+ semiconductor junction diode modified to function as an electron-beam target in an electron-bombarded semiconductor amplifier. It shows a semiconductor **10** with a conductive terminal layer **11**, and a p^+ region **12** on one side of an n layer or region **14.** An n^+ region **16** is on the other side of the n layer **14** and is metallically bonded to a conductive terminal mounting **18.**

The functions of the various elements are well known, as are the techniques for making them. However, the function of this amplifier is predicated on the bombardment of the n layer by an electron beam **6,** and the resulting effects. Consequently, the layer **11** and the p^+ region **12** must be as thin as possible to allow terminals passage of the bombarding electrons.

FIG. **2** represents the electric field profile of the n region of the semiconductor of FIG. **1.** This is best illustrated as a graph showing a curve **22** of the relationship between the electric field **24,** within the n region, and the distance **26** from the interface of the p^+-n junction. It is seen that the electric field decreases in a linear manner from the p^+-n junction interface to the n-n^+ interface. In this particular use, the curve **22** is significant because the creation of electron-hole pairs by the electron bombardment is a function of the strength of the electric field, and it will be apparent that the deeper the penetration of the electrons within the n region, the less efficient the generation of pairs will be.

FIG. **3** is an enlarged cross-section of a typical example of a p^+-i-n^+ semiconductor junction diode in accordance with this invention. This shows a semiconductor **30** with a conductive terminal layer **31,** a p^+ region **32,** an intrinsic layer or region **34,** an n^+ region **36,** and a conductive mounting terminal **38.**

Here again, the conductive layer **31** and the p^+ region **32** must be made thin enough to pass the bombarding electron beam **6** through to the intrinsic region. The functions of the various elements, and the various techniques for diffusing, evaporating, or otherwise forming the various elements of the diode are, otherwise, well known.

FIG. **4** represents the electric field profile of the i region of the semiconductor of FIG. **3.** This is best illustrated as a graph with the curve **42** showing the relationship between the electric field **44,** within the i region, and the distance **46** from the interface of the p^+-i junction. It is seen that the electric field is constant from the p^+-i junction interface to the i-n^+ interface. This is significant since, as noted earlier, the creation of electron-hole pairs by the electron bombardment is a function of the strength of the electric field. In this device, the pairs will continue to be generated at the same rate within the intrinsic, depletion region regardless of the depth of the penetration of the electrons. In addition, the p^+-i-n^+ diode can accommodate higher bias voltages, which, in turn, means greater output and efficiency.

FIG. **5** is a typical layout of an electron-bombarded semiconductor amplifier, along with the necessary circuitry for its function. It includes input terminals **61** and **62,** connected to a cathode **63** and a grid **64** respectively. The cathode is energized by a heater **65** in a well known manner to produce electrons. In this device the usual plate structure is replaced by a semiconductor diode target **30,** as described above, which is connected to the cathode **63** through a source of beam-accelerating potential **66,** which may be grounded at **67.** This produces the beam of electrons **6.** The heater, cathode, grid, and target are all contained within an evacuated tube structure **68.**

The semiconductor diode target **30** has its thin conductive terminal layer **31** and its conductive mounting terminal **38** connected in series with a source of target bias potential **70** and an output load **75,** which is connected across output terminals **76** and **77.** Since it is intended that this device be used at high frequencies, a choke **71** and a bypass capacitor **72** are included to keep undesirable a-c, RF energy out of the d-c source **70** in a well known manner.

In operation, the electrons generated by the heated cathode **63** are accelerated toward the semiconductor diode target **30** by the beam-accelerating potential **66.** As these electrons strike the surface of the semiconductor target, they pass through the very-thin conductive terminal layer **31,** and through the very-thin p^+ region **32,** to enter the intrinsic depletion region **34.** The electrons create electron-hole pairs inside of the intrinsic region by impact ionization. The electron-hole pairs are drawn through the semiconductor by the target bias potential **70** to be applied across the output load impedance **75.**

As the signal across the input terminals **61** and **62** modulates the grid **64,** the electron beam **6** is modulated to vary the velocity of the electrons bombarding the target. This, in turn, modulates the ionization of the charged pairs within the intrinsic region or depletion layer of the semiconductor, which, in turn, modulates the flow of current through the output load **75** to vary the voltage across the output termnals **76** and **77.** The electron-hole carrier pairs are created almost instantly and several thousand carrier pairs may be created by a single beam electron. This provides relatively large currents in the semiconductor controlled by the grid **64.**

In a typical embodiment of this invention as seen, for example, in FIGS. **3** and **5,** a silicon semiconductor **30** would be between 5 and 10 square mm.; conductive terminal layer **31** would be of aluminum and have a thickness of about 0.075 microns; the p^+ region **32** would have a thickness of about 0.2 microns; the intrinsic layer **34** would have a thickness of between 2 and 20 microns; and the n^+ region would have a thickness of between 10 and 20 microns. The thickness of the n^+ region is not critical.

The conductive mounting terminal **38** would be of copper and can be attached to the n^+ region **36** in any well known manner, such as by a gold-germanium bonding material.

The input applied across terminals **61** and **62** may be a signal from 0.01 to 10 milliwatts from a low-power RF source; the accelerating potential **66** would be about 10 kilovolts; the bias potential **70** would be about 200 volts; the output load **75** would be about 10 ohms. The choke **71** and the capacitor **72** would be about 100 nanohenries and 100 picofarads respectively, depending, of course, on the frequencies to be amplified.

The elementary electron-bombarded semiconductor amplifiers of the p^+-n-n^+ variety are discussed in an ECOM Technical Report No. 4727-2 prepared by C. B. Norris, Jr. on "Electron Physics Research, Electron-Beam Semiconductor Active Devices: Lowpass Amplifiers and Pulse Systems," of the United States Army Electronics Command, Fort Monmouth, N. J.

The conductive terminal layer **31** may be of any material that can be applied to the outer surface of the p^+ region. It would normally be a metal of between 0.05 and 0.1 microns thick. This could be reduced to minimize attenuation of the electron beam, but it must retain enough thickness for adequate conductivity.

The p^+ region **32** may be between .1 and .3 microns thick. Reducing the thickness of the p^+ region would, of course, decrease the attenuation of the electron beam, but, at some point, reduction in thickness would reduce the effectiveness of the p^+ layer, and its necessary conductivity.

The combined thickness of the conductive terminal layer **31** and the p^+ region **32** would normally be between 0.15 and 0.4 microns. It must in any case be thin enough to pass a substantial portion of the electron beam.

As noted earlier, the thickness of the *i* region **34** would vary according to the frequencies to be accommodated. The higher frequencies would require thinner *i* regions. For example, a 2 gigahertz signal would need a *i* region of about 10 to 12 microns thick, whereas a 4 gigahertz signal would need an *i* region of about 5 to 6 microns thick.

Since reducing the thickness of the *i* region would improve the frequency response, mainly by reducing the drift time, without introducing too many serious side effects, this would appear desirable. However, reducing the physical thickness of one of the basic layers would increase the difficulty of manufacturing, and this would be a limiting factor until the state of the art improves in this direction. Reducing the thickness of the *i* region would also increase the capacity between the electrodes, but this, in turn, would also reduce the bandwidth. The increase in capacity could be accommodated, but the reduction in bandwidth might be undesirable. In addition, as the accelerating voltages are increased, the electron beam penetration would approach the thickness of the *i* region to provide the ultimate limiting factor.

The conductive mounting terminal **38** would normally be of any electrical and heat conducting metal such as copper and may be of any desired size and shape suitable for mounting and functioning as a heat sink. It may also be water cooled to reduce the temperature of the semiconductor. This mounting terminal may be considerably larger than the body of the remaining structure **31–36.**

While many p^+-i-n^+ and other semiconductor junction devices, well known in the art, are relatively small, this device may be made and used as a large area diode. It can be made thin enough to accept high frequencies while gaining comparatively high currents through its large surface area.

The heat problems are not too severe because of the large-area diodes, of 5 to 10 square millimeters for example, with good heat conductivity. The target semiconductor is also bonded directly to the mounting terminal **38** that can be a good heat conductor as well as an electrical conductor.

All of this assembly must be positioned within an evacuated tube, as described in the publication by Norris, for effective use of an electron beam. The structure of an evacuated tube, itself, and variations of such a device are well known in the art.

The target bias **70** may be between **100** and **300** volts. Higher bias voltages may be used across the junction, within the electrical limits of the device, of course. Higher voltages will increase the current and the power output and permit the use of lower impedance output loads.

The beam accelerating potential **66** may be in the order of **10** kilovolts which is relatively high for vacuum tubes but is necessary to produce a high-velocity electron beam to penetrate the semiconductor target. Higher voltages will produce higher velocities and deeper penetration for greater electron-hole pair production. This, in turn, will be limited by the physical and electrical characteristics of the vacuum tube as well as the semiconductor.

It is to be understoood that I do not desire to be limited to the exact details of construction shown and described, for obvious modifications will occur to a person skilled in the art.

What is claimed is:

1. A silicon semiconductor diode target comprising:
an intrinsic layer of semiconductor material;
an n^+ region on one side of said intrinsic layer, said intrinsic layer having a thickness of less than 20 microns;
a p^+ region on the other side of said intrinsic layer where said p^+ region has a thickness of 0.2 microns;
a conductive terminal layer having one total surface area in contact with said p^+ region and extending across the entire surface area of said p^+ region on the side opposite said intrinsic layer, said p^+ region and said conductor terminal layer being together cumulatively less than 0.275 microns thick to permit the passage of high veloctiy bombarding electrons; and
a conductive mounting terminal, conductively bonded to said n^+ region, said conductive mounting terminal and said conductive terminal layer providing the electrical terminals of said semiconductor diode.

2. In combination with a semiconductor diode as in claim **1,** an evacuated vacuum-tube structure enclosing said semiconductor diode;
a source of electrons, enclosed within said vacuum tube structure, positioned to bombard said conductive terminal layer of said semiconductor diode;
a source of accelerating potential connected between said source of electrons and said semiconductor diode;
means for controlling the output of said source of electrons;
an output load; and
a source of bias potential connected in series with said output load and said terminals of said semiconductor diode.

3. A combination as in claim **2** wherein said source of electrons comprises a heater and a cathode; said source of accelerating potential forms a beam of electrons between said cathode and said semiconductor; said means for controlling the output of said source of electrons comprises a grid to modulate said beam of electrons; and said conductive terminal layer of said semiconductor is positioned to function as a target for said beam of electrons.

4. A combination as in claim **2** having a source of radio-frequency energy connected to said means for controlling the output of said source of electrons; a radio-frequency choke connected in series with said source of bias potential; a bypass capacitor connected in parallel with said choke and said source of bias potential; and a utilization circuit connected to said output load.

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