

[54] **PHOTOMULTIPLIER TUBE HAVING
IMPACT IONIZATION DIODE COLLECTOR**[75] Inventor: **Ronald H. Goehner**, Wayne, N.J.[73] Assignee: **Varian Associates**, Palo Alto, Calif.[22] Filed: **July 11, 1974**[21] Appl. No.: **487,704**[52] U.S. Cl. **313/1; 313/95; 313/105;
250/213 VT**[51] Int. Cl. **H01j 39/02; H01j 43/22; H01j 43/18**[58] Field of Search **313/103, 95; 328/243**[56] **References Cited****UNITED STATES PATENTS**

2,928,969	3/1960	Schneeberger	313/95 X
3,534,207	10/1970	Blamoutier et al.	313/95 X

Primary Examiner—Robert Segal
Attorney, Agent, or Firm—Stanley Z. Cole; D. R.
 Pressman; Robert K. Stoddard

[57] **ABSTRACT**

A photomultiplier tube (PMT) converts a received

light signal to an output electrical signal of substantially greater intensity by employing a photocathode to convert incident light to free electrons, a plural dynode accelerating structure for effectively multiplying said free electrons, and an impact ionization diode (IID) for further multiplying and collecting said free electrons to provide a corresponding electrical output signal. The PMT can be an electrostatic device, in which the photocathode and the dynodes are mounted in opposed staggered positions, or a static crossed field device, in which the photocathode and the dynodes all are mounted opposite an accelerating rail and a magnetic field is provided to urge the electrons laterally along the tube. The IID's junction is reverse biased and the entire diode is maintained at a substantially higher potential than the last dynode. The PMT can be gain controlled or turned off without affecting dynode potentials by controlling the IID's potential. Due to the gain provided by the IID, dynode current can be reduced greatly, thereby to increase substantially the tube's life without affecting its overall gain.

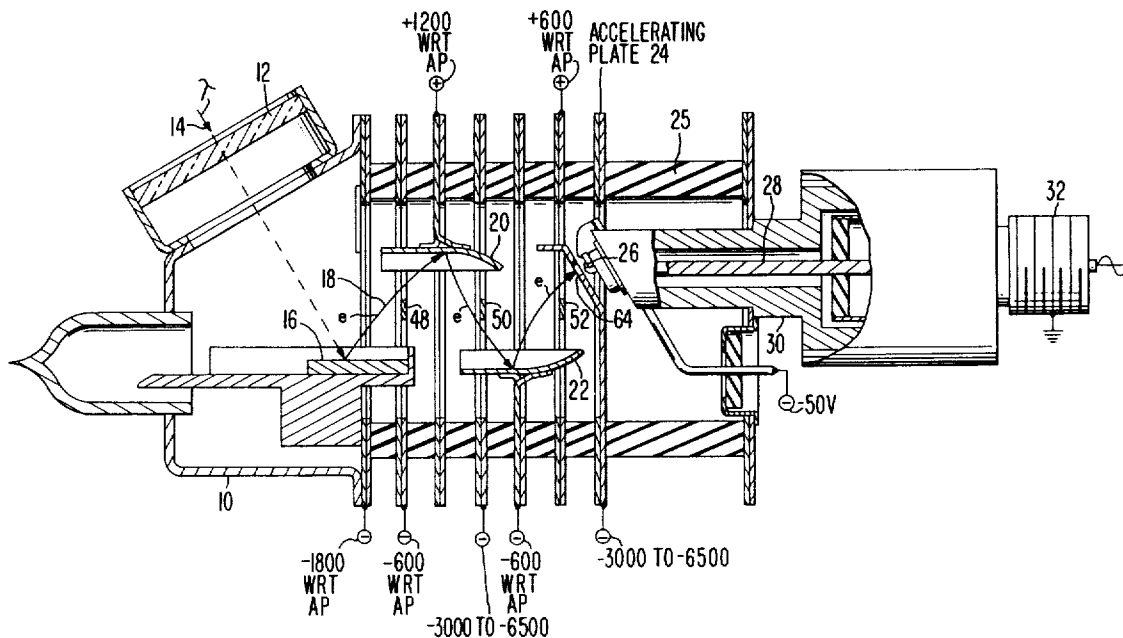
8 Claims, 7 Drawing Figures

FIG. 1

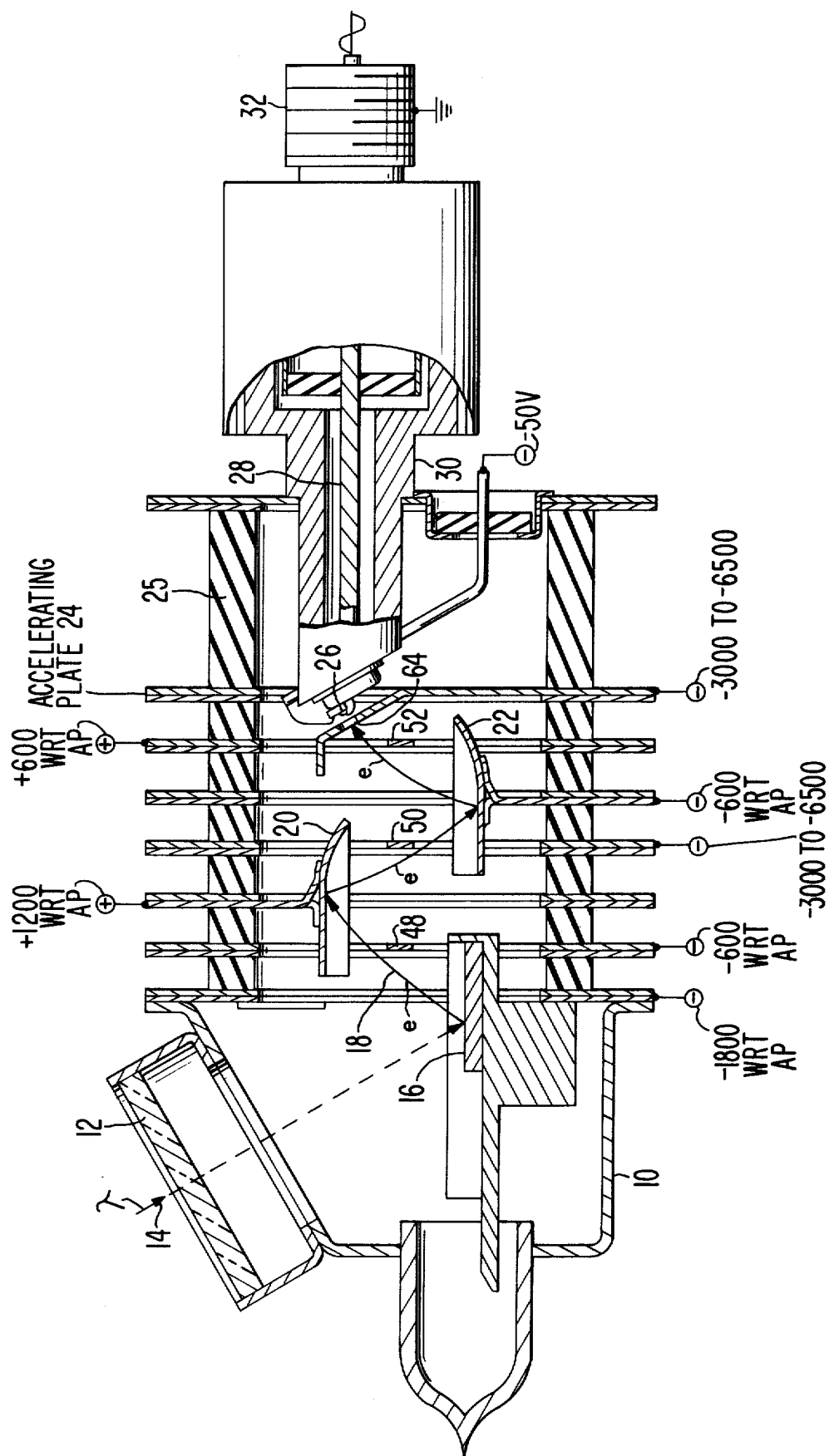


FIG 2a

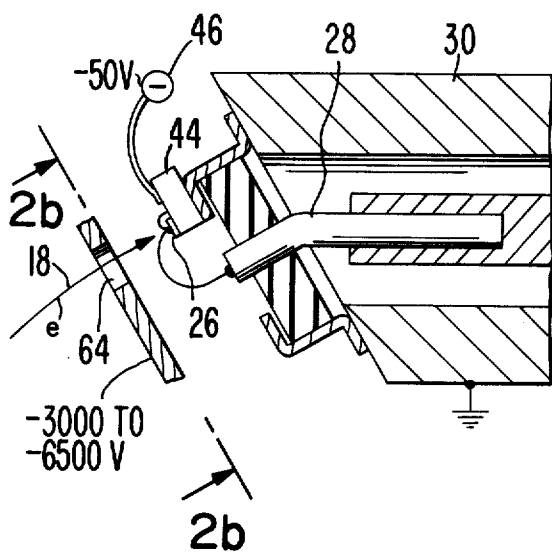


FIG. 2b

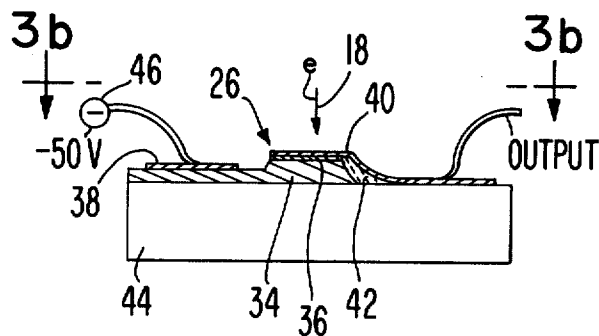
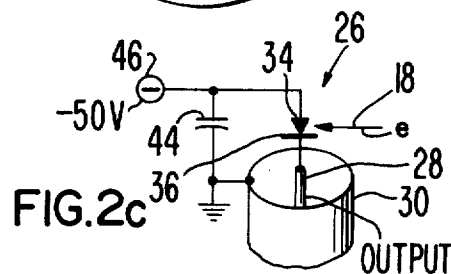
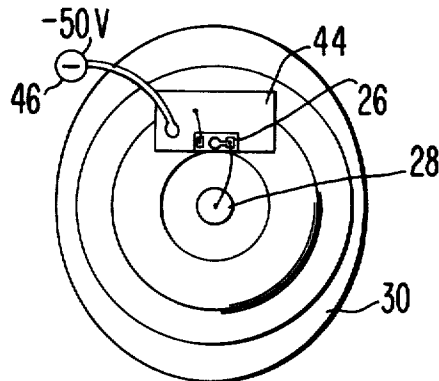


FIG. 3a

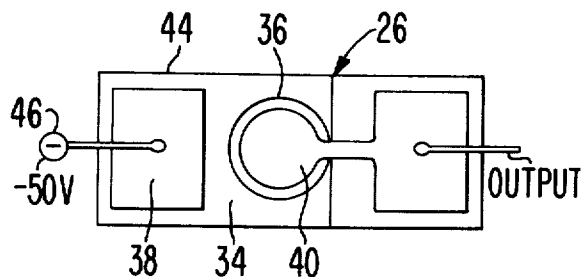
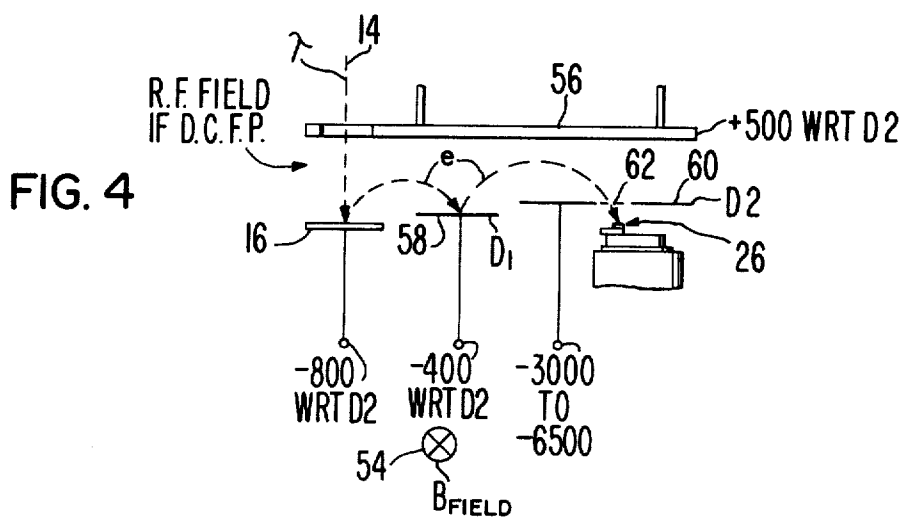


FIG. 3b



PHOTOMULTIPLIER TUBE HAVING IMPACT IONIZATION DIODE COLLECTOR

FIELD OF INVENTION

This invention relates to photomultiplier tubes in general and in particular to photomultiplier tubes whose gain can be controlled and increased and whose life can also be increased.

PRIOR ART

Heretofore photomultiplier tubes consisted of a vacuum enclosure containing a photocathode, a series of dynodes, and an electron collector. Light admitted through a window in the tube and shined on the photocathode caused electrons to be emitted therefrom. These electrons were made to impinge on the successive dynodes, causing multiple electron multiplications by secondary emission. After impingement on the last dynode, the electrons were collected and delivered on an output lead of the tube to provide an output signal which was proportional to, but much stronger than, the input light signal. Various means were employed to cause the electrons to impinge on the successive dynodes, including radio frequency fields, magnetic fields, successively increasing potentials applied to the dynodes, and strategic placement of the dynodes; as these means are either wellknown in the art or described in the other applications referred to herein, and as they are not directly germane to the present invention, they will not be discussed in detail herein.

One major difficulty associated with prior art high speed photomultiplier tubes is poor longevity. Such tubes have short longevity because the electron stream therein impinges on the dynodes with sufficient force to wear down the dynode surfaces to such an extent as to render their operation marginal, usually after only 100 hours of operation. Moreover due to electron bombardment of the dynodes, material is liberated from the dynodes which "poisons" the atmosphere in the tube (which contains a critical partial pressure of cesium), destroying the properties of the photocathode therein. This low longevity is quite serious since high speed photomultiplier tubes of the type described herein sell at prices from \$6,000 to \$10,000 each; when coupled with their extremely short life, the cost per hour of operating these tubes becomes extremely high.

Another disadvantage of high speed photomultiplier tubes of the type described herein is lack of gain control capability. This is because, to operate properly, the various electrodes of the tube must have relatively critical potentials applied thereto. While changing these potentials will tend to change the gain of the tube, it is not possible to do this in a practical sense because changing the potentials of the electrodes will usually adversely effect the operation of the tube to such an extent as to render it inoperable for the intended purpose.

Accordingly several objects of the present invention are to increase the life of high speed photomultiplier tubes and to provide a means of gain controlling photomultiplier tubes. Further objects and advantages of the invention are to increase the speed of photomultiplier tubes, to reduce the dynode current in photomultiplier tubes, to decrease the cost per hour of operation of photomultiplier tubes, to provide a means of readily turning off high speed photomultiplier tubes, to provide a means of increasing gain of photomultiplier tubes, and to provide a new type of hybrid photomultiplier

tube. Further objects and advantages of the invention will become apparent from a consideration of the ensuing description thereof.

REFERENCES

- Additional details of tubes of the types described herein are described in the following related cases which are assigned to the present Applicant's assigned and which are incorporated herein by reference:
- U.S. Pat. No. 3,757,157; 1971 Nov. 26, Abraham-Enck: Improved dynode structure for crossed field electron multiplier devices.
 - Application Ser. No. 452,151; 1974 Mar. 18; Enck-/Goehner/Guy: Means to reduce dark current in photomultipliers.
 - Application Ser. No. 471,418; 1974 May 20; Enck: Means to reduce dark current in photomultipliers.
 - Additional details of diodes of the type described herein are described in, e.g., "Theoretical Optimization of EPS Targets" by Silzars, Knight and Norris, ED-20 IEEE Trans. Elec. Dev. 193 (March 1974).

REFERENCE NUMERALS

10	enclosure	38	contact to substrate
12	window	40	contact to surface layer
14	light	42	insulating layer
16	photocathode	44	chip capacitor
18	electrons	46	diode bias
20	first dynode (FIG. 1)	48	first slat
22	second dynode (FIG. 2)	50	second slat
24	accelerating plate	52	third slat
25	ceramic ring	54	magnetic field
26	impact ionization diode	56	rail
28	center conductor	58	first dynode (FIG. 4)
30	outer conductor	60	second dynode (FIG. 4)
32	output connector	62	mesh window
34	substrate of IID26	64	aperture
36	surface layer of IID26		

DRAWINGS

FIG. 1 is a cross-sectional view of a high speed photomultiplier tube according to the invention.

FIGS. 2A and 2B are cross-sectional and plan views of the diode collector portion of the tube of FIG. 1.

FIG. 2C is an equivalent circuit diagram of the diode collector portion of FIG. 1.

FIGS.

FIGS. and 3B are cross-sectional and plan views of the diode per se of FIG. 2A.

FIG. 4 is a cross-sectional view of the dynode and collector portion of a crossed field photomultiplier tube according to the invention.

DESCRIPTION—FIG. 1—ELECTROSTATIC TUBE

The electrostatic tube of FIG. 1 comprises a vacuum enclosure 10 containing a window 12 for admission of light 14 so that said light can be directed to a photocathode 16.

Photocathode 16 can be a III-V device, such as binary GaAs, which has a 0.53μ sensitivity, or a quaternary III-V compound, such as InGaAsP, which has a 1.06μ sensitivity. Alternatively S-1 (1.06μ) or S-20 (0.53μ) photocathodes can be used.

Electrons 18 generated by photocathode 16 are directed to a first dynode 20 and thence to a second dynode 22. From the second dynode 22 the electrons pass through an aperture in an accelerating plate 24 to an impact ionization diode 26 where they are collected and delivered on a coaxial line comprising a center

conductor 28 and an outer conductor 30. An electrical output signal is taken at output connector 32 at the end of the coaxial line.

Enclosure 10 is fabricated of a series of flange sections, such as that forming accelerating plate 24, interspersed with cylindrical ceramic sections, such as 25. The various electrodes in the tube are connected to or are integral with the flanges, as described in more detail infra.

Impact ionization diode 26, best shown in FIGS. 3A and 3B, comprises a semiconductor substrate 34 of one conductivity type having a raised or mesa portion across which is formed an epitaxial thin surface layer 36 of the same conductivity type. A contact 38 is made to substrate 34 and a Schottky barrier contact 40 is made to surface layer 36. As best shown in FIG. 3B, contact 40 has a broad circular lefthand (Schottky barrier) portion connected to a rectangular right-hand (contact) portion by a narrowed neck portion. An insulating layer of silicon dioxide 42 (FIG. 3A) is provided to insulate neck portion of contact 40 from substrate 34.

The entire impact ionization diode 26 is about 10 mils by 25 mils in size, with the mesa portion thereof being about 5 mils in size. Substrate 34 is preferably P-type silicon having a resistivity of 0.1 ohm-cm and P-type surface layer 36 is formed epitaxially to have a resistivity of about 10 ohm-cm. The Schottky barrier portion of contact 40 preferably is aluminum about 400 Å thick.

Impact ionization diode 26 is mounted on a chip-type bypass capacitor 44. Capacitor 44 is mounted between substrate 34 of diode 26 and outer conductor 30 of the coaxial line, thereby to provide an ac connection or bypass between the anode 34 of capacitor 26 and outer conductor 30, as indicated in the equivalent circuit diagram of FIG. 2C. Diode 26 is back-biased by a negative source 46 connected to its anode, the cathode of diode 26 being connected to center conductor 28 which is normally held at ground potential, as is outer conductor 30.

Various other potentials are applied to the tube electrodes, as indicated in FIG. 1. Accelerating plate 24 is maintained at a potential of -3,000 to -6,500 volts with respect to diode 26 and ground, the precise potential being adjusted according to the amount of gain desired in the tube. Dynode 22 is maintained at a potential of -600 volts with respect to accelerating plate 24, dynode 20 is maintained at a potential of 1,200 volts with respect to accelerating plate 24 and photocathode 16 is maintained at a potential of -1,800 volts with respect to accelerating plate 24.

In order to provide high initial accelerating force adjacent each electron emissive surface, thereby to reduce electron transit time displacement, a series of "slats" or projections into the main cavity of the tube are provided. Each slat is normally maintained at a higher potential than either the electron emissive surface downstream or upstream thereof, thereby to shape the electron accelerating fields in the tube properly. Due to electron ballistic effects, substantially no electrons are intercepted by such slats. A first slat 48 projects into the space between photocathode 16 and first dynode 20 and is maintained at a potential of -600 volts with respect to accelerating plate 24; a second slat 50 is positioned in the space between first dynode 20 and second dynode 22 and is normally maintained at

the potential of accelerating plate 24; and a third slat 52 is positioned between second dynode 22 and accelerating plate 24 and is normally maintained at a potential of 600 volts with respect to accelerating plate 24.

Due to the flange-type section construction of tube 10, each slat may be formed by appropriately shaping each of the flanges forming part of the structure of the tube.

The potentials of the photocathode, dynodes, and slats are varied (preferably by simple voltage divider circuitry—not shown) to provide the aforementioned fixed potential differences between these electrodes and plate 24 when the potential of plate 24 is varied.

FIG. 4—STATIC AND DYNAMIC CROSSED FIELD TUBE EMBODIMENTS

In the electrostatic tube of FIG. 1, the progression of the electrons from the photocathode to the first dynode, from dynode-to-dynode, and from final dynode to impact ionization diode collector 26 was achieved through the use of strategic placement of electrodes maintained at successively higher potentials. In the crossed field tube of FIG. 4, all of the dynodes are maintained at increasing potentials and are mounted at successively elevated positions, but since they are all mounted on one side of the tube, additional means are required to cause the electron stream to impinge upon these dynodes and to be drawn from the dynodes. In a static crossed field tube, an orthogonal magnetic field 54 and an elevated potential rail 56 are provided for this purpose. In a dynamic crossed field photomultiplier (DCFP), an RF (radio frequency) field is also provided in the tube's cavity, as indicated. Full details of dynamic and static crossed field tubes, including the operation, envelope and other physical structure thereof are described in the aforementioned Abraham-/Enck U.S. Pat. No. 3,757,157.

The tube contains a photocathode 16 as in FIG. 1 positioned under a window in the envelope of the tube so as to receive light 14 from a source outside the tube, a first dynode 58 positioned to receive electrons from photocathode 16, and a second dynode structure 60 having a mesh opening thereof 62 designed to admit electrons from dynode D1 to an impact ionization diode collector 26 similar to that of FIG. 1. In the static tube, potentials are applied to the dynodes and collector structures as indicated. As in FIG. 1, the potentials of photocathode 16 first dynode 58 and rail 56 are always maintained at the same potential with respect to second dynode 62 (D2), whose potential can be varied within the range indicated to control the gain of the tube. In the DCFP, the dynodes preferably are all at the same potential and physical height, or can be a single elongated dynode, as indicated in said Abraham/Enck patent.

Magnetic shielding means (not shown) are also provided around diode 26 and the area thereabove to shield the electron stream in the area above the diode from magnetic field 54 so that the electron stream will not be curved in the region immediately above the diode and so that the diode will be shielded from the magnetic field which might interfere with operation thereof.

OPERATION

The operation of both type tubes is similar but will be described with respect to the presently preferred embodiment (FIG. 1). When a light source 14 (e.g., from

a distant laser of the correct frequency is directed through window 12 on photocathode 16, it causes photocathode 16 to emit electrons in well-known fashion. The electrons emitted by photocathode 16 are initially accelerated by first slat 48 and then by dynode 20 upon which they impinge violently to generate copious secondary electrons in well-known fashion. The secondary electrons from dynode 20 are initially accelerated by second slat 50 and then by second dynode 22 upon which they impinge more violently, again to generate copious secondary electrons. These are initially accelerated by third slat 52 and then by accelerating plate 24 such that they pass through aperture 64 in the accelerating plate impinge even more violently upon impact ionization diode 26. The electrons are collected by diode 26, causing an output signal to be provided on center conductor 28 with respect to outer conductor 30. This output signal will vary in accordance with the intensity of input light signal 14, but will have substantially more energy than the former.

Due to the gain provided in diode 26—i.e., an electron multiplication of about 1,000—the current on the dynodes can be (and in the described embodiment is) substantially reduced while still providing the same overall gain. This reduces dynode wear and outgasing of the dynodes due to electron impingement thereon, thereby increasing the longevity of the tube. The current on the dynodes can actually be reduced to about 1 microampere, a level low enough to reduce dynode wear sufficiently so that the operating life of the tube will approximate its shelf life. This contrasts with prior art photomultipliers in which the tube performance was degraded to about 90 percent of its original quality in about 100 hours.

An additional and substantial advantage of the invention is the gain control available by varying the potential between the collector (diode 26) and the dynode structure. As is well-known, it is impractical to reduce the gain of a conventional photomultiplier tube by reducing the interdynode potentials because these are usually set to operate at critical values so that changing same will disrupt the operation of the tube sufficiently to preclude this as a practical method of changing gain. In the present tubes, by varying the potential of the accelerating plate 24 with respect to ground or the potential of collector diode 26, and by varying the potentials of all other dynodes and the photocathode so as to maintain a constant potential between these elements and the accelerating plate, it is possible to decrease the gain of the tube by a substantial factor, or even to turn it off entirely.

That is, when the potential of accelerating plate is at its maximum negative value (−6,500 V) the gain of the tube will be maximized, but when the potential is at its least negative value and range indicated (−3,000 V) the gain of the tube will be minimized.

Through the use of this method of varying the potentials on the tube, the tube can be automatically gain controlled (AGC'd) as is possible with other amplification devices such as transistors and vacuum tubes. This is believed to represent a substantial advance in the art.

The tube can also be turned off by reducing the potential between accelerating plate and diode 26 to a

low value.

Also the gain of the tube can be increased with respect to prior art tubes merely by incorporating impact ionization diode 26 therein without reducing dynode current. Moreover the gain and life of prior art tubes can both be increased by incorporating diode 26 and partially reducing dynode current.

While the above description contains many specificities, these should not be construed as limitations on the scope of the invention. Accordingly the scope of the invention should be construed only according to the following claims and their legal equivalents.

What is claimed is:

1. A photomultiplier tube comprising a hermetically sealable enclosure having a transparent area for admission of light, a photocathode positioned in said enclosure for receiving said light and converting same to free electrons, at least one dynode positioned in said enclosure for receiving said free electrons from said photocathode and multiplying same, and means positioned to receive free electrons from said dynode for simultaneously providing multiplication of received electrons and collection of same on a conductor to provide an output signal on said conductor, said means positioned to receive free electrons comprising a diode capable of multiplying and collecting received free electrons by impact ionization.

2. The tube of claim 1 wherein said dynode is positioned facing said photocathode and said means is positioned facing said dynode.

3. The tube of claim 1 including a plurality of dynodes, each maintained at a greater potential than the one next closest to said photocathode.

4. The tube of claim 1 further including means for providing a magnetic field through said tube for urging free electrons emitted by said photocathode to said dynode, said tube including an accelerating rail, said photocathode and said dynode facing said accelerating rail.

5. The tube of claim 1 wherein said enclosure is evacuated and further including means for maintaining said dynode and said means at successively greater potentials than said photocathode, and means for controlling independently the potential of said means.

6. The tube of claim 1 including a plurality of dynodes, each maintained at a greater potential than the one next closest to said photocathode, adjacent ones of said dynodes, said photocathode, and said means facing each other, said means being maintained at a greater potential than any of said dynodes.

7. The tube of claim 1 including a plurality of dynodes, each maintained at a greater potential than the one next closest to said photocathode, an accelerating rail facing all of said dynodes and said photocathode, said means being maintained at a greater potential than any of said dynodes, and means providing a magnetic field through said dynodes in a direction for urging electrons emitted by said photocathode along said dynodes to said means.

8. The tube of claim 4 further including means for injecting radio frequency energy into said enclosure for urging said electrons to impinge upon said dynode.

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