



US005804833A

United States Patent [19]

[11] Patent Number: **5,804,833**

Stettner et al.

[45] Date of Patent: **Sep. 8, 1998**

[54] **ADVANCED SEMICONDUCTOR EMITTER TECHNOLOGY PHOTOCATHODES**

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5,646,479 7/1997 Troxell 313/495

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[21] Appl. No.: **722,448**

[22] Filed: **Oct. 10, 1996**

[51] Int. Cl.⁶ **H01L 29/06; H01L 29/12**

[52] U.S. Cl. **257/10; 257/11; 257/442;**
257/443; 257/466; 313/309; 313/336; 313/351;
313/500; 313/501

[58] Field of Search **257/10, 11, 442,**
257/443, 466; 313/309, 336, 351, 500,
501

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The Semiconductor Field-Emission Photocathode; Dieter K. Schroder, R. Noel Thomas, James Vine, H.C., Nathanson, Dec. 1974, IEEE Transactions on Electron Devices, vol. Ed-21, No. 12, pp. 785-798.

Primary Examiner—William Mintel

Attorney, Agent, or Firm—Gottlieb, Rackman & Reisman, P.C.

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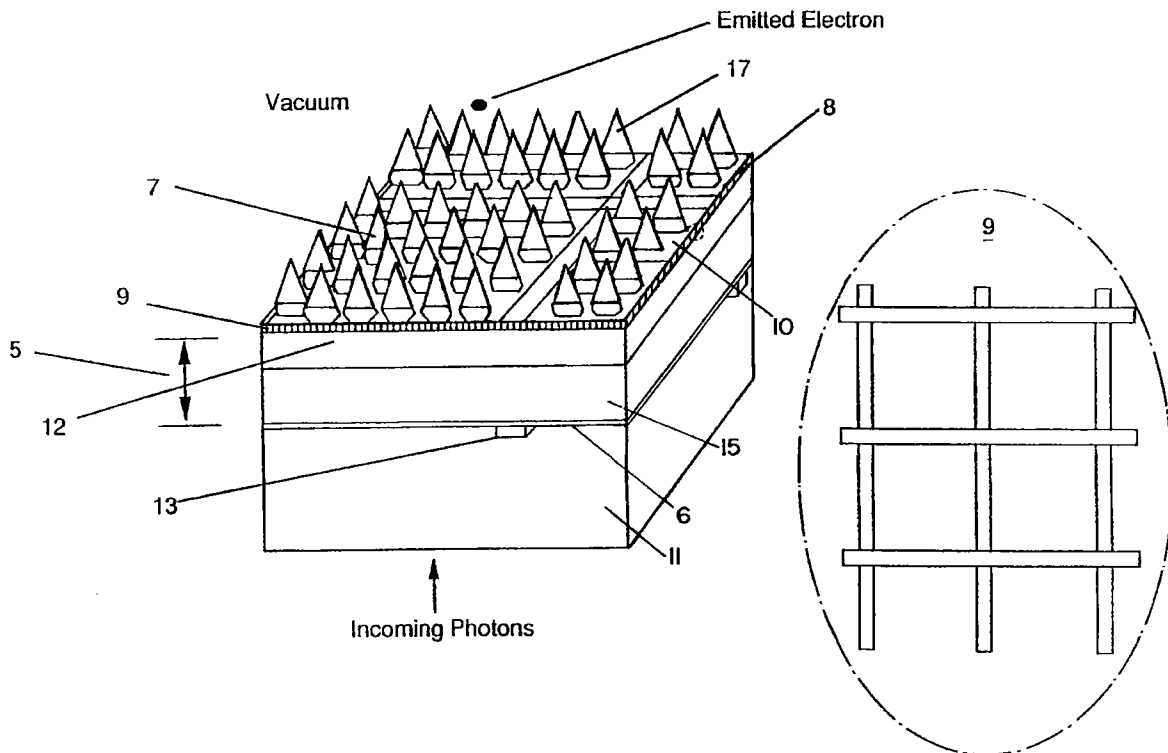
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[57] ABSTRACT

A detector to be used for detecting photons from the visible to far infrared spectrum is described. The detector uses unique photocathodes called Advanced Semiconductor Emitter Technology (ASET) as its critical element for converting the detected photons to electrons which are emitted into a vacuum. The electron is multiplied by accelerations and collisions creating a signal larger than the sensor noise and thus allowing the photon to be detected. ASET is/composed of distinct detector and emitter technologies.

33 Claims, 10 Drawing Sheets



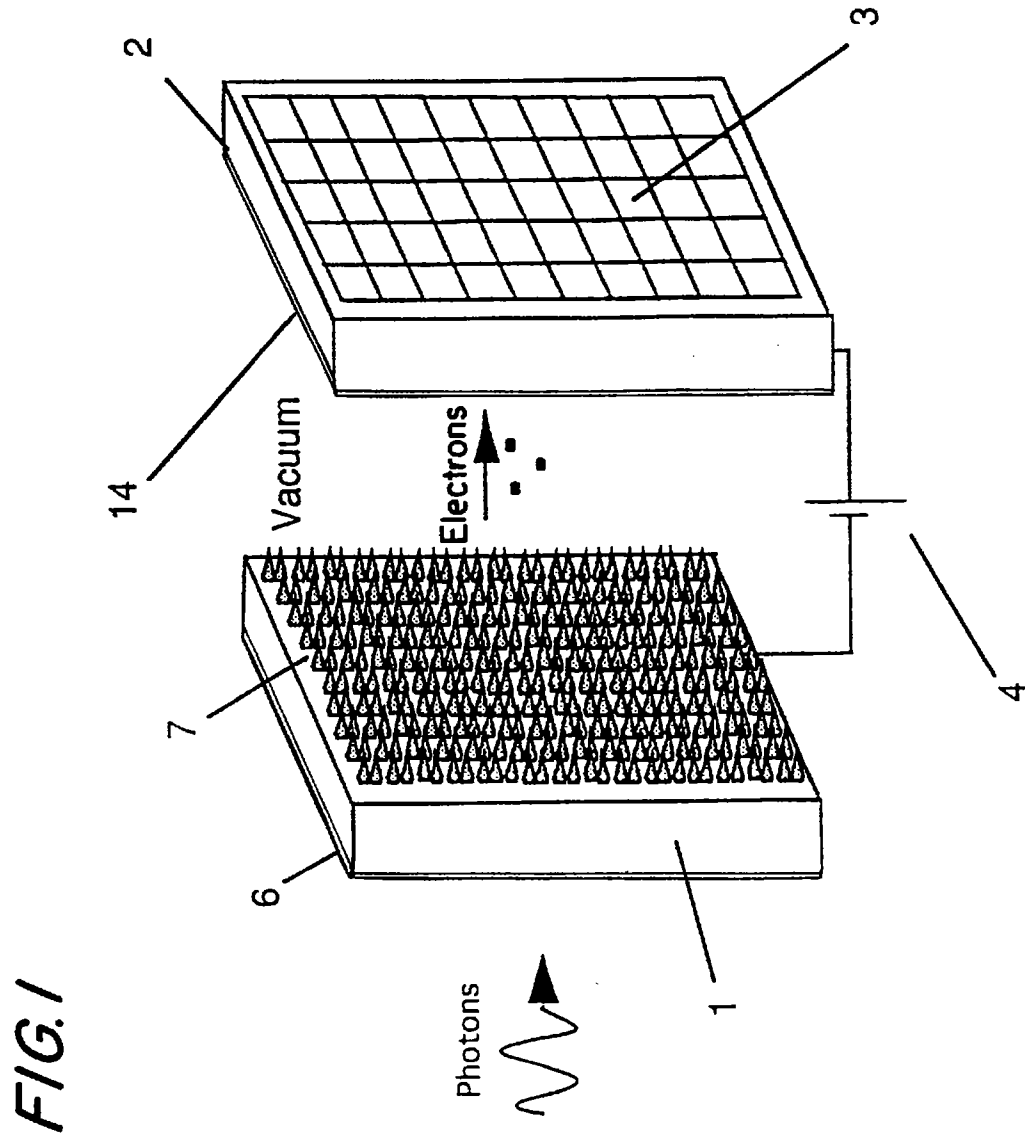


FIG. 1

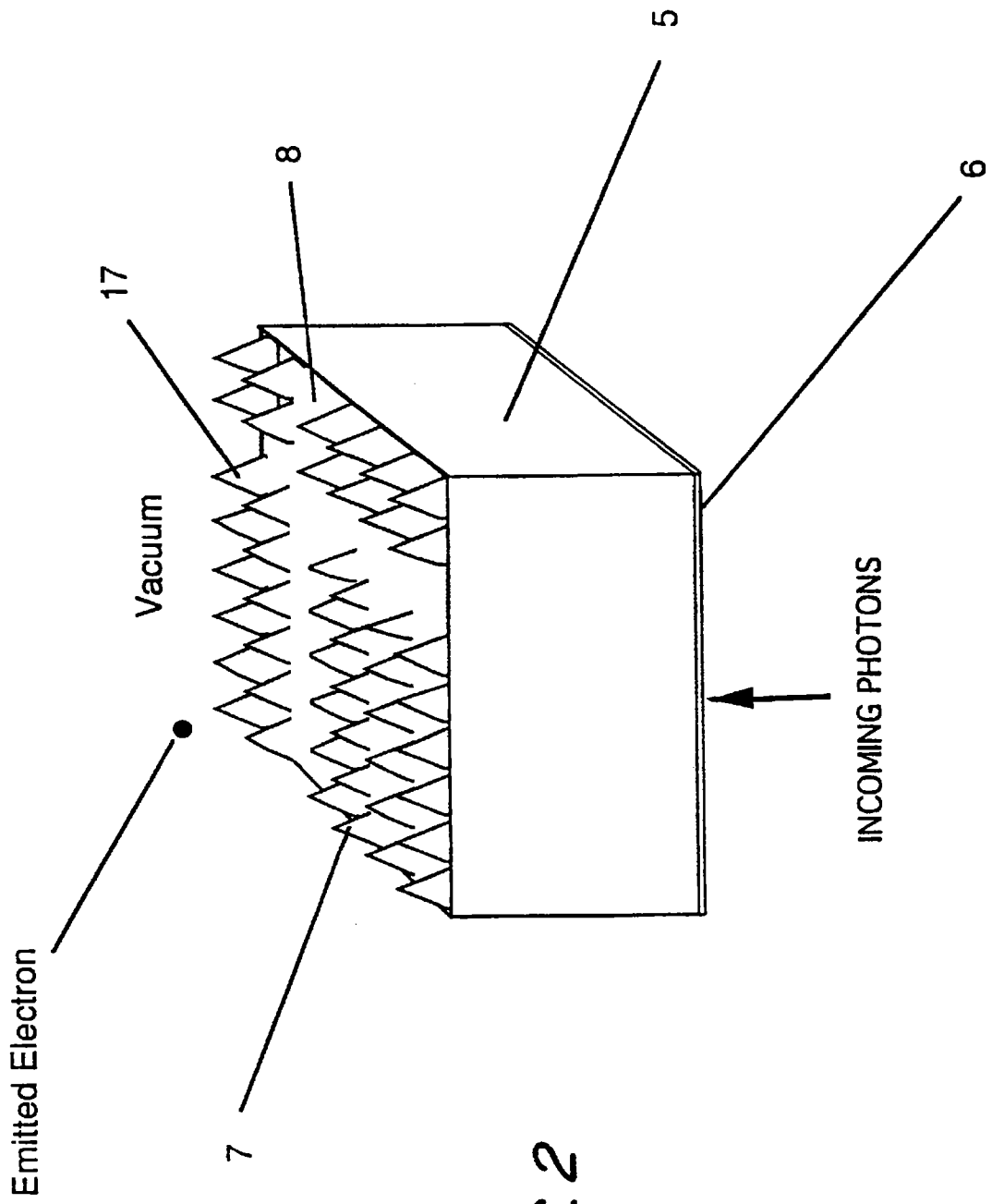


FIG. 2

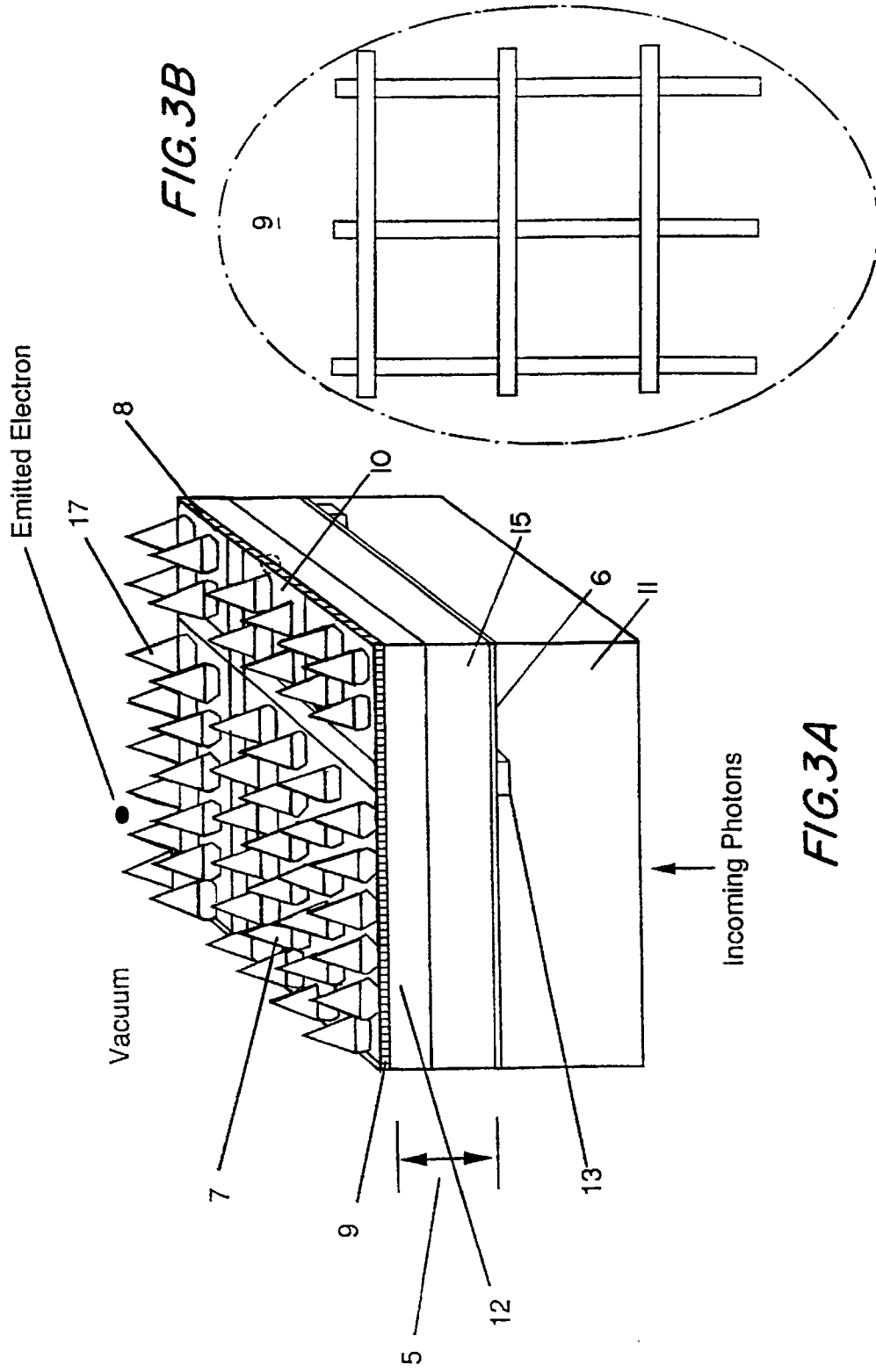


FIG. 4A

40 MIL (1000 μM) LIGHTLY DOPED
(HIGH RESISTIVITY) STARTING
WAFER

STEP 1

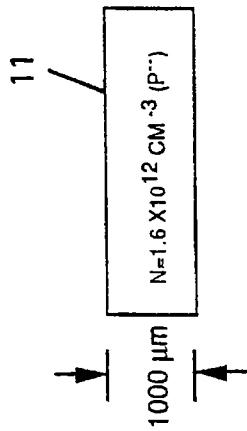


FIG. 4B

FORM NON-PATTERN TRANSPARENT
WINDOW BY EITHER A BORON
IMPLANT OR A EPITAXIAL GROWTH

STEP 2

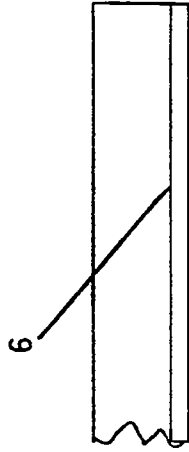


FIG. 4C

GROW FIELD OXIDE AND PATTERN
FOR FIELD EMITTER TIPS.

STEP 3 16

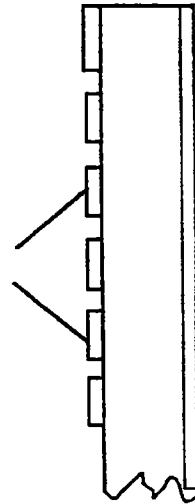
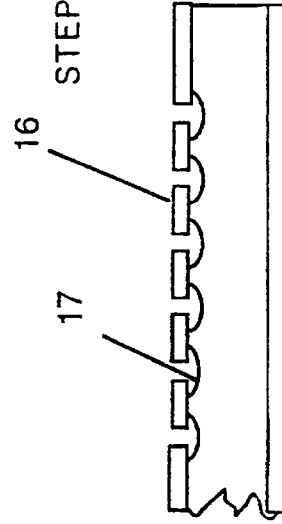


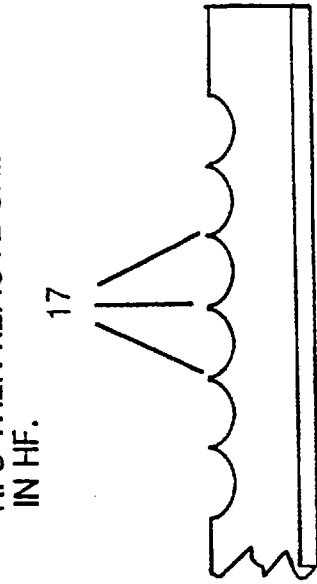
FIG. 4D

CHEMICALLY ETCH SILICON TO
UNDERCUT OXIDE DISCS.

STEP 4



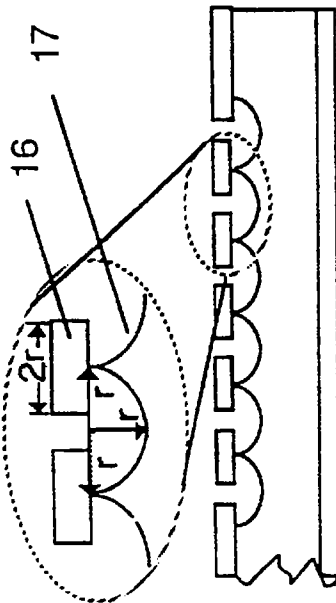
QUICK DIP-ETCH IN SILICON ETCH SOLUTION TO SHARPEN EMITTER TIPS THEN REMOVE OXIDE DISCS IN HF.



STEP 6

FIG.5B

CONTINUE TO ETCH SILICON UNTIL EMITTER TIPS FORM.



STEP 5

FIG.5A

FIG. 6A

20 MIL (500 μm) LIGHTLY DOPED STARTING WAFER.

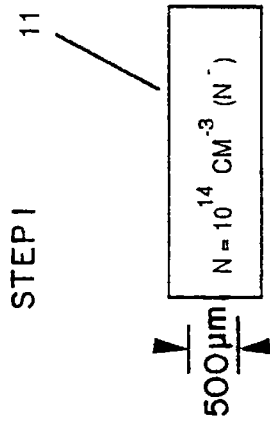


FIG. 6B

PATTERN AND ETCH KEYS INTO SILICON FOR MASK ALIGNMENT BEFORE AND AFTER EPITAXIAL GROWTH.

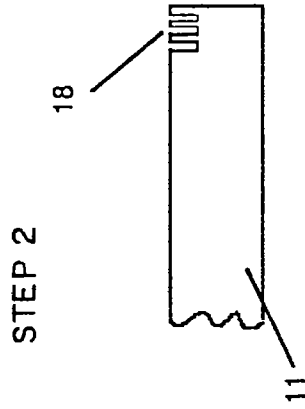


FIG. 6C

NON-PATTERNED EPITAXIAL LAYER FOR TRANSPARENT CONTACT; IMPLANTED BURIED GRID.

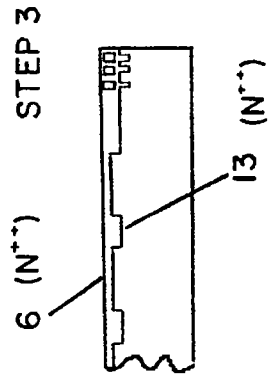


FIG. 6D

DETECTOR AND BLOCKING LAYERS #1 AND #2 ARE EPITAXIALLY GROWN.

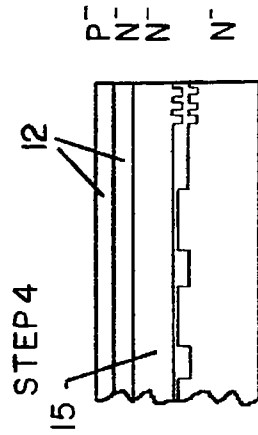


FIG.7A

IMPLANTED GRID ELECTRODE

STEP 5 9 (P⁺⁺)

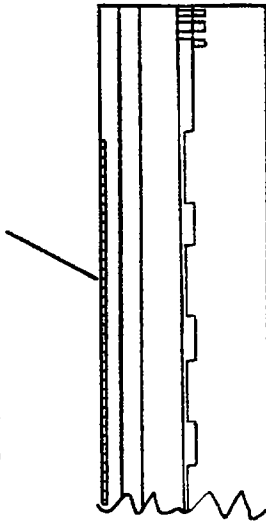


FIG.7B

SILICON LAYER IS EPITAXIALLY GROWN FOR EMITTERS.

STEP 6 EMITTER STRUCTURE LAYER

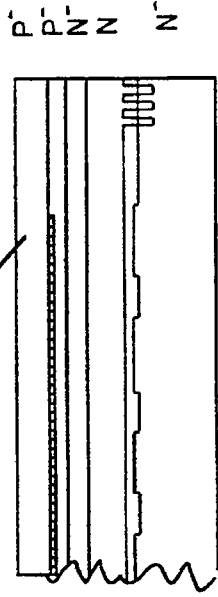


FIG.7C

PATTERN V-GROOVE SILICON ETCH AND IMPLANT TO BACKSIDE CONTACT AND GRID ELECTRODE.

STEP 7 20 19 9

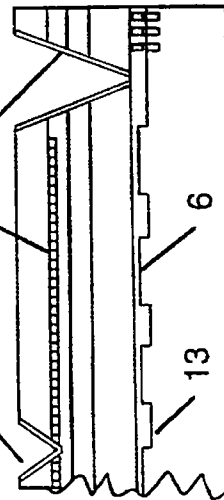


FIG.7D

GROW FIELD OXIDE AND PATTERN FOR FIELD EMITTER TIPS.

STEP 8 16

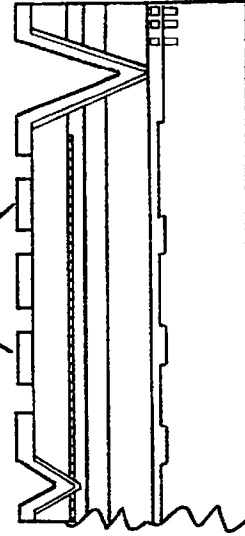


FIG. 8A

CHEMICAL ETCH TO FORM
EMITTER STRUCTURE

STEP 9

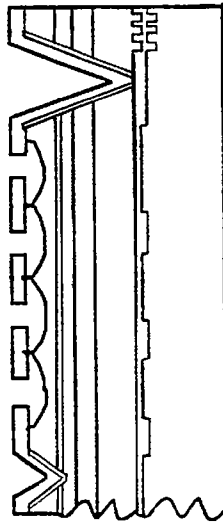


FIG. 8B

REMOVE FIELD OXIDE. DRAWING IS
NOT TO SCALE.

STEP 10

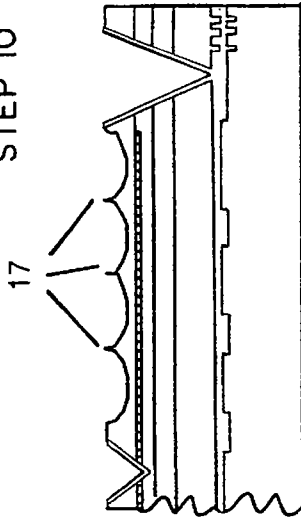


FIG. 8C

SPUTTER PURE ALUMINUM ON
WAFERS. COAT WAFER WITH
PHOTORESIST AND THEN PATTERN
PHOTORESIST.

STEP 11

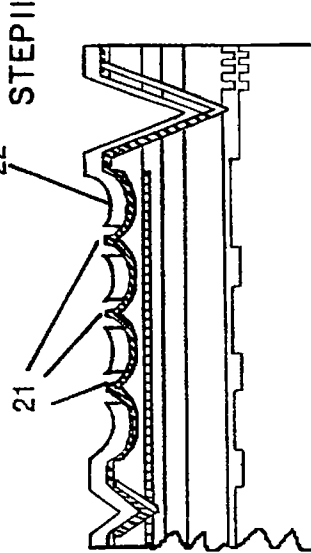
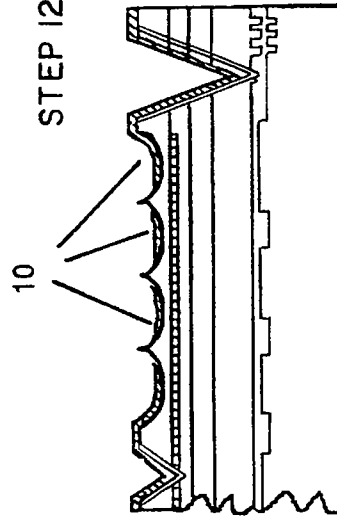


FIG. 8D

ETCH ALUMINUM PATTERN FOR
ELECTRIC FIELD SHIELDS

STEP 12



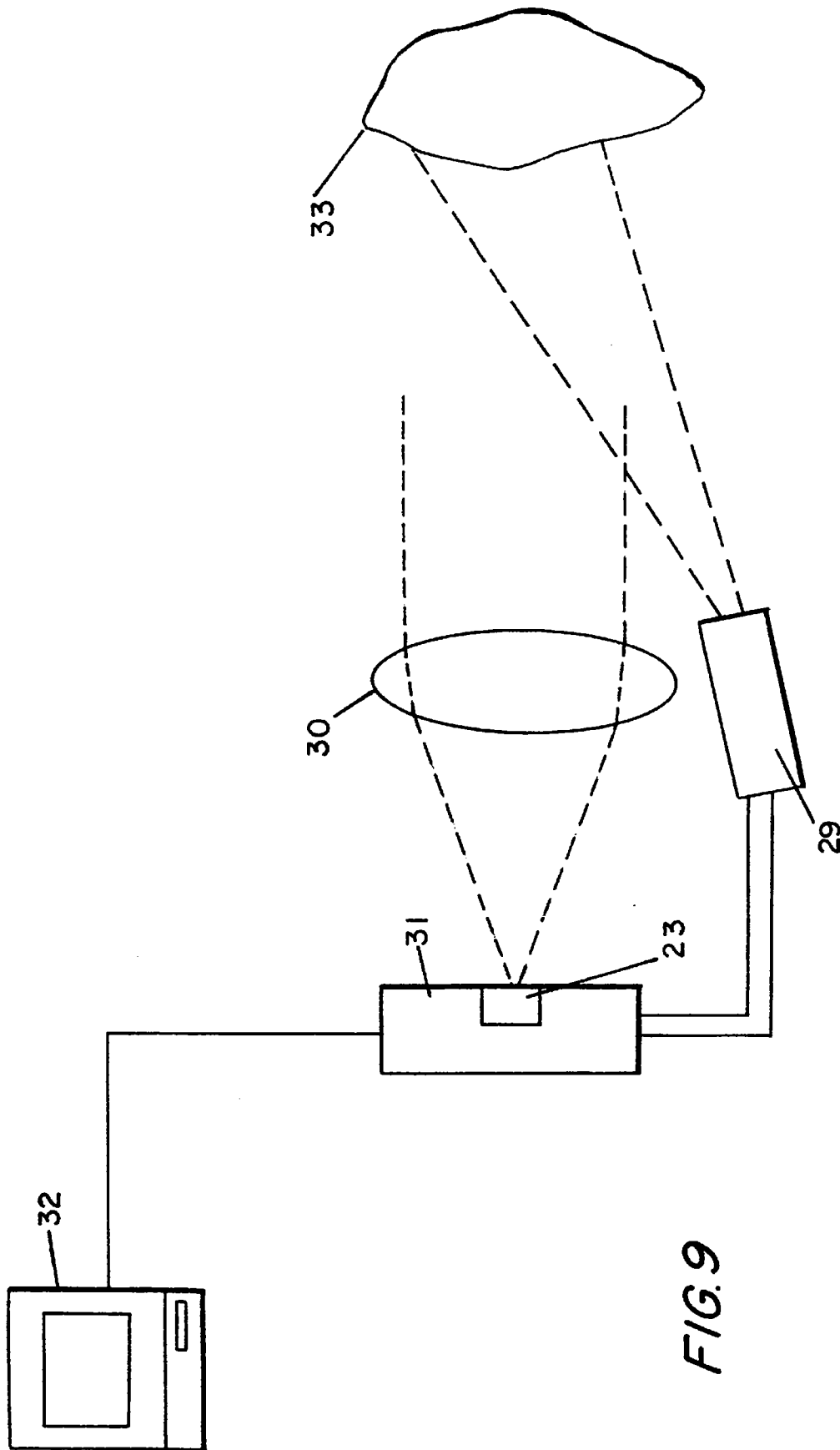


FIG. 9

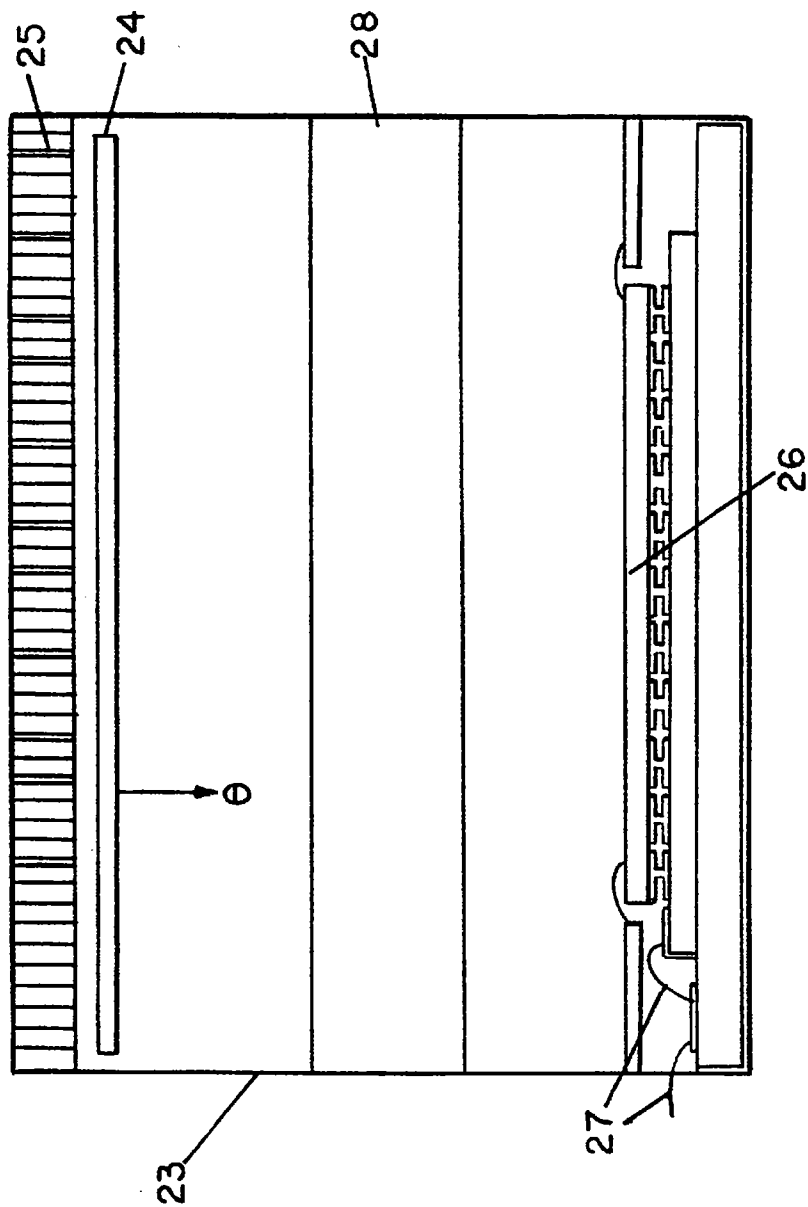


FIG. 10

ADVANCED SEMICONDUCTOR EMITTER TECHNOLOGY PHOTOCATHODES

FIELD OF THE INVENTION

This invention relates to photocathode devices. In particular, it relates to photocathodes combining solid-state detector and emitter techniques. It also pertains to photocathodes having high quantum efficiency and useful for wavelengths on the order of 1–24 μm .

BACKGROUND OF THE INVENTION

Conventional photocathodes are used in a number of photon amplifier applications including photomultipliers (PMTs), micro-channel-plate (MCP) amplifier tubes and Digicons. The photocathode detects the photon and emits an electron. The electron (i.e., the photoelectron current) is amplified by one of the previously mentioned technologies and the resulting signal is larger than the sensor noise. However, conventional photocathodes have low quantum efficiency and respond to photons in a limited visible range; the visible spectrum is roughly 0.4 to 0.7 μm . Quantum efficiency in this context refers to the average number of electrons emitted per incident photon of a given wavelength.

PMTs, a particular electron amplifier using dynodes, are applied in a number of medical and laser detection applications. MCP amplifier tubes are used in similar applications, but because of their multiple-pixel imaging capability they are also used in night-vision goggles and imaging laser radar (LADAR). Night-vision MCP image tubes are vacuum structures containing a photocathode, a microchannel plate and a phosphor. Microchannel-plates amplify the photocathode electrons produced by dim-light photons, by collisions with the glass walls of the MCP, and these electrons, in turn, produce increased levels of visible light via collision with the phosphor.

In photon counting applications, a microchannel plate or photomultiplier tube increases the single-photon signal level above the sensor noise, thereby increasing sensitivity of the sensor to the level at which photon counting can be performed. In a digicon the electron emitted by a photocathode is guided by a magnetic field and accelerated by an electric field, to energies of thousands of electron volts. The photoelectron impacts a silicon diode array and amplification results by impact ionization because it requires only about 3.3 eV to produce an electron-hole pair.

Conventional photocathodes such as S-20 have a useful spectral range of about 0.45 μm to 0.55 μm , where the quantum efficiency is about 10%; the quantum efficiency drops dramatically as the wavelength increases: at 0.9 μm it is only about 1%. "Special Purpose Photosensitive Devices", IIT Publication, IIT Electro-Optical Products Division, Tube and Sensor Laboratories, Fort Wayne, Ind. Currently to detect Nd:YAG laser light the wavelength is halved (frequency doubling) using a nonlinear crystal with roughly a factor of 4 loss of photons. Use of low quantum efficiency conventional photocathodes further reduces the detection efficiency.

Currently there are no photocathodes in the short wavelength, mid wavelength or long wavelength infrared (about 1–24 μm). Unlike frequency-doubled detection systems used with the Nd:YAG laser, there are currently no photocathodes that can be used with the CO₂ laser.

Conventional photocathodes are also difficult to make and require a very high vacuum due to their sensitivity to contamination.

Solid-state detector and emitter technologies are known. The particular emitter technology used in embodiments of this invention is based upon the silicon emitter technology described in the following references: D. K. Schroder et al, "The Semiconductor Field Emission Cathode", IEEE Trans., Vol. ED-21, No. 12 Dec. 1974; R. N. Thomas and H. C. Nathanson, "Transmissive Mode Silicon Field Emission Array Photoemitter", Appl. Phys. Lett., Vol. 21, No. 8, 15 Oct. 1972; R. N. Thomas, R. A. Wickstrom, D. K. Schroder and H. C. Nathanson, Fabrication and Some Applications of Large-Area Silicon Field Emission Arrays, Solid-State Electronics, 1974, Vol. 17, pp. 155–163; References 2–4. An alternative metal-emitter technology exists, C. A. Spindt, K. R. Shoulders and L. N. Heynick, U.S. Pat. Nos. 3,755,704 (1973), 3,789,471 (1973), 3,755,704 (1973), 3,789,471 (1973), 3,812,559 (1974). This metal-emitter technology is unsuitable to combine with detector technologies. In addition the metal emitter technology has a much larger work function or electron affinity than the semiconductor technology and therefore requires a higher operating voltage. The vacuum-surface interface of the semiconductor acts to reduce the electron affinity below that of the solid semiconductor material.

BRIEF DESCRIPTION OF THE PRESENT INVENTION

The Advanced Semiconductor Emitter Technology (ASET) photocathode devices described in this patent combine solid-state detector and emitter technologies into one device with very significant advantages over existing photocathode technology. ASET utilizes detectors operating over a very broad spectral range, from the visible to the far infrared, with high quantum efficiency. These detectors can not be used as photocathodes themselves but in combination with solid-state emitter technology they become very efficient very broad-spectrum photocathodes. One of the virtues of photocathodes is that they can be used in an electron amplification configuration to detect individual photons. The ASET emitter technologies are combined with another solid state chip in an evacuated enclosure to form a compact, electron-amplifying detector so sensitive it can detect individual photons in the visible to the far infrared. One such embodiment of the present invention is called the proximity-focused photon detector.

It is an object of the present invention to provide Advanced Semiconductor Emitter Technology (ASET) Photocathode devices. One of the ASET photocathode devices, the ASET-V, has a quantum efficiency of 60% to 70% at 0.5 μm and 80% to 100% at 0.9 μm , about a factor of 7 to 100 larger than conventional photocathodes.

It is a further object of the present invention to provide an ASET-V photocathode having a spectral range extending out to 1.1 μm , making it applicable to detecting signals from near-infrared Neodymium YAG (Nd:YAG, 1.06 μm) lasers.

It is a further object of the present invention to identify or see light about one to two orders of magnitude less intense as compared to conventional photocathodes. High quantum efficiency at the Nd:YAG wavelength means that for higher laser power applications, instead of increasing laser power, a sensitive detector such as ASET-V could be used. In photon counting applications, ASET-V is equivalent to an increase in Nd:YAG laser power by roughly a factor of 30. (Because of laser material heating, increasing laser power while maintaining a useful repetition rate is a technical problem.)

It is a still further object of the present invention to provide ASET-IR technology, having a quantum efficiency

of greater than 50% and a spectral range is from 2 μm to 24 μm . This spectral range includes the CO_2 -laser wavelength, 10.6 μm and other lasers that can be used for remote spectroscopy of atmospheric pollutants.

It is a further object of the present invention to provide an ASET-IR more sensitive than any known infrared detector (IR) detector—with a suitable electron amplifier it can detect individual IR photons—having clear applications for passive detection of faint long wavelength infra red emitting objects and potentially very large cost savings, particularly for satellite systems.

It is a still further object of the present invention to provide uses of the ASET-IR in CO_2 laser radar (ladar) and ladar-like applications.

A still further object of the present invention is the use of the ASET-IR, as a CO_2 laser photocathode, to achieve the effective equivalent of an increase in CO_2 laser power by about a factor of 1000, with respect to maximum range using current direct-detection detector technology. In spite of the inefficiency of the Nd:YAG frequency doubled photocathode system it is still useful for extending the range of Nd:YAG ladars.

Yet a still further object of the present invention is to provide such devices that can be made by most foundries, are stable chemically and it can handle a few orders of magnitude higher pressure than conventional photocathodes. This will make ASET vacuum tube manufacturing much simpler and less expensive than conventional photocathode vacuum tubes.

Yet another object of the present invention is to replace existing photocathodes with a much higher quantum efficiency technology and to extend photocathode applications from the near IR to the LWIR. Even if the only application was detection of Nd:YAG or CO_2 laser photons, the impact of this extension should be enormous.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a preferred embodiment of the present invention, the proximity-focused photon detector employing the ASET photocathode device.

FIG. 2 is a perspective view of a preferred embodiment of the visible to near infrared ASET photocathode device.

FIG. 3 is a perspective view of a preferred embodiment of the near to far infrared ASET photocathode device. The blowout shows the structure of the grid electrode.

FIG. 4 shows the first four processing steps for the ASET-V.

FIG. 5 shows the last two processing steps for the ASET-V.

FIG. 6 shows the first four processing steps for the ASET-IR.

FIG. 7 shows the second four processing steps for the ASET-IR.

FIG. 8 shows the last four processing steps for the ASET-IR.

FIG. 9 is a cross section view of a vacuum tube detector employing the ASET photocathode.

FIG. 10 is a diagram of an imaging or pollutant analysis system employing ASET vacuum tube detector.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE PRESENT INVENTION

A preferred embodiment of the present invention, the proximity-focused photon detector using Advanced Semi-

conductor Emission Technology (ASET) as a photocathode device, is described. The proximity-focused detector is depicted in FIG. 1 and is capable of detecting the smallest particle of light, the photon, with high efficiency. The proximity focused detector in FIG. 1 is comprised of an ASET photocathode device 1, a diode array 2 with a corresponding readout unit cell electronics array 3, fabricated on the front side of the diode array, and a voltage source 4 which accelerates electrons emitted from the photocathode device 1, through a vacuum, into the diode array 2. The back contact 14 of the diode array 2 is the anode for the photocathode device 1. Typical dimensions of the arrays are a few square millimeters (mm) to a few hundred square centimeters. A typical distance between the arrays is 1 mm and a typical source voltage 4 is 10 kilovolts.

Two preferred embodiments of the ASET photocathode device are also described. A small section of the first embodiment is depicted in FIG. 2 and a small section of the second embodiment is depicted in FIG. 3. Both embodiments, absorb light and emit electrons. The ASET photocathode device is capable of detecting a photon of light, with high efficiency, when used with a suitable electron amplification means. The proximity focused detector configuration in FIG. 1 provides one particular electron amplification means. The first ASET photocathode device embodiment is most appropriate for shorter wavelengths of light, ultraviolet, through the visible, to near infrared; it is termed ASET-V. The second ASET photocathode device embodiment is most appropriate for longer wavelengths of light, Long Wavelength Infrared (LWIR); it is termed ASET-IR.

The preferred embodiment of the ASET-V photocathode device, a small section of which is depicted in FIG. 2, comprises a detector structure 5, a backside electrical contact or cathode 6, and an emitter structure 7. The emitter structure is composed of an array of tiny cone-shaped emitters 17. This cone-shaped emitter array is either continuous or interrupted by pixel spaces 8 which define pixels. The detector and emitter structures are one continuous piece of semiconductor material. A typical piece of material would be a crystalline silicon wafer 100 mm in diameter and 1 mm thick. Typical pixel dimensions are 30 μm to 150 μm . One ASET-V might take up the whole wafer or just a small portion of it. Typically, the contact 6 is either ion-implanted in the wafer or a highly doped contact layer is grown on the back surface of the wafer. The concentration of the contact doping times its depth is small enough that a negligible number of photons are absorbed in the contact. Typical dimensions of the cone-shaped emitters are 3 to 20 microns (μm) in height and 3 to 20 microns in base diameter. The substance may be applied at the tip of the cone to reduce the electron affinity of the solid state material. Cesium is an example of this substance.

The preferred embodiment of the ASET-IR, a section of which is depicted in FIG. 3, comprises a detector structure 5 a backside electrical contact 6 and an emitter structure 7. The emitter structure is composed of an array of tiny cone-shaped emitters 17. The cone-shaped emitter array can be continuous or interrupted by pixel spacing 8. The ASET-IR is further composed of an electrical contact or shield 10, which covers the lower part of the emitters, a grid electrode 9, and a substrate 11 upon which the ASET-IR is fabricated. The detector structure 5 is composed of a number of layers: the detector layer 15, and one or two blocking layers 12. The backside electrical contact 6 is associated with an optional window grid 13 which defines pixels and enhances the electrical conductivity of the backside electrical contact.

