United States Patent [19]

Kennedy

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[45] **June 4, 1974**

[54] **TUNEABLE INFRARED PHOTOCATHODE**

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[73] Assignee: **The United States of America ss represented by the Secretary of the Navy,** Washington, D.C.

[22] Filed: **Nov. 15, 1972**

[21] Appl. No.: **306,786**

[52] **U.S. Cl.** .... **357/30,** 357/16, 357/61, 250/211 J

[51] **Int. Cl.** **H01l 15/00**

[58] **Field of Search**... 317/234 N, 235 AC, 235 AP; 250/211 J

[56] **References Cited**

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Attorney, Agent, or Firm—Edward G. Kelly; Herbert Berl; Milton Lee

[57] **ABSTRACT**

A tuneable field assisted photocathode structured as a three layer double heterojunction device with a low work function cesium oxide coating on the electron emitting surface. An internal field assistance bias aids the flow of electrons from a narrow bandgap region, where they are photo-generated, to the wider bandgap negative electron affinity surface region for vacuum emission.

6 Claims, 7 Drawing Figures

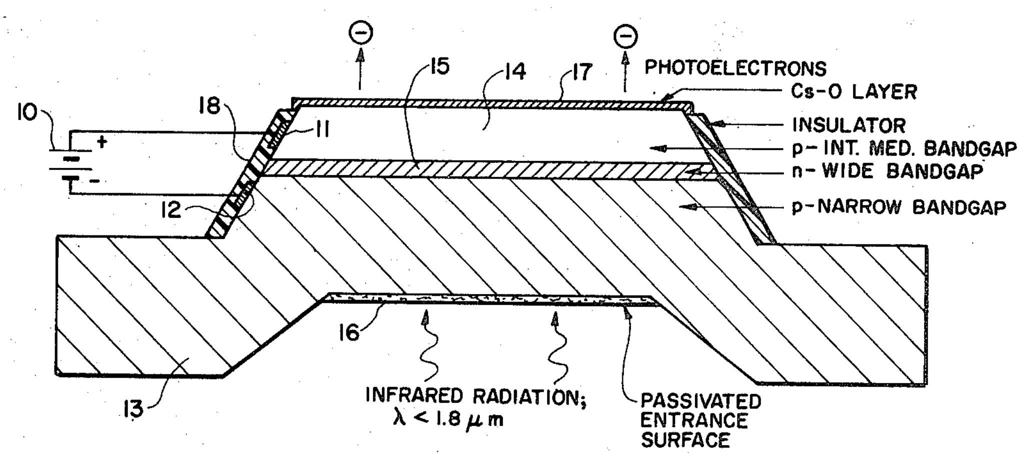
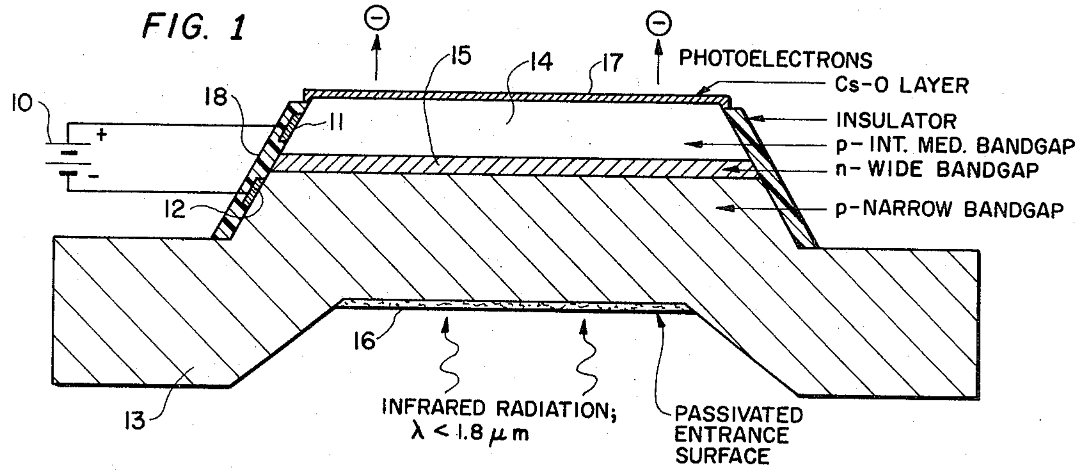


FIG. 1



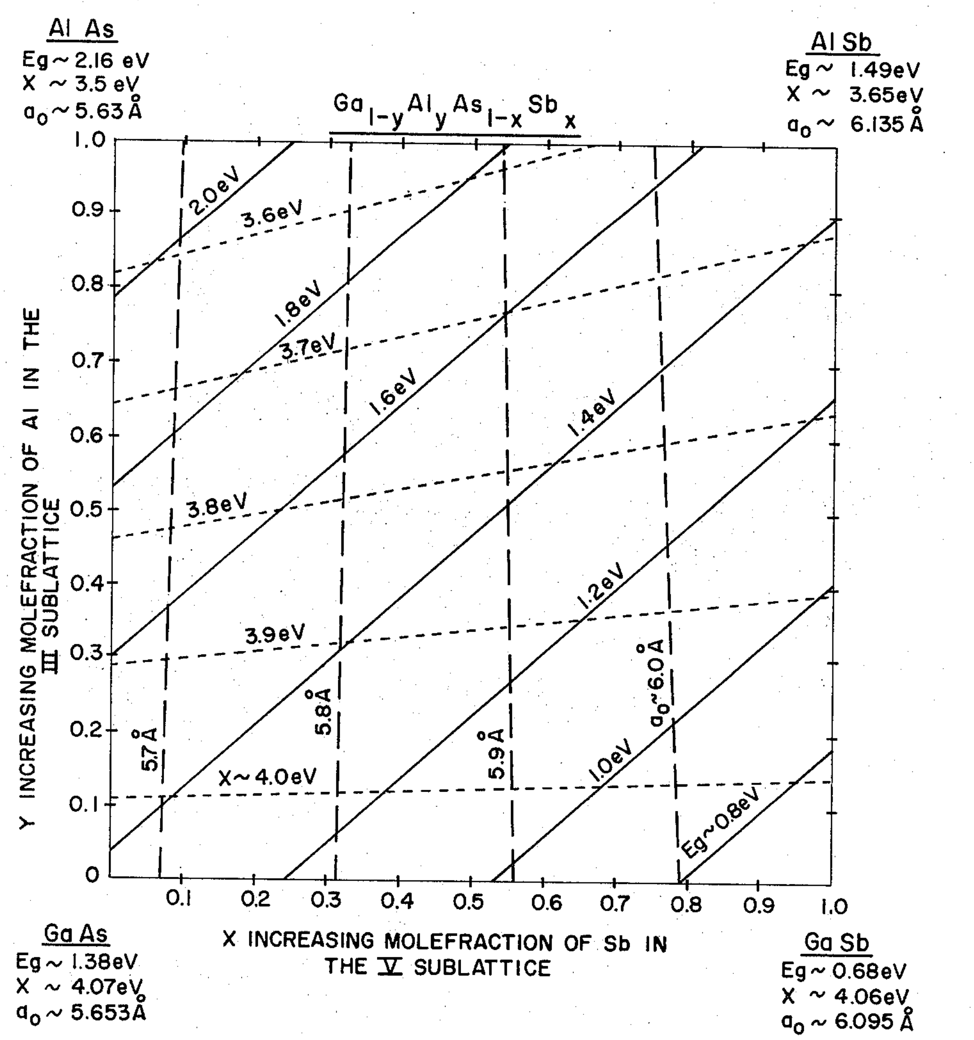
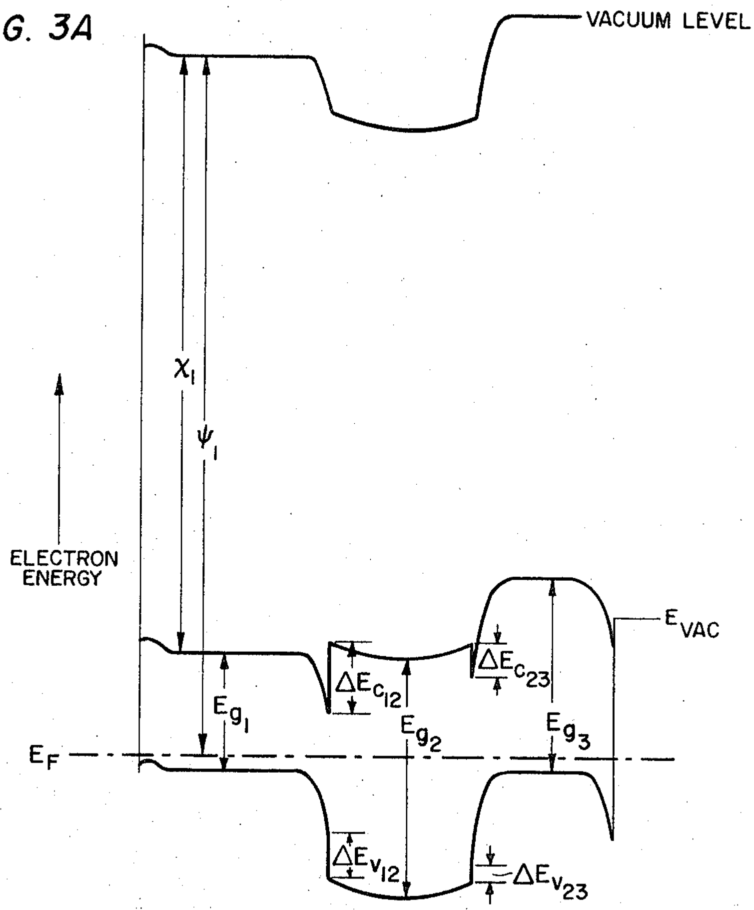


FIG. 2

LEGEND:
——— ISO BANDGAP @ T = 300°
-------- ISO ELECTRON AFFINITY
— — — ISO LATTICE CONSTANT

FIG. 3A



$GaSb_{80}As_{20}/AlSb_{75}As_{25}/Al_{70}Ga_{30}Sb_{75}As_{25}/Cs\text{-}O$

FIG. 3B

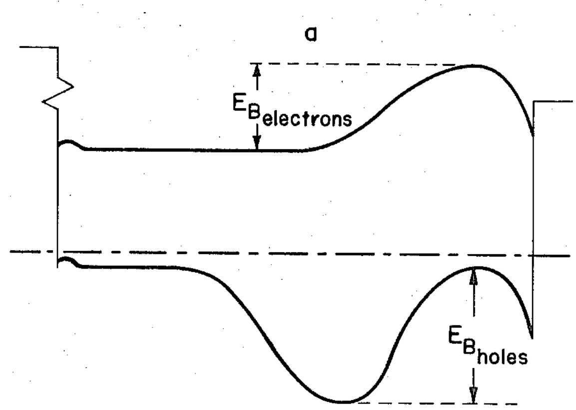


FIG. 4

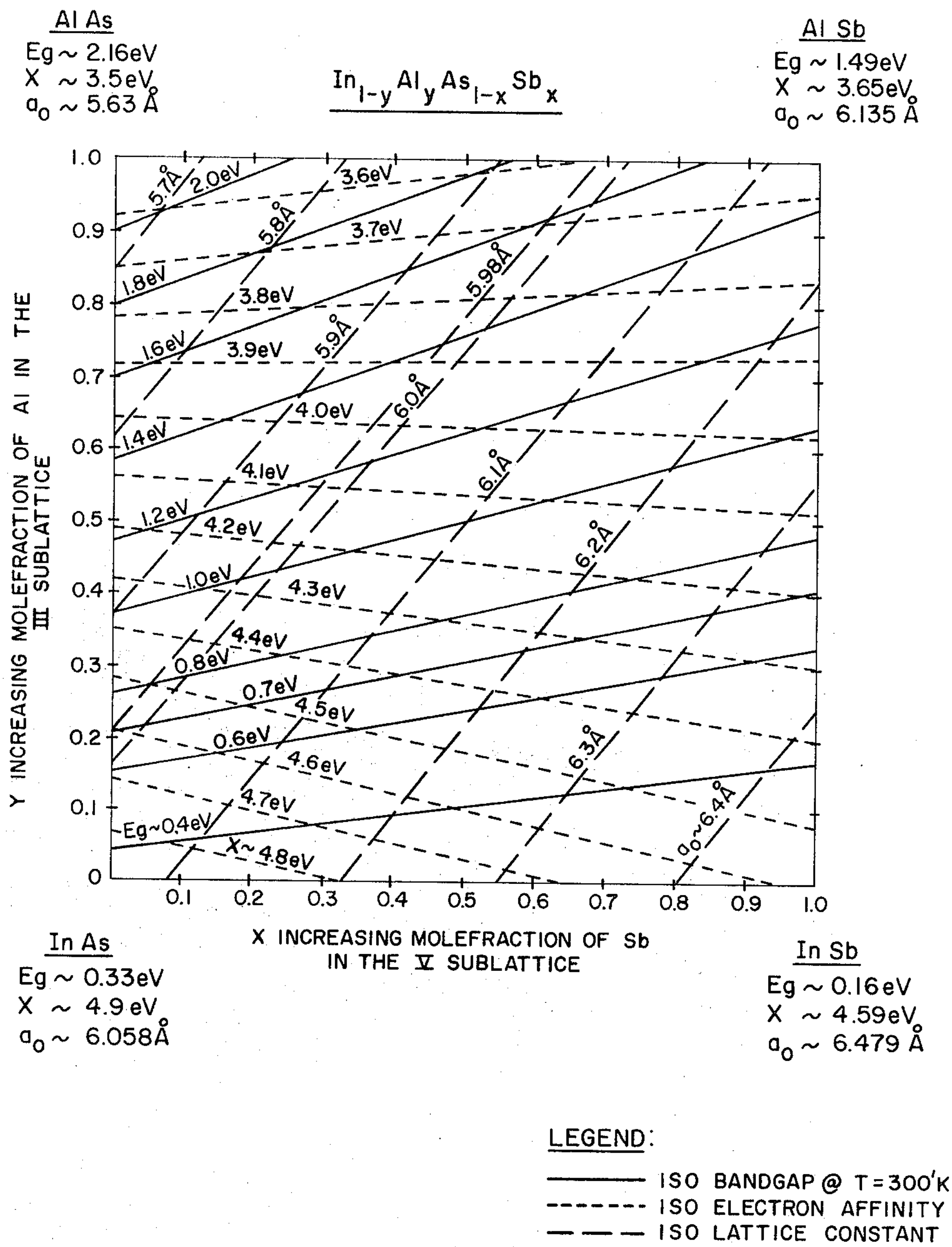

Al As
Eg ~ 2.16eV
X ~ 3.5eV
a0 ~ 5.63 Å
$In_{1-y}Al_yAs_{1-x}Sb_x$
Al Sb
Eg ~ 1.49eV
X ~ 3.65eV
a0 ~ 6.135 Å
Y INCREASING MOLEFRACTION OF Al IN THE III SUBLATTICE
X INCREASING MOLEFRACTION OF Sb IN THE V SUBLATTICE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2.0eV
1.8eV
1.6eV
1.4eV
1.2eV
1.0eV
0.8eV
0.7eV
0.6eV
Eg~0.4eV
3.6eV
3.7eV
3.8eV
3.9eV
4.0eV
4.1eV
4.2eV
4.3eV
4.4eV
4.5eV
4.6eV
4.7eV
X~4.8eV
5.7Å
5.8Å
5.9Å
5.98Å
6.0Å
6.1Å
6.2Å
6.3Å
a0~6.4Å
In As
Eg ~ 0.33eV
X ~ 4.9 eV
a0 ~ 6.058Å
In Sb
Eg ~ 0.16eV
X ~ 4.59eV
a0 ~ 6.479 Å
LEGEND:
ISO BANDGAP @ T=300°K
ISO ELECTRON AFFINITY
ISO LATTICE CONSTANT

FIG. 5A

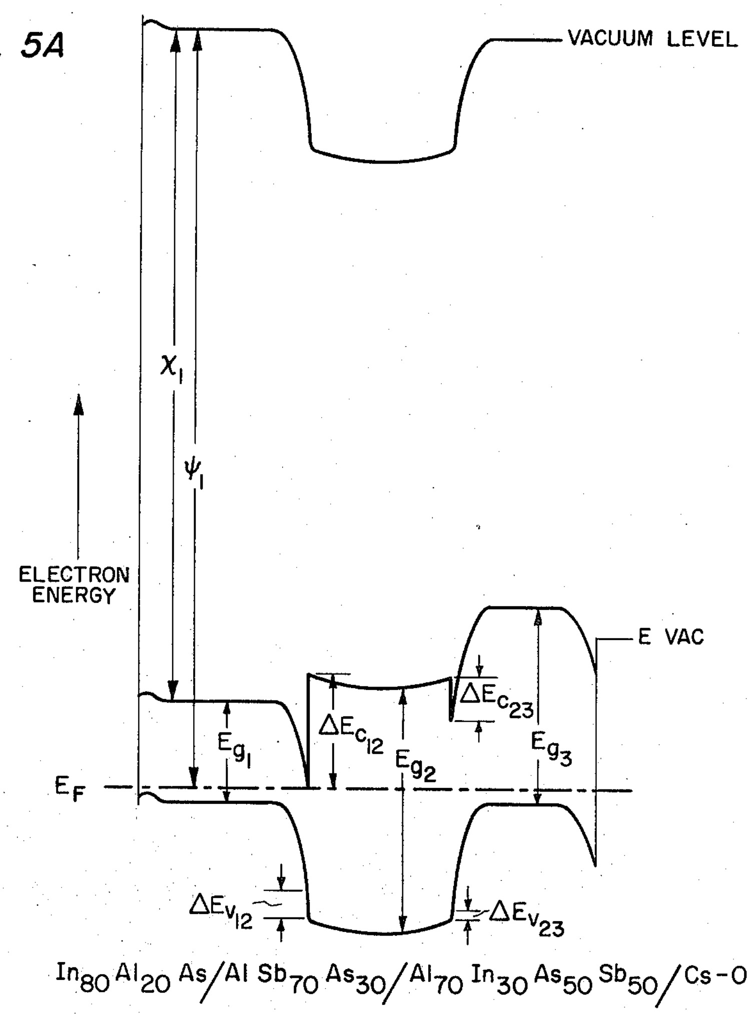
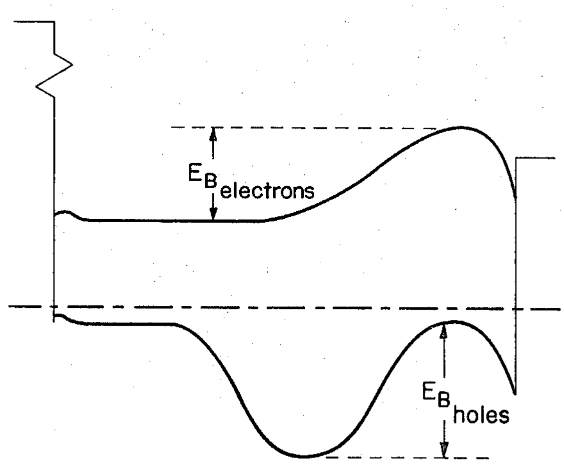

VACUUM LEVEL
χ_1
ψ_1
ELECTRON ENERGY
E VAC
$\Delta E_{c_{12}}$
$\Delta E_{c_{23}}$
E_{g_1}
E_{g_2}
E_{g_3}
E_F
$\Delta E_{v_{12}}$
$\Delta E_{v_{23}}$
$In_{80}Al_{20}As/AlSb_{70}As_{30}/Al_{70}In_{30}As_{50}Sb_{50}/Cs\text{-}O$

FIG. 5B


$E_{B_{electrons}}$
$E_{B_{holes}}$

TUNEABLE INFRARED PHOTOCATHODE

The invention described herein may be manufactured, used, and licensed by or for the Government for governmental purposes without the payment to me of any royalty thereon.

BACKGROUND OF THE INVENTION

This invention disclosure relates to photocathodes, and more particularly to tuneable field assisted photocathodes responsive to infrared radiation.

Prior art attempts to fabricate high performance field assisted infrared photocathodes of III–V quaternary compounds have not met with very great success. Some of the major problems lie in the field enhancement area where external field enhancement induces only a small threshold extension that renders such a method practically useless. Moreover, the high fields required to produce this effect in proximity focused image intensifier tubes usually create arcing, due to the microscopic irregularities either on the cathode or on the phosphor surfaces. Geometric effect at these points of irregularities increase the electric field locally that invaribly produces electrical breakdowns. Even though internal field enhancement with back biased p-n junctions will induce a bandgap limited threshold extension, it suffers from a significant reduction in area efficiency which is primarily due to the fact that efficient photoemission takes place only along a strip on the *p* side of the junction regions where the work function lowering is the most effective.

The graded bandgap approach is one of the most elegant attempts to overcome these problems, but it suffers from the technical difficulties in applying a bias potential across the device. This device is essentially a low to medium conductor and the heating due to power consumption generally renders it inoperative.

Most of the proposed homo-heterojunction and heterojunction devices of different materials are conceptually feasible, but the current transport across the junctions under low level injection is very low. Moreover, the impurity doping associated with the interdiffusion of materials at the heterojunction interface creates a built in potential barrier which essentially blocks the current flow.

SUMMARY OF INVENTION

The present invention very effectively overcomes the disadvantages of the prior art while simultaneously encompassing all the advantages thereof. Transporting of the photogenerated electrons through the heterojunctions is significantly enhanced by fabricating both heterojunctions of ternary and quaternary III–V semiconductors that have identical lattice constants and by utilizing an emitter layer having a wide enough bandgap to provide for a high efficiency negative electron affinity photoemitter. Moreover, with these types of materials, the heterojunctions can be graded over the composition range from one bandgap to the other, which eliminates the notch and spike type conduction band edge discontinuities created by an abrupt change in the electron affinities.

The general purpose of this invention is to effect the development of high efficiency photocathodes sensitive in the 1 – 2 micrometer spectral range. This purpose is accomplished by structuring a three layer double heterojunction photocathode such as pInAlAs/nAlSbAs/p+AlInAsSb or pGaSbAs/nAlSbAs/p+AlGaSbAs which has a constant lattice constant and operates on a field enhanced electron transfer principle from the narrow to the wider bandgap regions for effecting an efficient vacuum emission of photoelectrons generated in the 0.65 – 0.7 electron volt bandgap region, which obviously is too narrow for direct emission over the vacuum surface barrier.

BRIEF DESCRIPTION OF THE DRAWINGS

The exact nature of this invention will be readily apparent from consideration of the following specification relating to the annexed drawings wherein:

FIG. 1 depicts a cross section view of a three layer, double heterojunction infrared photocathode;

FIG. 2 shows design curves of the electronic properties of the $Ga_{1-y}Al_yAs_{1-x}Sb_x$ quaternary alloy system;

FIGS. 3A, 3B and 5A, 5B portray energy band diagrams for field assisted semitransparent or opaque infrared photocathode sensitivities out to 1.6 and 1.8 microns respectively; and

FIG. 4 shows design curves of the electronic properties of the $In_{1-y}Al_yAs_{1-x}Sb_x$ quaternary alloy system.

DESCRIPTION OF THE INVENTION

The double heterojunction type field assisted photoemitter shown in FIG. 1 is designed to operate in the 1 – 2 micrometer spectral region where currently no direct vacuum photoemission is possible. The reason for this spectral range limitation of state-of-the-art photocathodes is that even the most suitable photoelectronic materials (e.g. GaAs, InP, GaInAs, InAsP and Si) with the lowest work function cesium oxide surface treatment exhibit an approximately 1.1 electron volt surface barrier. This corresponds to a threshold of 1.1 micrometers. However, vacuum photoemission past 1.1 micrometers can be obtained if the generation of photoelectrons occur in a 0.6–0.7 electron volt bandgap material and if these electrons are transferred into another semiconductor with a bandgap of 1.3–1.4 electron volts from which the probability of escape is high.

The principle of operation of the device in the present invention fully meets these requirements. The narrow bandgap (0.7–0.8 electron volts) GaSbAs or InAlAs layers serve as the detector of infrared radiation and the cesium oxide treated AlGaSbAs or AlInAsSb layers as the high quantum efficiency photoemitter. Sandwiched between the detector and the emitter is wide bandgap (1.65–1.75 electron volt) AlSbAs layer which has an approximately 0.3–0.5 electron volt larger barrier to hole current than to electrons. Thus, the flow of electrons is aided but the hole current is blocked when the emitter layer is biased positively with respect to the detector layer.

Experiments with heterojunctions has shown that in the case of abrupt junctions at low injection levels the transport efficiency is low. This is because either of the spike and notch type discontinuities in the conduction band as predicted by theory, or due to strain induced interface states that can take up some of the charge. Actually interface states could be an advantage since the empty donor like states are positive which should aid the initial current flow. Even when these type of states are occupied they are neutral as opposed to the acceptor like states which when occupied are negative and thus would reduce or block the flow of electron current. However, the problem associated with the surface or interface states can be significantly reduced by grading the hetero-junctions as shown in FIG. 3B and FIG. 5B.

The fabrication of graded junctions is actually the most preferred method for the following reasons; 1. reduces the strain due to small variations in the lattice constants and thermal expansion coefficient, 2. the width of the middle layer is reduced and thus the charge transfer efficiency is increased, and 3. higher level of n-type doping of the center layer is possible. Actually, the net barrier height to the hole current depends strongly on the n-type doping of the center layer, but the level of doping must satisfy the requirement that the entire region is totally depleted of electrons in order not to produce cold cathode action. In this case any free charge is only a contribution to the dark current (noise). Thus, if by grading the heterojunctions the center layer is made very narrow, on the order of a few hundred Angstroms, heavy n-type doping is allowable, since the requirement to create charge neutrality in both heterojunction depletion regions will totally deplete the center layer.

Referring specifically to FIG. **1**, one embodiment of the envisioned photocathode is shown in cross section fabricated as a functional structure in a mesa configuration. The particular design configuration is not critical to the operation of the device such that variation thereof may be made to meet the particular criteria required by the various uses thereof. A biasing source **10** is shown connected in a biasing relationship across terminals **11** and **12.** Terminal **12** is conductively attached to the light absorbing layer **13** and terminal **11** is likewise connected to the electron emitting layer **14.** With the polarity of bias shown, the transport of photogenerated electrons is greatly enhanced across the double junction at the interfaces of layers **13, 14** and **15.** In the particular embodiment shown, layer **13** is of a p-type material having a narrow bandgap. A portion of one surface of layer **13** may be treated to produce a passivated entrance surface for the radiation impinging thereon. Surface treatment for passivation is a well known practice in the art and will not be further explored here.

Layer **15**, hetero-epitaxially grown on layer **13** is a totally depleted wide bandgap n-type material which possesses the sole function of blocking the hole current during biasing, whereas layer **14** is a p-type intermediate bandgap material functioning as an electron emitter and the thin layer **17** is a low work function material, in this instance a coating of cesium oxide.

An insulating layer **18** of silicon nitride or silicon dioxide completely encapsulates electrical contacts **11** and **12** to prevent the shorting out of the junctions.

The design curves of FIGS. **2** and **4** show the electronic and crystallographic properties of the $Ga_{1-y}Al_yAs_{1-x}Sb_x$ and $In_{1-y}Al_yAs_{1-x}Sb_x$ quarternary alloy systems respectively.

In the diagram the bandgap, electron affinity and crystallographic lattice constant variations are superimposed on the alloy compositional plane in a topological representation. The curves are generated by plotting the bandgaps (E_g) electron affinities (x) and lattice constant (a_o) values of the four individual binary III–V components (i.e. GaAs, AlAs, AlSb and GaSb in the case of FIG. 2 and InAs, AlAs, AlSb, and InSb in the case of FIG. 4) at the corners of the rectangular alloy composition base plane. A bandgap surface, an electron affinity surface and a lattice constant surface is drawn across the corner points. In these three dimensional diagrams the elevation represents the variations in the bandgap, electron affinity and lattice constants as a function of composition. Intercepts of these surfaces with a plane that is parallel with the alloy composition plane will produce constant bandgap, constant electron affinity and constant lattice spacing lines. The orthogonal projection of these lines onto the compositional base plane result in the topological representation. Moreover, the perimeter of the quaternary diagram represent the variations in the electronic and crystallographic properties of four different ternary alloy systems. (i.e. GaAlAs, AlAsSb, AlGaSb and GaAsSb of FIG. **2** and InAlAs, AlAsSb, AlInSb and InAsSb of FIG. **4**)

From the point of view of the three layer double heterojunction photocathode the optimized set of parameters would provide the largest bandgap range at a constant lattice spacing. Thus, depending on the infrared threshold requirement of the detector, the chemical composition of each of the three layers with appropriate bandgaps can be determined by reading along a constant lattice spacing line on the diagram.

FIGS. 3A, 3B, 5A and 5B are energy band diagrams for a field assisted semitransparent or opaque infrared photocathode that is sensitive out to 1.6 microns for FIGS. 3A and 3B and to 1.8 microns for FIGS. 5A and 5B. The electronic material used is the $Ga_{1-y}Al_yAs_{1-x}Sb_x$ quaternary alloy system shown in FIG. **2** and the $In_{1-y}Al_yAs_{1-x}Sb_x$ quaternary alloy system in FIG. **4.** To optimize the electronic properties of the material and also to satisfy the bandgap requirements of the device, the alloy is graded along the 6 angstrom and 5.98 angstrom constant lattice spacing lines, respectively. This results in an alloy composition from FIG. **2** of $GaSb_{80}As_{20}/AlSb_{75}As_{25}/Al_{70}Ga_{30}Sb_{75}As_{25}$ for the three layers and an alloy composition from FIG. **4** of $In_{80}Al_{20}As/AlSb_{70}As_{30}/Al_{70}In_{30}As_{50}Sb_{50}$ for the three layers.

FIGS. 3A and 5A show interface - state free energy band diagrams of the p-n-p hyper abrupt heterojunction structure. Eg denotes the magnitude of the energy bandgap and ΔE_c the conduction band edge discontinuities. The surface of the emitting layer is activated to a state of negative electron affinity. FIGS. 3B and 5B show the same heterojunction structure as in 3A and 5A respectively but it is graded to eliminate the notch and spike type discontinuities, $\Delta E_{c_{12}}$ and $\Delta E_{c_{23}}$, in the conduction band edge. The graded potential, $E_{B_{electrons}}$ due to electron affinity variation can be reduced and eliminated by the application of an external voltage. The ability to block the hole current during biasing is provided by the barrier to holes $E_{B_{holes}}$ being 0.3 to 0.5 volts larger than the barrier to electrons $E_{B_{electrons}}$.

Various modifications are contemplated and may obviously be resorted to by those skilled in the art without departing from the spirit and scope of the invention, as hereinafter defined by the appended claims, as only one embodiment thereof has been disclosed.

I claim:

1. An epitaxially graded multijunction photoemitter responsive to radiation in the 1–2 micrometer spectral region comprising a three layer double heterojunction structure having an essentially constant lattice spacing throughout, wherein:

a first layer of light absorbing III–V compound alloy semiconductor material having a narrow bandgap in the range of 0.65 – 0.8 eV functions as a detector of incident infrared radiation;

a second layer of III–V compound alloy semiconductor material having a wide bandgap in the range of 1.65 – 1.75 eV is heteroepitaxially grown on the first layer and functions to block the hole current and aid the electron current when biased positively with respect to the detector layer;

a third layer of III–V compound alloy semiconductor material having an intermediate bandgap, with respect to layers one and two, epitaxially grown on the second layer for functioning as a high quantum efficiency electron emitter;

first and second electrically conductive terminals attached respectively to the first and third layers of the heterojunction structure for effecting a positive biasing across the second layer with respect to the detector layer.

2. The epitaxially graded multijunction photoemitter of claim **1** wherein the three layers of III–V compound alloy semiconductor material consist of GaSbAs, AlSbAs and AlGaSbAs respectfully.

3. The epitaxially graded multijunction photoemitter of claim **1** wherein the three layers of III–V compound alloy semiconductor material consist of InAlAs, AlSbAs and AlInAsSb respectfully.

4. The photoemitter of claim **2** wherein the specific composition of the III–V quaternary compound alloys are determined in accordance with the alloy composition of $Ga_{1-y}Al_yAs_{1-x}Sb_x$ as read from the design curve of FIG. **2.**

5. The photoemitter of claim **3** wherein the specific composition of the III–V quaternary compound alloys are determined in accordance with the alloy composition of $In_{1-y}Al_yAs_{1-x}Sb_x$ as read from the design curve of FIG. **4.**

6. The photoemitter of claim **1** further including a layer of low work function material immediately absorbed on the exposed surface of the third layer of the electron emitting semiconductor material.

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